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ABSTRACT

Investment in the United Kingdom Continental Shelf (UKCS) involves three separate but highly interrelated activities: exploration, development and production. The exploration and extraction decisions were analysed recently by Pesaran (1990) and Favero (1990).

The aim of this paper is to provide a model of the investment decision in the UKCS, where the development process is explicitly modelled within an intertemporal optimization framework. The model highlights the importance of the lengthy time lags that exist between price and tax changes and changes in oil supplies from the UKCS. The empirical results show significant improvements over the previous studies, demonstrate the importance of theoretical considerations in modelling the oil supply process, and illustrate the pitfalls involved in relying on standard unrestricted distributed lag models in econometric analysis of oil investment.

CONTENTS

1.INTRODUCTION

The aim of this paper is to propose and estimate an econometric model for the exploration development and extraction of oil in the North Sea. The starting points of our analysis are the recent studies by Pesaran(1990) and Favero(1991). Pesaran (1990) proposes and estimates an intertemporal model of the exploration and production policy of price–taking suppliers. The optimal decision rules for exploration and production are derived by solving a constrained stochastic intertemporal profit maximization problem. The model recognizes two types of costs: exploration expenditures and the costs of development and production which is assumed to be a convex function varying positively with the rate of extraction and negatively with the level of remaining proven reserves. This cost function is justified on the basis of the available engineering information concerning the determinants of the pressure dynamics of the petroleum reserves [Uhler(1979)]: current extraction, by reducing the level of reserves and the reservoir's pressure tends to increase extraction costs. By the same argument, any increase in reserves, reduces future extraction costs.

The firm faces two constraints : a technical relation linking the change in reserves to production, discovery and revisions to previously discovered reserves, and a discovery function, proposed originally by Kaufman (1975), which makes discovery a concave function of the rate of exploratory effort and its cumulative level. The solution of the intertemporal optimization problem facing the firm yields two decision rules, one for the rate of production and the other for the rate of exploratory effort.
These decision rules are then consistently estimated by the Non Linear Instrumental Variables method. Pesaran(1990) obtains the following results:

- The Rational Expectations Hypothesis applied to oil prices is rejected in favour of the Adaptive Expectations Hypothesis

- The estimates of the parameters of the costs function imply marginal extraction costs in the range \$2.98\$–\$151.02, which is clearly implausible

- A point estimate for the discount rate is obtained from the coefficient on prices in the equation for the rate of extraction. A sensitivity analysis on the results reveals that the lower the value of the discount rate, the better is the fit of the equation and the higher the estimates of the marginal extraction costs. This trade–off between statistical fit and the plausibility of the estimates leads the author to set the discount rate to infinite, to obtain marginal extraction costs ranging between \$2.17 and \$17.25.

– The value of zero for the discount factor is retained when the exploration equation is estimated. The results suggest that the discovery decline phenomenon may have already started on the UKCS.

Favero (1991) investigates the effects of omission of taxation from the model. This later paper shows that the tax system in the UKCS has been non–neutral and should therefore be allowed for in the analysis of oil production and exploration. When the tax system is explicitly included into the model, more plausible estimates of the marginal extraction costs are obtained and the Rational Expectations hypothesis applied to prices cannot be rejected. However, the trade–off between statistical fit and implausibility of the estimates is still present and a discount factor of zero is therefore imposed in the supply equation and maintained in the exploration equation.

This paper builds on the above two papers and explicitly allows for the development phase in the oil supply process. The common assumption in the theory of exhaustible resources of a fixed stock of reserves from which extraction takes place [see, for example, Hotelling (1931), Stiglitz (1976), Das Gupta and Heal (1979)] does not apply to the North Sea, where the investment decision in exploration and development largely determine the quantity of reserves available for production, with average lags as long as five or six years. Pesaran (1990) recognizes the importance of this point but confines his analysis to exploration. However, as recently pointed out by Adelman (1990), development also plays a crucial role in the oil supply process.

The present paper provides a model of the investment decision on the UKCS, where the development process is modeled explicitly, along with the exploration and extraction stages, within an intertemporal optimization framework. The paper also presents new empirical results on the extraction and exploration equations and highlights the importance of allowing for the long lags that exist between prices and tax changes and their effects on oil supplies.

The paper is organized as follows: section 2 contains a descriptive analysis of a typical investment project in the North Sea, and provides the background to the economic and econometric analyses that follow. The theoretical model is set out in section 3. The relevant decision rules are derived and discussed in section 4, while section 5 presents the results and discusses their statistical and economic significance.

2. OIL INVESTMENT IN THE NORTH SEA

A typical investment project in the North Sea consists of three main phases: exploration, development, and extraction. The development phase can be sub–divided into an appraisal stage and a proper development stage. The three main phases are illustrated in figure 1, where the cumulative cash flow for a typical field on the UKCS is shown[1]. In this illustration the project's life–time is about thirty years. Not surprisingly, there is considerable uncertainty surrounding the exploration activity. It generally takes from six to ten years before a field worth developing is discovered. Once discovered, a further eight years elapse on average before the field is developed and made ready for production. It is worth noting that, from the date that the project is undertaken, it takes about fifteen years before it reaches payback. It is therefore important to take account of these long lags in the econometric analysis of the investment process in the North Sea. However, before embarking on the development of a suitable econometric framework capable of accommodating these long lags, it is instructive to examine in more details the three main phases of an investment project.

2.1 Exploration

The exploration phase comprises three main activities: scouting, concession and exploration. Before drilling exploration wells on the UKCS a company has to obtain a license. The application for a license is preceded by a scouting stage, in which a company undertakes geological surveys of an area and examines available data on wells drilled in the general vicinity. The licensing process is the first intervention of the government in the investment process. Licenses have been awarded in rounds usually on a discretionary basis, and only exceptionally blocks have been offered for auction.
The criteria according to which applicants are judged are published in the Gazette, a formal paper produced by the government. Applicants are mainly judged on their technical competence, on their financial capabilities, and on their past exploration record. The license stipulates the relinquishment and the date of expiry, the rental and royalty and the work program. The relinquishment clause states that after a period of six to seven years a fixed proportion (which varies from 50 per cent to 75 per cent in the different licensing rounds) of the block awarded has to be returned to the government. The license usually remains in force for forty years before expiring. Companies are required to pay a license rental, which increases over time, and a royalty, which is currently set at 12.5 per cent of the total revenue from oil and gas production. Lastly, on the awarding of licenses companies commit themselves to an exploration work programme.

After the license has been awarded the drilling stage begins. First exploration wells

[1]The idea of this figure is taken from Lovegrove (1985)

are drilled. At this stage companies usually hire a rig and drill "wildcat" wells. If the wells do not turn out to be dry the company enters the appraisal phase, drilling delineation wells and analyzing the various development options.

The available time series on exploration are the total exploration expenditure and the number of exploration and appraisal wells drilled. Figure 2 displays the number of exploration and appraisal wells drilled, and the real oil price.[2] Casual observation reveals immediately a link between the exploratory effort and the (expected) real oil prices. Such a relation is one of the "stylized facts" that we take into account in the specification of the economic and the econometric models.

2.2 Development

Development activity can be separated into two stages: appraisal and technical development activities. After licensing, there is a second level of intervention by the government in the investment activity: the Annex B approval. In order to obtain permission to proceed with development and extraction, firms must submit the Annex B to the Secretary of State for Energy. Before taking the formal step of submitting the Annex B, firms first carry out appraisal drilling and, if this is satisfactory, they set out a project plan, in collaboration with the Department of Energy. When a satisfactory plan is completed, it is formalized into the Annex B. The Annex B specifies the type of development envisaged, the off–shore loading system, the location of platform, sub–sea wells, pipelines, the terminals and the maximum and the minimum quantity of oil and gas that are expected to be produced each year. Once the Annex B has been approved, firms go on with development expenditures which, as defined in the "Brown Book"[3], include expenditure on platform structures, modules and equipment, offshore loading system, pipelines, terminals and development wells.

We define the development lag as the time period between the discovery of a field and the production start–up. As shown in figure 5, the total development lag varies from field to field. It has a mean lag of 24 quarters and a standard deviation of 13 quarters. The total development lag can be split into two components: the appraisal lag and the technical development lag. The appraisal lag (figure 3) is the period between the date of discovery of the field and the date of government approval of the development plan for the field (i.e. the approval of the Annex B). Appraisal lag has a mean of 15 quarters with a standard deviation of 14 quarters. The technical

[2]The UK real oil prices are computed by deflating the price of Brent crude with the average quarterly index of export prices of industrial countries computed by the IMF (see the Data Appendix in Pesaran(1990) for more details)

[3]Brown Book is the common name for a yearly publication of the U.K. Department of Energy entitled "Development of the Gas and Oil Resources of the United Kingdom"

development lag (figure 4) is the period between the date of Annex B approval and the date of production start–up. It has a mean of 9 quarters with a standard deviation of 4 quarters.

Since in our study we will use aggregate time series data, it is important to consider the frequency distribution of development lags, weighted for the total reserves recoverable from each field. The weighted appraisal lag has a mean of 9 quarters with a standard deviation of 6 quarters. The weighted technical development lag has a mean of 10 quarters with a standard deviation of 5 quarters. The time span taken by development is a crucial feature of investment in the North Sea and it will play a central role in the formulation and the estimation of our model.

The amount of development effort is one of the key decision variables for the firm operating on the UKCS. To proxy development effort in our econometric study we use the number of development wells drilled in each period. As we have done for exploratory effort, we plot it along with real oil prices in figure 6. Also here the outstanding feature is the relation between (expected) real oil prices and development effort.

2.3 Extraction

The quarterly rate of extraction of oil, as displayed in figure 7, shows fluctuations around a non–linear trend. Neither the trend nor the fluctuations seem, at first sight, to be influenced by the level of real oil prices. In figures 8 and 9 we report the pattern of production from individual oil fields of different sizes. It is noticeable that the production profiles from big, medium and small oil fields are very similar, and do not vary much across different time periods, which featured very different levels of real oil prices.[4]

Two aspects of the extraction phase are particularly relevant to econometric modeling: operating expenditure and taxation. Operating expenditure reflects costs of extraction. Figure 10 shows the movement of this variable expressed in real terms. There is a clear upward trend in operating expenditures and it seems to be strongly related to the production pattern. It is also noticeable that the pattern of operating expenditure is different from the pattern of exploration and development expenditures in that it does not seem to be influenced by price movements. Pesaran (1990) proposes a model of operating expenditure which takes account of the available engineering information concerning the pressure dynamics of the petroleum reserves. The function is assumed to be convex with positive marginal cost of extraction. For a given level of reserves, costs are assumed to be negatively related to reserves, capturing the fact that the amount of reserves in the ground determines the pressure dynamics of the

[4]The production pattern for the individual fields are obtained from NatWest Wood McKenzie.

reservoir, and the higher the pressure the lower the cost of extraction. Pesaran (1990) does not estimates the operating cost function directly but derives estimates for its parameters from the Euler Equation for the intertemporal optimization problem of the representative firm. We retain such a specification for the costs of extraction but we estimate it directly, using the data on operating expenditure provided in the "Brown Book".

The second aspect of the production stage relevant to the modeling exercise is the fiscal regime. The taxation system on the United Kingdom Continental Shelf (UKCS) has been extensively considered in another paper [Favero(1992)] and we will only briefly review the main aspects of it here. The oil fiscal regime on the UKCS was introduced by the Oil Taxation Act in 1975 and operates essentially in three stages [Mabro et.al.(1986)].

The first stage is the payment of a royalty based on the gross field revenues. The royalty can be paid in cash or in kind and it has been fixed at 12.5 per cent of the revenue over the entire sample period. The second stage is the Petroleum Revenue Tax (PRT). The PRT is assessed on a field by field basis: around each field a notional "ring fence" prevents external influences affecting the amount of the PRT bill paid. In practice a company has as many PRT assessments as it has shares in different fields, and company losses in one field cannot be set against profits in other fields. The third stage is the Corporation Tax (CT). CT is levied on the operating company and not on individual fields. Both the royalties and the PRT are deductible from the CT. As shown in Favero (1992), oil taxation is not neutral in the UK and it is therefore important that it is explicitly accounted for in the econometric analysis.

3.AN INTERTEMPORAL MODEL OF EXPLORATION, DEVELOPMENT AND EXTRACTION

In modeling the different stages of the oil supply process in the UKCS, we assume that producers are risk neutral and decide on the exploratory efforts, x_{1t}, x_{1t+1} ..., and the development efforts $x_{2t}, x_{2t+1}...$, and extraction $q_t, q_{t+1},...$by maximizing the expected discounted future streams of post–tax profits conditional on the information set Ω_{t-1}. The intertemporal optimization problem to be solved is defined by:[5]

$$\max_{\substack{q_t, q_{t+1}\cdots \\ x_{1t}, x_{1t+1}\cdots \\ x_{2t}, x_{2t+1}\cdots}} E\left\{\sum_{s=0}^{\infty} \beta^s \Pi_{t+s} | \Omega_{t-1}\right\}, \tag{1}$$

where $0 \leq \beta < 1$ is the discount factor and Π_t is the after–tax producer profit defined as,

$$\Pi_t = \alpha_{1t} p_t q_t - \alpha_{2t} C(q_t, Z_{t-1}) - \alpha_{3t} w_{1t} x_{1t} - \alpha_{3t} w_{2t} x_{2t},$$

where

$$\alpha_{1t} = \{1 - (\tau_{1t} + \tau_{4t}) - \tau_{2t}[1-(\tau_{1t}+\tau_{4t})] - \tau_{ct}[1-(\tau_{1t}+\tau_{4t}) - \tau_{2t}[1-(\tau_{1t}+\tau_{4t})]]\},$$
$$\alpha_{2t} = [1-\tau_{2t} - \tau_{ct}\tau_{2t}],$$
$$\alpha_{3t} = [1-\tau_{2t}\rho_t - \tau_{ct}\tau_{2t}\rho_t],$$

q_t:rates of extraction

x_{1t}:the rate of exploratory effort

w_{1t}:unit cost of exploratory effort

w_{2t}: unit cost of development effort

τ_{2t}: Petroleum Revenue Tax

τ_{3t}: Advance Petroleum Revenue Tax

Z_t: the level of recoverable reserves

x_{2t} :the rate of development effort

p_t : real well–head price

τ_{1t}: royalty

ρ_t: 1+ uplift on exploration costs

τ_{4t}: Supplementary Petroleum Duty

The forms of the tax variables α_{1t}, α_{2t} and α_{3t} are derived and extensively discussed in Favero (1991). Here it suffices to say that α_{1t} captures the impact of the tax system on the producer's revenue, while α_{2t} and α_{3t} capture the impact of the tax system on production, exploration and development costs.[6] The after–tax profits varies inversely with α_{1t} and directly with α_{2t} and α_{3t}. In fact α_{1t} is a measure of the reduction in the

[5]Notice that we are assuming that the time horizon of the firm is infinite. In reality the time horizon is long but finite (in the region of 35 years, for a large field). However, so long as β is not too close to unity our approximation should be valid.

[6]Using aggregate data, we cannot distinguish between allowances for development costs and allowances for exploration costs, therefore we have only one variable α_{3t} which is intended to capture allowances for development and extraction costs together .

marginal revenue due to taxation, while α_{2t} and α_{3t} are measures of the reduction in the marginal extraction and explorations cost due to allowances in the tax system.

The representative firm's total cost consists of three components : the exploration expenditure $w_{1t}x_{1t}$, the development expenditure $w_{2t}x_{2t}$, and the operating expenditure $C(q_t,Z_{t-1})$. The rate of exploratory effort, x_{1t}, is measured by the number of exploratory wells drilled. w_{1t} represents the unit cost of the exploratory effort, computed as the ratio of the total exploration expenditure to the number of exploratory wells drilled. The rate of development effort, x_{2t}, is measured by the number of development wells drilled after Annex B approval. The unit cost of development effort, w_{2t}, is then obtained as the ratio of total development expenditure to the number of development wells drilled.

The functional form for the operating expenditure is given by

$$C(q_t,Z_{t-1})/q_t = \delta_0 + \delta_1/q_t + \frac{1}{2}\left(\delta_2 + \frac{\delta_3}{Z_{t-1}}\right)q_t + \epsilon_t, \tag{2}$$

where q_t is the rate of extraction, Z_{t-1} is the size of the available reserves and ϵ_t represents unobserved random shocks to marginal extraction costs assumed to be orthogonal to the information set available at time t–1, $E(\epsilon_t \mid \Omega_{t-1})=0$.

In solving the optimization problem, the firm faces the following constraints:

$$q_t = \gamma Z_t, \tag{3}$$

$$\lim_{s\to\infty} Z_s = 0, \tag{4}$$

$$Z_t - Z_{t-1} = -\gamma Z_t + \mu(x_{2t-m})D_{t-(m+k)} + u_{1t}, \qquad E(u_{1t} \mid \Omega_{t-1})=0, \tag{5}$$

$$D_t = f\left[x_{1t}, X_{1t}\right] + u_{2t}, \qquad E(u_{2t} \mid \Omega_{t-1})=0, \tag{6}$$

$$X_{1t} = X_{1t-1} + x_{1t}. \tag{7}$$

Equation (3) reflects the fact that production is technically constrained to be a fraction of recoverable reserves and its time profile is determined primarily by engineering considerations rather than by economic optimization. Once a field is developed, it is the pressure dynamics of the field which largely determines the rate of extraction (see figure 8 and 9 and their discussion in section 2.3). Our linear specification could be interpreted as a local approximation to a more complicated non–linear relation. Equation (4) is the end point constraint for reserves and states that recoverable reserves will eventually run out. The change in the stock of recoverable reserves is defined by (5) as the difference between the new additions to recoverable reserves and the rate of extraction, plus a term representing revisions/extensions to the reserves.

The additions to recoverable reserves are assumed to be a fraction, μ, of past discoveries D, where μ is assumed to be an increasing function of past development effort and m is the length of the technical development lag. The total development lag, m+k, is the sum of the technical development lag, m, and the appraisal lag, k.
In principle m and k may vary with oil prices, but, as a first approximation, we consider them as fixed.[7] Equation (6) is the discovery function and relates the amount of discoveries, D_t, to exploratory effort x_{1t} and cumulative exploratory effort X_{1t}. Finally, equation (7) is an identity expressing the relation between the stock and the flow of exploratory effort, X_{1t} and x_{1t}, respectively.

3.1 Derivation of the Euler Equations

Given the price, cost and tax expectations $p^e_{t+s}=E(p_{t+s}|\Omega_{t-1})$, $w^e_{t+s}=E(w_{t+k}|\Omega_{t-1})$, $\tau^e_{i,t+k}= E(\tau_{i,t+k}|\Omega_{t-1})$, and an initial level of recoverable reserves, relations (1)–(7) completely define the decision environment of the firm. The First Order Conditions (FOC) for optimality can be obtained from unconstrained optimization of the following Lagrangean function:

$$L= E\left(\sum_{s=0}^{\infty}\beta^s G_{t+s}|\Omega_{t-1}\right),$$

with respect to $x_{1t+s}, x_{2t+s}, Z_{t+s}, X_{1t+s}$, $s= 0,1,2...$ where

$$G_t= \alpha_{1t}p_t(\gamma Z_t) - \alpha_{2t}\left(\delta_0+ \delta_1\gamma Z_t +.5\left(\delta_2 +\delta_3/Z_{t-1}\right)(\gamma Z_t)^2\right) - \alpha_{3t}w_{1t}x_{1t} -\alpha_{3t}w_{2t}x_{2t}+$$
$$+ \lambda_{1t}(X_{1t}-X_{1t-1}-x_{1t}) + \lambda_{2t}\left[Z_t- Z_{t-1} +\gamma Z_t -\mu(x_{2t-m})D_{t-m-k}-u_{1t}\right],$$

the auxiliary variables λ_{1t} and λ_{2t} are the Lagrange multipliers and the constraints (3) and (6) have been substituted directly in the objective function.
Focusing on the current decision variables, the Euler equations for this optimization problem can be written as[8]

$$E_{t-1}\left(\alpha_{1t}p_t\gamma-\alpha_{2t}\delta_1\gamma-\alpha_{2t}\gamma Z_t\left(\delta_2+\delta_3/Z_{t-1}\right)+.5\beta\alpha_{2t+1}(\gamma Z_{t+1})^2\left(\delta_3/Z_t^2\right)+\lambda_{2t}(1+\gamma)-\beta\lambda_{2t+1}\right)=0, \tag{8a}$$

$$E_{t-1}\left(-\alpha_{3t}w_{2t} -\beta^m\lambda_{2t+m}D_{t-k}\partial\mu(x_{2t})/\partial x_{2t}\right)= 0, \tag{8b}$$

[7]The preliminary results in Favero et al.(1991) suggest that the oil price expectations have a stronger impact on the appraisal lag than on the technical development lag. This can be explained by the fact that,once the Annex B is approved, the firms are precommitted to carry out a development program and hence have very little room to manouvre.

[8]It is assumed that the relevant transversality conditions are satisfied, and that the resultant solution is an interior one.

$$E_{t-1}\left(-\alpha_{3t}w_{1t} - \beta^{k+m}\lambda_{2t+m+k}\mu(x_{2t+k})(\partial D_t/\partial x_{1t}) - \lambda_{1t}\right)=0, \tag{8c}$$

$$E_{t-1}\left(-\beta^{k+m}\lambda_{2t+m+k}\mu(x_{2t+k})(\partial D_t/\partial X_{1t}) + \lambda_{1t} - \beta\lambda_{1t+1}\right)=0, \tag{8d}$$

$$E_{t-1}\left[Z_t - Z_{t-1} + \gamma Z_{t+\tau} - \mu(x_{2t+\tau-m})D_{t+\tau} - u_{1t}\right]=0, \tag{8e}$$

$$E_{t-1}(X_{1t} - X_{1t-1} - x_{1t})=0, \tag{8f}$$

where equations (8a)–(8f) have been obtained by differentiating the Lagrangean function with respect to Z_t, x_{2t}, x_{1t}, X_{1t}, λ_{1t} and λ_{2t}, respectively [see Whittle (1982)]. These relations form a set of highly non–linear stochastic equations, containing the non–observable co–state variables $\lambda_{1t}$and λ_{2t}. To obtain estimable relations we first use (8b), (8c) and (8d) to derive the following equations

$$E_{t-1}\lambda_{2t+m} = -E_{t-1}(\alpha_{3t}w_{2t})/\left((\beta^m D_{t-k}\partial\mu(x_{2t})/\partial x_{2t})\right) \tag{9a}$$

$$E_{t-1}\lambda_{1t} = -E_{t-1}(\alpha_{3t}w_{1t}) - \beta^{k+m}(\partial D_t/\partial x_{1t})E_{t-1}\left(\mu(x_{2t+k})\lambda_{2t+m+k}\right) \tag{9b}$$

The variables λ_{1t} and λ_{2t} can be interpreted as the net return to exploration and the net return to development at the margin, respectively. The net return to development is negatively related to the expected post–tax unit cost of exploratory effort, $\alpha_{3t}w_{2t}$, and is positively related to the marginal productivity of the development effort. The discount factor in (9a) enters as β^m because reserves for which development is begun at time t will contribute to firm's revenue only after production start–up, i.e. m periods later. Equation (9b) states that the net expected return to exploration at time t is negatively related to the expected unit cost of exploratory effort, $\alpha_{3t}w_{1t}$, and is positively related to the marginal productivity of exploratory effort appropriately discounted, $\beta^{k+m}(\partial D_t/\partial x_{1t})$. The discount factor in (9b) enters as β^{m+k} because actual discovery contributes to firm's revenue only after production start–up, i.e. m+k periods after the discovery date. However, the proportion of newly discovered reserves that becomes productive in m+k periods depends on the net return to development effort once Annex B approval is granted (i.e. after k periods), and hence the term $E_{t-1}\left(\mu(x_{2t+k})\lambda_{2t+m+k}\right)$.

4. THE EXTRACTION AND DEVELOPMENT EQUATIONS

For econometric analysis we need relationships that do not involve the unobservable co–state variables λ_{1t} and λ_{2t}. In view of the fact that decision to explore locks the firm into future development programs (k periods ahead), the elimination of the lagrange multipliers from the Euler equations requires the representative firm to know at time t–1 the level of development efforts that it is contemplating embarking upon at time t+k. We therefore assume that x_{1t} and x_{2t+k} are in the firm's information set at time t–1.[9] Also because of the effect of the development on future extractions, as reflected in equations (3) and (5), the firm needs to know the likely rate of development at time t+1, in order to solve for the contemporaneous extraction decision. However, this does not imply that the firm is making a pre–commitment and, as new information accrues, the development decision may be adjusted. Thus, we assume that the planned rate of development effort for period t+1 is in the firm's information set at time t–1, and equation (8b) can be used to eliminate λ_{2t} from equation (8a) to obtain:

$$
\begin{aligned}
&E_{t-1}\Big(\alpha_{1t+m}p_{t+m}\gamma - \delta_1\gamma\alpha_{2t} - \alpha_{2t+m}\gamma Z_{t+m}(\delta_2 + \delta_3/Z_{t+m-1}) + \\
&+.5\beta\alpha_{2t+m+1}(\gamma Z_{t+m+1})^2(\delta_3/Z^2_{t+m}) - (1+\gamma)[\alpha_{3t}w_{2t}/(\beta^m D_{t-k}\partial\mu(x_{2t})/\partial x_{2t})] + \\
&+\beta[\alpha_{3t+1}w_{2t+1}/(\beta^m D_{t-k+1}\partial\mu(x_{2t+1})/\partial x_{2t+1})]\Big)=0. \qquad (10)
\end{aligned}
$$

Similarly, since we are assuming that the firm at time t–1 knows the rate of development efforts in periods t+k and t+k+1, using (9a) and (9b) one obtains

$$
E_{t-1}\lambda_{1t}=-E_{t-1}(\alpha_{3t}w_{1t})-\beta^{k+m}(\partial D_t/\partial x_{1t})\Big(\mu(x_{2t+k})[\alpha_{3t+k}w_{2t+k}/(\beta^{m+k}D_t\partial\mu(x_{2t+k})/\partial x_{2t+k})\Big), \qquad (9c)
$$

which, if substituted in (8d), yields

$$
\begin{aligned}
&E_{t-1}\Big(-\beta^{k+m}\mu(x_{2t+k})(\partial D_t/\partial X_{1t})[\alpha_{3t+k}w_{2t+k}/(\beta^{m+k}D_t\partial\mu(x_{2t+k})/\partial x_{2t+k})] \\
&-[\alpha_{3t}w_{1t}+\beta^{k+m}\mu(x_{2t+k})(\partial D_t/\partial x_{1t})\alpha_{3t+k}w_{2t+k}/(\beta^{m+k}D_t\partial\mu(x_{2t+k})/\partial x_{2t+k})]+ \\
&+\beta\{\alpha_{3t+1}w_{1t+1}-\beta^{k+m+1}\mu(x_{2t+k+1})(\partial D_{t+1}/\partial x_{1t+1})[\alpha_{3t+k+1}w_{2t+k+1}/ \\
&/(\beta^{m+k+1}D_{t+1}\partial\mu(x_{2t+k+1})/\partial x_{2t+k+1})]\}\Big)=0. \qquad (11)
\end{aligned}
$$

Equations (10) and (11) do not depend on the non–observable co–state variables and, in principle, could be consistently estimated by Generalized Method of Moments

[9] Here we are also implicitly assuming that there is no active market in discovered oil fields.

(GMM) [see Hansen(1982)], for a given parametric form of the discovery and the development functions, namely the functions f(.) and μ(.) in (5) and (6), respectively. Unfortunately, given the data limitations, this procedure cannot be implemented in the case of the present problem. The valid instruments for estimating the parameters in (10) and (11) are dated t–m–k–1 or before, and the evidence in section 2 suggests estimates of k and m in the region of 9 quarters.

To proceed with estimation we will consider a linearized version of (10) and (11) and estimate supply and development equations of the following type

$$q_t = \beta_0 + \beta_1 q_{t-1}/Z_{t-2} + \beta_2 (q_{t-1}/Z_{t-2})^2 + \beta_3 \alpha_{3t-m} w_{2t-m} + \beta_4 \alpha_{3t-m+1} w_{2t-m+1} + \beta_5 \alpha_{1t} p_t^e + \beta_6 D_{t-m-k} + \beta_7 x_{2t-m} + \xi_{1t}, \quad (10a)$$

$$x_{2t} = \gamma_0 + \gamma_1 x_{2t-1} + \gamma_2 \alpha_{3t} w_{2t} + \gamma_3 \alpha_{3t-k} w_{1t-k} + \gamma_4 x_{1t-k} + \gamma_5 x_{1t-k+1} + \gamma_6 D_{t-k} + \xi_{2t}. \quad (11a)$$

In equation (10a), obtained by linearizing (10), extraction is related to operating costs, price expectations, the after–tax unit cost of development lagged m periods (to allow for the technical development lag), development effort lagged m periods, and discoveries lagged m+k periods.

One important feature of the above supply equation lies in its dynamic specification, whereby the lags involved between exploration, development and extraction are obtained from a microeconomic analysis of the duration lags across oil fields in the UKCS. This formulation is in contrast with the familiar dynamic specification methodology, where the lag lengths are derived empirically using the general to specific methodology [Hendry et al.(1984)].

In equation (11a) the rate of development effort depends on its own lag, on the post tax unit development costs, on the post–tax unit exploration costs lagged k and k+1 periods and on discoveries lagged k periods. The structure of the equation reflects the nature of the optimization problem which requires that the firm at time t takes a simultaneous decision on the rate of development efforts at times t+k and t+k+1. The theoretical rationale that underlies the supply equation also applies to the development equation.

4.1 The Empirical Results

In deriving the extraction and the development equations (10a) and (11a), we have made use of the form of the operating cost function given by (2). It is important to present empirical evidence on how well such a functional specification performs in practice. Making use of data on proven reserves as a proxy for recoverable reserves we have estimated equation (2) over the period 1978(3)–1989(2)

$$C_t = \underset{(-3.34)}{-440.35} + \underset{(4.20)}{6.11}q_t + (\underset{(-3.18)}{-.0013} + \underset{(2.23)}{11.33}/Z_{t-1})q_t^2 + \hat{\epsilon}_t q_t \qquad (12)$$

$\bar{R}^2$=.85 F–Statistic F(3,40)=79.49 σ = 39.02
Mean of Dependent Variable = 323.19

Serial Correlation: χ_4^2 = 4.95 (.30), Functional Form: χ_1^2 = 0.79(.37),

Normality: χ_2^2 = 0.40 (.81), Heteroscedasticity: χ_1^2 = 1.50 (.22),

where q_t is the rate of extraction, and C_t is total real operating expenditure[10]. The equation is estimated by OLS and t–ratios are reported with the estimated coefficients. In principle the rate of extraction may not be weekly exogenous for the relevant parameters in the cost function. In fact, even if the rate of extraction is totally determined by pressure dynamics of the oil fields, the cost of extraction will still be influenced by the techniques used to compensate the reduction in the reservoir's pressure caused by extraction (typically water injection). In principle, any modification in the operating costs achieved by technical progress may be reflected in an increase in the rate of extraction. Therefore, the existence of a simultaneous feedback between operating costs and production is in principle admissible. However the estimation of the cost function by IV method, using q_{t-1}, q_{t-1}^2 and q_{t-1}^2/Z_{t-1} as instruments, does not modify the OLS estimates reported above. In fact, when we tested the null of weak exogeneity of q_t and q_t/Z_{t-1} for the parameters of interest in the cost function, using a Hausman (1978) test, we could not reject it.

The operating cost function in (12) fits well and passes all the diagnostic tests[11]. Moreover it implies estimates for the marginal extraction costs that are within the acceptable range of 1–4$ per barrel. The estimated marginal extraction costs, with confidence bounds computed as twice the standard errors, are displayed in Figure 11. These estimates are more plausible than those obtained indirectly by Pesaran (1990) and Favero (1992).

Having shown that the data evidence does not reject our assumed specification for the operating cost function, we can turn now to the estimation of the extraction and the development equations (10) and (11). Estimation results for these equations are reported in Tables 1 and 3, respectively. From the statistical point of view, both equations fit very well and pass all the diagnostic tests, with the only exception of

[10]By estimating equation (12) in the unit cost form, namely by regressing C_t/q_t on a costant, $1/q_t$, q_t and q_t/Z_{t-1}, we obtained very similar results.

[11]The estimations are carried out on Microfit 3.0. See Pesaran and Pesaran(1991) for details on the estimation and on the computation of the diagnostic statistics

some marginal evidence of serial correlation in the residuals from the extraction equation. Figures 12 and 13 display the fitted and the actual values for the extraction and development equations, respectively.

The new results for the production equation reaffirm earlier findings on seasonality and on the importance of adaptive expectations for prices. They also reinforce the results obtained by Pesaran(1990) on the significance of the non–linear terms in the reserve variable, which captures the negative relationship existing between the level of reserves and the marginal extraction costs. There is no discrepancy between the signs of the estimated parameters and their theoretical values, although it is not possible to test formally the restrictions implied by the theory. This is primarily due to the fact that we have estimated a linearized form of the decision rules (10) and (11) without specifying explicitly the functional forms of the discovery and the development functions. However, the main contribution of this study in providing an empirical explanation of extraction on the UKCS, lies in demonstrating the significance of past discoveries, development and development costs for the determination of the rate of extraction. Using the information on development lag of individual oil fields, we have captured the impact of discoveries by considering an average of discoveries lagged 19,20,21,22 quarters. Similarly development effort and unit cost of exploratory effort lagged 9 and 10 quarters are relevant to explaining current rates of extraction. As in Pesaran (1990) and Favero(1991) the price variable is statistically highly significant.[12] It is worth noting that in the short–run the elasticity of production with respect to price (computed at the sample means) is .037, with a standard error of .004, while in the long run it becomes 1.04, with a standard error of .11. This result is generated by the structure of our model: current price signals have little direct effect on current rates of extraction, which are assumed to be largely determined by technical constraints. However, current price signals affect future production by determining the level of exploratory and development efforts. Since exploratory and development efforts require some time before they can have any effect on production, long lags must elapse before prices have any effect on production. It is very remarkable that the length of these lags is such that no traditional method of dynamic econometric specification, without the help of the theoretical insights regarding the structure of the investment activity in the United Kingdom Continental Shelf, would have led us to the supply equation estimated in this paper.

To evaluate the relevance of the individual oil fields data on appraisal and technical development lags for the dynamic specification of the supply function, we

[12]In principle it is possible that the adaptive expectations we have used are capturing a non–linear deterministic trend in the extraction function. To rule out such a possibility we have performed non–nested encompassing tests of our estimated model versus an alternative one, in which the price variable is substituted by a linear and a quadratic trend. The non–nested test clearly rejects the latter model.

carried out a sensitivity analysis by estimating the extraction equation (10a) for different values of k and m. The results are summarized in table 2. Panel A of this table gives the maximized log–likelihood values, while panels B and C present, respectively, the estimates of the coefficients of the discovery variable and of the price expectations variable (with the corresponding t–ratios in brackets) for different values of m and k in the range of 1–15 quarters[13]. These results clearly demonstrate the importance of a correct choice of the development and the appraisal lags (m and k) for the empirical performance of the extraction equation. As the lag lengths are allowed to deviate from the estimates obtained from individual oil fields data, the performance of the extraction equation worsens and the discovery variable looses its statistical significance. The price expectations variable is always significant but its t–ratio more than doubles when the lag lengths are specified in accordance with the microeconomic information. Finally, it is worth noting that the standard error of our model for production is about 40 per cent lower than the one obtained for the preferred extraction equation in Pesaran (1990) and Favero (1992).

The estimate of the development function is given in Table 3. To our knowledge this is the first example of such an econometric relation. With the exception of the coefficient of the unit cost of exploration, all estimated coefficients are statistically significant at the 5 percent level. The equation fits reasonably well and passes the diagnostic tests for serial correlation, functional form misspecification, non–normality and heteroscedasticity. Development depends negatively on development costs, and on exploration costs lagged k periods, again our choice for k is the result of the analysis of individual fields. Development also depends positively on past discoveries, and is significantly affected by exploratory effort lagged k and k+1 periods. Since we have not specified a functional form for the development and the discovery functions , [f(.) and μ(.)], unfortunately it is not possible to comment on the sign of the coefficients on the exploratory effort variables. We also carried out a sensitivity analysis on the appropriateness of the lag length chosen for the appraisal lag. Table 4 presents the maximized log–likelihood values for the development equation estimated over the sample 1978(3)–1989(2), with values of k in the range 1–10. The results once again re–affirm our conclusion concerning the long lags that are involved in the development process and clearly show that a choice of lag lengths shorter than the estimate obtained from the analysis of individual fields, results in a substantial reduction in the fit of the estimated development equation.

Overall, the results from the estimation of the two linearized versions of the extraction and development equations confirm the importance of dynamic specification

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[13]All the different dynamic specifications of the extraction equation were estimated over the same sample period, namely 1978(3)–1989(2). It is important to note that considering lag lengths longer than those considered in table 2 and 4, requires data on development and exploration expenditures starting well before 1976, which are not available.

in explaining investment in the North Sea. The next item on our research agenda is the specification of suitable discovery and development functions and the simulation of the full model to evaluate its predictive performance. We also plan to apply our methodology to the study of the oil investment in other regions of the world.

5. CONCLUSIONS

The aim of the present paper has been to model the behaviour of firms on the UKCS, after a careful examination of the structure of their investment decisions. The specification of a model in which exploration and development are the crucial decision variables to the firm led us to the estimation of reduced equations for extraction and development with lag lengths that are much longer than it is usually contemplated in the traditional applied econometrics work. Our results have important implications for economic policy and for the evaluation of oil price shocks: the effect of any change in exogenous variables, like oil prices or the structure of taxation, is likely to be fully observed on oil production only after long lags, largely determined by the average length of the appraisal and technical development lags, in the region of five to six years.

From a methodological point of view our specification strategy highlights the importance of economic theory in econometric modeling of Oil Investment in the North Sea and makes clear the drawbacks of the application of traditional dynamic specification strategies in absence of a priori information on the dynamics of the variables included in the model.

TABLE 1: THE EXTRACTION EQUATION

Dependent variable is q_t

44 observations used for estimation from 78Q3 to 89Q2

Regressor	Coeff.	S.E.	T [Prob]
CONSTANT	− 4.32	14.48	−0.29[.760]
S14	5.21	1.61	3.23[.000]
S24	− 11.48	2.01	−5.69[.000]
S34	1.27	1.90	0.66[.500]
q_{t-1}/Z_{t-2}	−2910	1802	−1.61[.110]
$(q_{t-1}/Z_{t-2})^2$	52342	24300	2.15[.030]
$\alpha_{3t-9}w_{2t-9}$	−155.68	39.49	−3.99[.000]
$\hat{p}_t(.96)$	14.19	1.68	8.42 [.000]
$.25(\sum_{i=19}^{22} D_{t-i})$	0.0210	0.0038	5.49 [.000]
$\alpha_{3t-10}w_{2t-10}$	118.17	42.19	2.80 [.000]
x_{2t-10}	1.52	0.30	5.08 [.000]

F—statistic F(10, 33) 198.14 [0.00]

$\bar{R}^2$	.978	S.E. of Regression	5.87
RSS	1140.0	Mean of Dependent Variable	198.5000
DW—stat.	2.46	Maximum of the log—likelihood	—134.

Diagnostic Tests

Test	LM Version	F Version
A:Ser. Corr.	χ^2_4=12.69[.013]	F(4,29)=2.94[.037]
B:Func.Form	χ^2_1=1.30 [.253]	F(1,32)=0.97[.330]
C:Normality	χ^2_2=1.59 [.451]	Not applicable
D:Heterosc.	χ^2_1=.84 [.358]	F(1,42)=0.82[.369]

S14 S24 and S34 are seasonal dummies, q_{t-1}/Z_{t-2} is the ratio of extraction to available reserves $\alpha_{3t}w_{2t}$ are the post—tax unit costs of development, x_{2t} is development effort (measured as the number of development wells drilled in each period), D_t are discoveries and $\hat{p}_t(.96) = .04\sum_{i=0}^{\infty}(.96)^{i-1}p_{t-i-1}$ are the adaptive expectations for the real oil price. The value of .96 reported for the adaptive coefficient, is the maximum likelihood estimate computed by grid search over the range [0,1] [see Pesaran(1990)]

TABLE 2: SENSITIVITY OF THE EXTRACTION EQUATION TO THE CHOICE OF THE APPRAISAL AND THE TECHNICAL DEVELOPMENT LAGS*

PANEL A: The Maximized log–likelihood values

Development lag (m)→ Appraisal lag (k) ↓	In quarters 1	5	10
1	–134.10	–135.82	–134.63
5	–143.28	–138.34	–142.47
9	–137.28	–140.18	–128.40
15	–143.00	–155.64	–148.08

PANEL B: The estimated coefficients and the t–ratios of the discovery variable

Development lag (m)→ Appraisal lag (k) ↓	In quarters 1	5	10
1	.032(1.63)	–.002(–0.10)	–.020(1.30)
5	–.003(–0.17)	–.047(–2.80)	–.004(–1.10)
9	–.033(–2.19)	–.004(–0.53)	.021(5.49)
15	–.005(–0.75)	.004(0.72)	–.002(–0.68)

PANEL C: The estimated coefficients and the t–ratios of the price expectations variable

Development lag (m)→ Appraisal lag (k) ↓	In quarters 1	5	10
1	11.04(4.7)	7.56(3.6)	13.70(6.2)
5	8.49(3.6)	8.32(4.0)	10.48(5.0)
9	9.20(3.7)	8.62(3.8)	14.19(8.4)
15	9.65(3.6)	10.28(4.4)	10.72(4.9)

* k and m are, respectively, the length of the appraisal and of the technical development lags, in quarters. The discovery variable is defined by $.25 \sum_{i=0}^{3} D_{t-m-k-i}$, where D_t is the amount of oil discoveries in period t. The price expectations is defined by $\hat{p}_t(.96) = .04 \sum_{i=0}^{\infty} (.96)^{i-1} p_{t-i-1}$, where p_t are the real oil prices.

TABLE 3: THE DEVELOPMENT EQUATION

Dependent variable is x_{2t}

44 observations used for estimation from 78Q3 to 89Q2

Regressor	Coefficient	S.E.	T.[Prob]
CONSTANT	20.78	7.64	2.71[.010]
x_{2t-1}	0.58	0.11	5.31[.000]
$\alpha_{3t}w_{2t}$	−53.33	15.89	−3.35[.002]
$\alpha_{3t-9}w_{1t-9}$	− 0.89	1.90	−0.47[.642]
x_{1t-8}	− 0.92	0.17	−5.40[.000]
x_{1t-9}	0.69	0.22	3.16[.003]
$\sum_{i=8}^{9} D_{t-i}$	0.005	.0018	2.66[.011]

F–statistic F(6, 37)	34.43 [.000]		
$\bar{R}^2$	0.85	S.E. of Regression	2.24
RSS	186.18	Mean of Dependent Variable	29.61
DW–stat.	1.88	Maximum of Log–Likelihood	−94.16

Diagnostic Tests

Test Stat.	LM Version	F Version
A:Ser.Corr.	χ_4^2= 0.80[.938]	F(4,33)=0.15[.960]
B:Funct. Form	χ_1^2= 3.03[.082]	F(1,36)=2.66[.111]
C:Normality	χ_2^2= 0.14[.931]	Not applicable
D:Heterosc.	χ_1^2= 0.37[.538]	F(1,42)=0.36[.549]

x_{1t} and x_{2t} are, respectively, the levels of exploratory and development efforts, $\alpha_{3t}w_{1t}$ and $\alpha_{3t}w_{2t}$ are the unit post–tax costs of exploration and development, respectively. D_t are discoveries.

TABLE 4: SENSITIVITY OF THE DEVELOPMENT EQUATION TO THE CHOICE OF THE APPRAISAL LAG*

In Quarters

k	1	2	3	4	5	6	7	8	9	10
LOGL	–105	–107	–107	–106	–104	–103	–100	–98	–94	–97

*The development equation (11a) is estimated over the sample period 1978(3)–1989(2). The figures reported in the table are the values of the maximized log–likelihood function of the development equation for different choices of the appraisal lag k.

REFERENCES

Adelman M.A.(1990) "Mineral Depletion, with Special Reference to Petroleum", The Review of Economics and Statistics, 72, pp.1—10

Clunies Ross A.I.(1982) "North Sea Oil and Gas Taxation: a case for reform" The Three Banks Review pp.32—45

Das Gupta, P.S. and Heal G.M. (1979) Economic Theory and Exhaustible Resources, Cambridge University Press, Cambridge

Devarajan S.,Fisher A.(1982) "Exploration and Scarcity", Journal of Political Economy,90,pp.1279—1290

Eckbo P.L.,Jacoby H.D.,Smith J.(1978) "Oil Supply forecasting: a disaggregated approach" The Bell Journal of Economics and Management Science pp.218—235

Epple D.N.(1985) "The econometrics of exhaustible resource supply: a theory and application " in T.Sargent(ed.) Energy, Foresight and Strategy,Resources for future,Washington

Erickson E., Spann R.(1971) "Supply Response in a Regulated Industry", The Bell Journal of Economics and Management Science,2, pp. 94—121

Farzin,H.(1986) "Competition in the market for an Exhaustible Resource" JAI Press,Greenwich, Connecticut

Favero,C.A.(1992) 'Taxation and the Optimization of Oil Exploration and Production: The U.K. Continental Shelf" Forthcoming in Oxford Economic Papers

Favero C.A., M.H. Pesaran ,and S. Sharma (1991) "Duration Analysis of Development Lags of the Oil Fields on the UKCS", under preparation

Fisher F.M. (1964) "Supply and costs in the U.S. Petroleum Industry: two econometric studies,The John Hopkins Press,Baltimore

Hann D. (1985) "Political and Bureaucratic Pressures on UK Oil taxation Policy" Scottish Journal of Political Economy

Hann D., Rowland C.(1986) "UK Oil Taxation: Failings and Reform" Surrey Energy Economics Centre D.P. no.32

Hansen L.P.(1982) "Large Sample Properties of Generalized Method of Moments Estimators" Econometrica, 50, pp. 1029—1053

Hausman J.(1978) "Specification tests in Econometrics", Econometrica, 46, pp.1251—1270

Hendry D.F, Pagan A.R. and Sargan J.D.(1984) "Dynamic Specification", Ch.18 in Z.Griliches and M.D.Intrilligator (eds.), The Handbook of Econometrics, North Holland

Hotelling H.(1931) "The Economics of Exhaustible Resources", Journal of Political Economy, 39, pp.137—175

Kaufman G.M.(1975) "Statistical Analysis of the Size Distribution of Oil and Gas discovery" in Studies in Petroleum Exploration No.1,AIME

Kemp A.,D.Cohen (1980) "The Impact of the system of Petroleum Taxation in the UK on Oil Operations and Government Revenue" The Frase of Allander Institute, Research Monograph 8

Khazzoom J.D.(1971) "The FPC Staff's econometric model of natural gas supply in the U.S." The Bell Journal of Economics and Management Sciences,2,pp.51–93

Jarque C.M.,Bera A.K. (1980)"Efficient Tests for Normality, Homoscedasticity and Serial Independence of Regression Residuals", Economic Letters, 5–6, pp.255–59

Lovegrove J.(1985) "Lovegrove's Guide to Britain's North Sea Oil and Gas" Energy Publications, Cambridge

Mabro et.al(1986)"The market for North Sea crude oil" Oxford University Press, Oxford

Mazzarino G.(1987)"Databank,a Program for the Management of Time Series",Oxford, Institute of Economics and Statistics

McCallum B.T(1976) "Rational Expectations and the estimation of econometric models:an alternative procedure" International Economic Review,17, pp.484–490

Pesaran M.H.(1987) "The limits to Rational Expectations", Oxford, Basil Blackwell

Pesaran M.H.(1990) "An econometric analysis of the exploration and extraction of oil in the U.K. Continental Shelf" The Economic Journal, 100, pp.367–391

Pesaran M.H.,Pesaran B.(1991) "Micro–Fit 3.0 :An interactive Econometric Software Package,Oxford University Press, Oxford, forthcoming

Pindyck R.S.(1978) "The optimal exploration and production of non–renewable resources", Journal of Political Economy, 86,pp.841–861

Sargan J.D. (1958) "The estimation of economic relationships using Instrumental Variables" Econometrica, 26, pp.72–90

Seymour A.(1990) "The oil price and non–OPEC oil supplies" Oxford Institute for Energy Studies Papers on the World Petroleum Market

Stiglitz J.E.(1976) "Monopoly and the Rate of Extraction of Exhaustible Resources", The American Economic Review, pp.655–661

Uhler R.S.(1976) "Costs and Supply in Petroleum Exploration: the case of Alberta", Canadian Journal of Economics,9,pp.72–90

White H.(1982) "Maximum Likelihood Estimation of Misspecified Models" Econometrica, 50, pp.1–25

Whittle P.(1982) "Optimization Over Time" Wiley Series in Probability and Mathematical Statistics

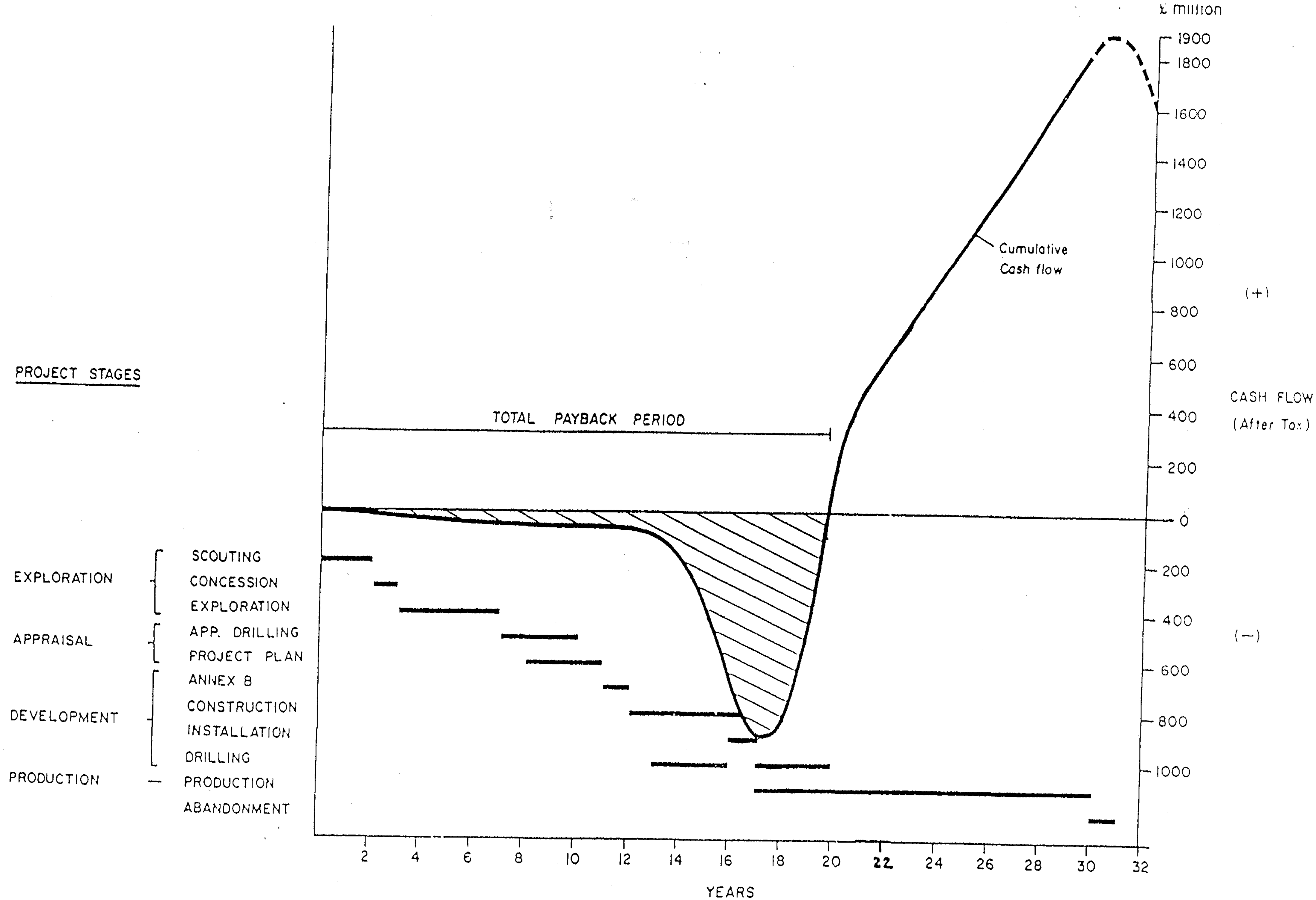

Figure 1:Cumulative Cash Flow for a typical North Sea oil field
million of pounds (current prices)

Source: Lovegrove (1985)

Figure 2: Exploratory Wells Drilled (x) and Real Oil Prices (p)

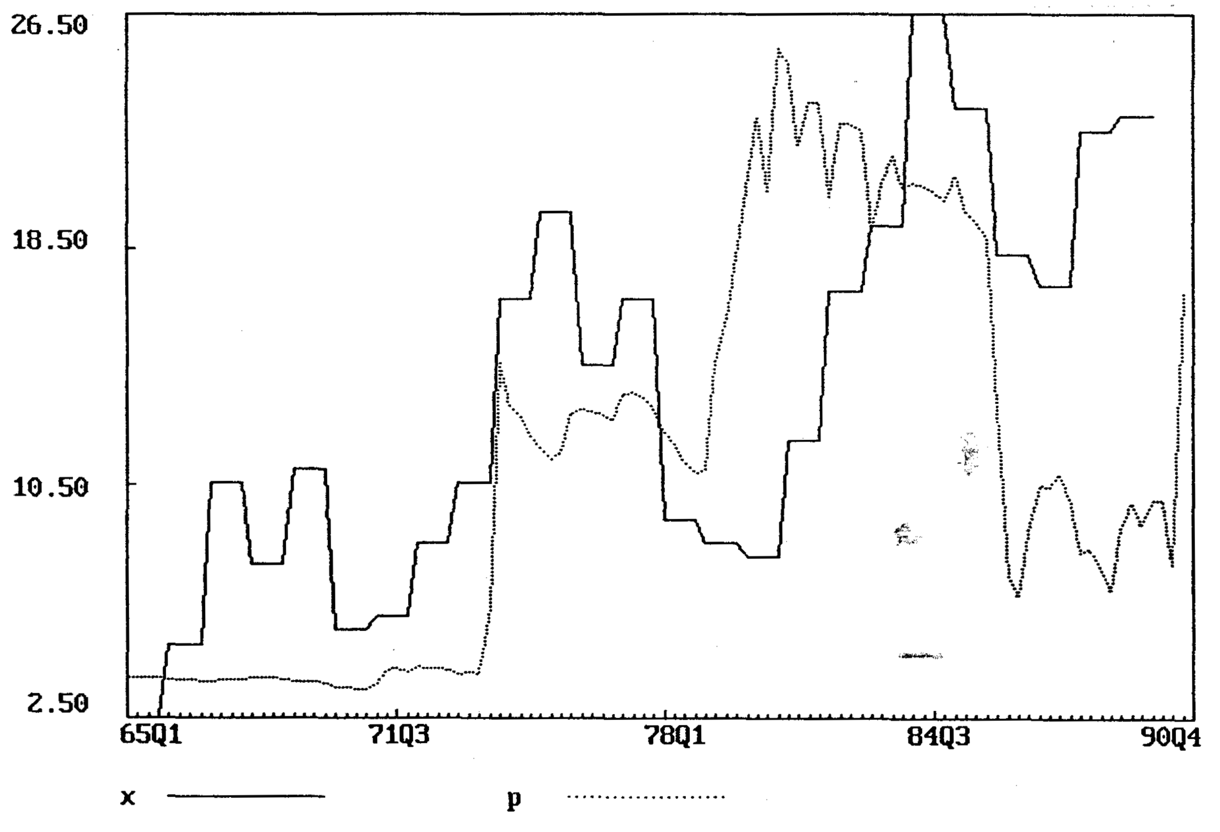

Figure 3: Histogram For the Appraisal Lag

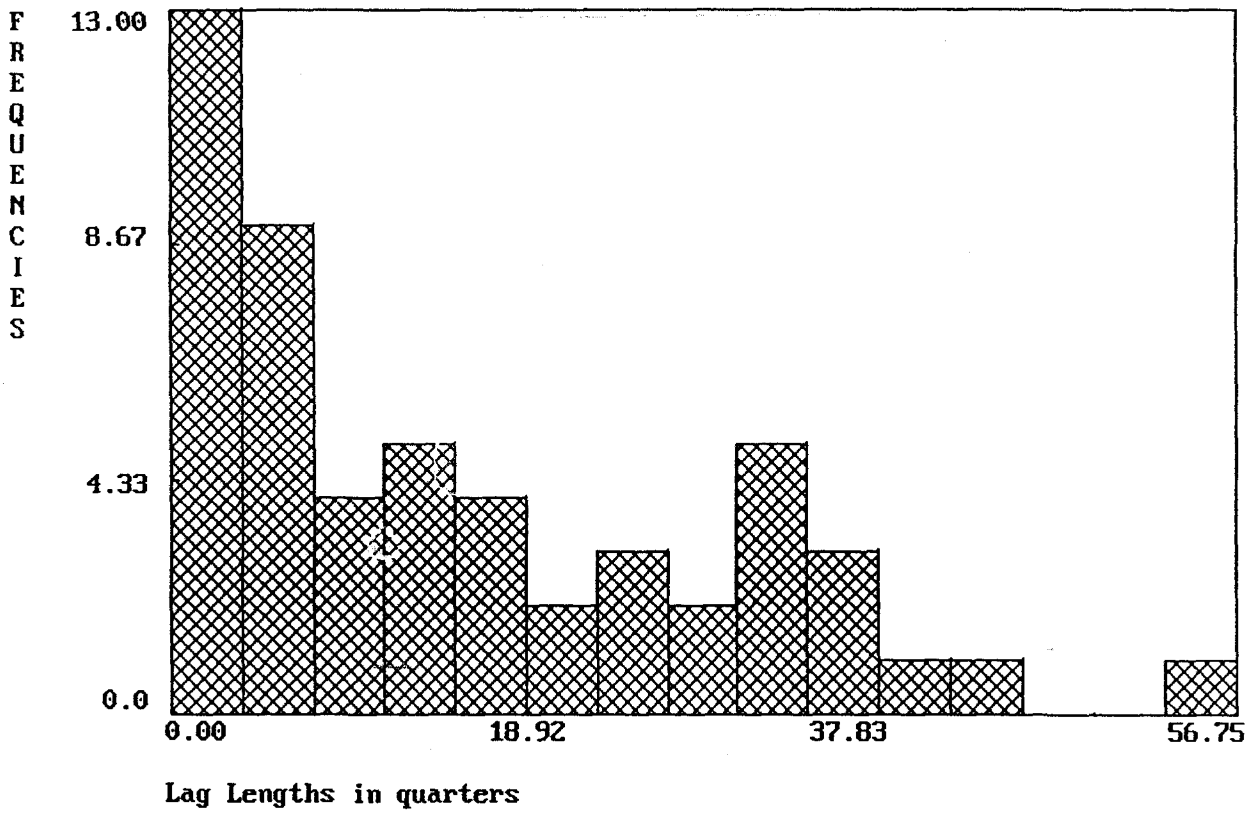

Figure 4: Histogram For The Technical Development Lag

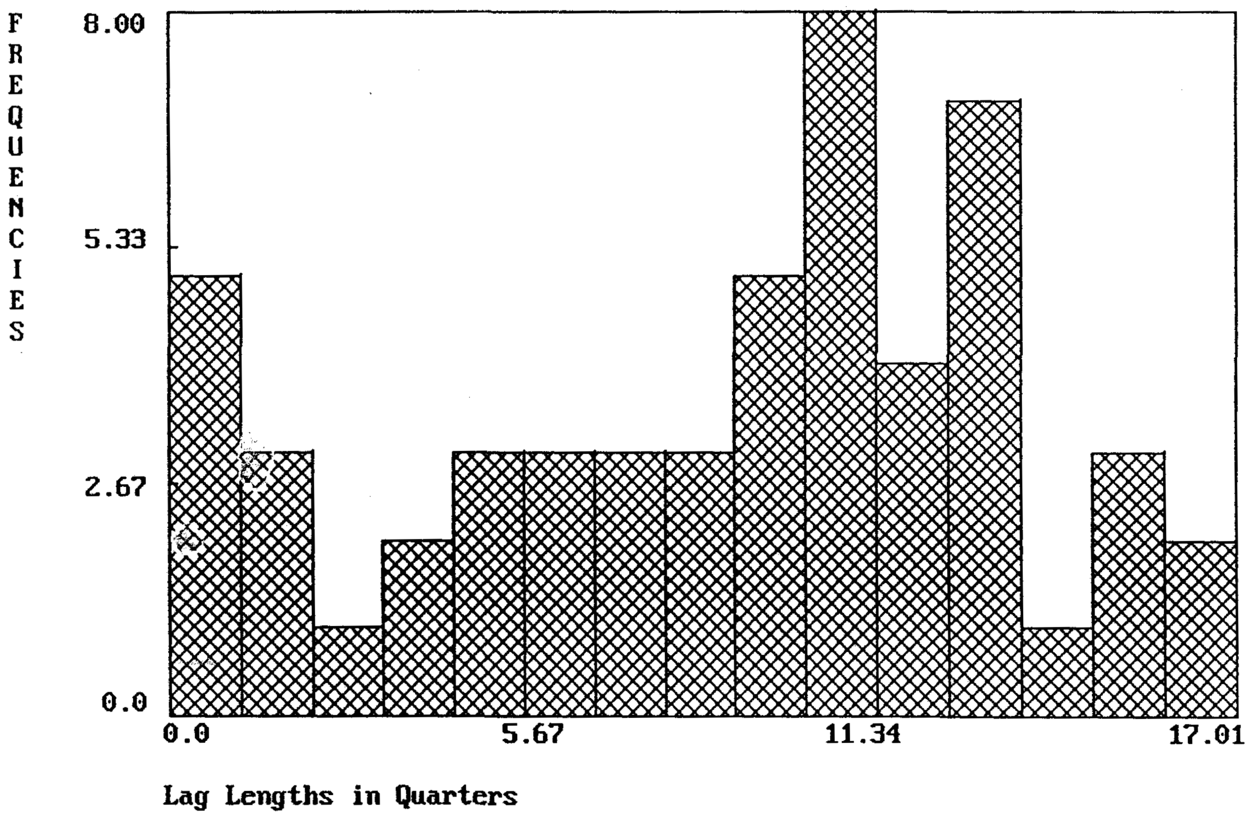

Figure 5: Histogram For The Total Development Lag

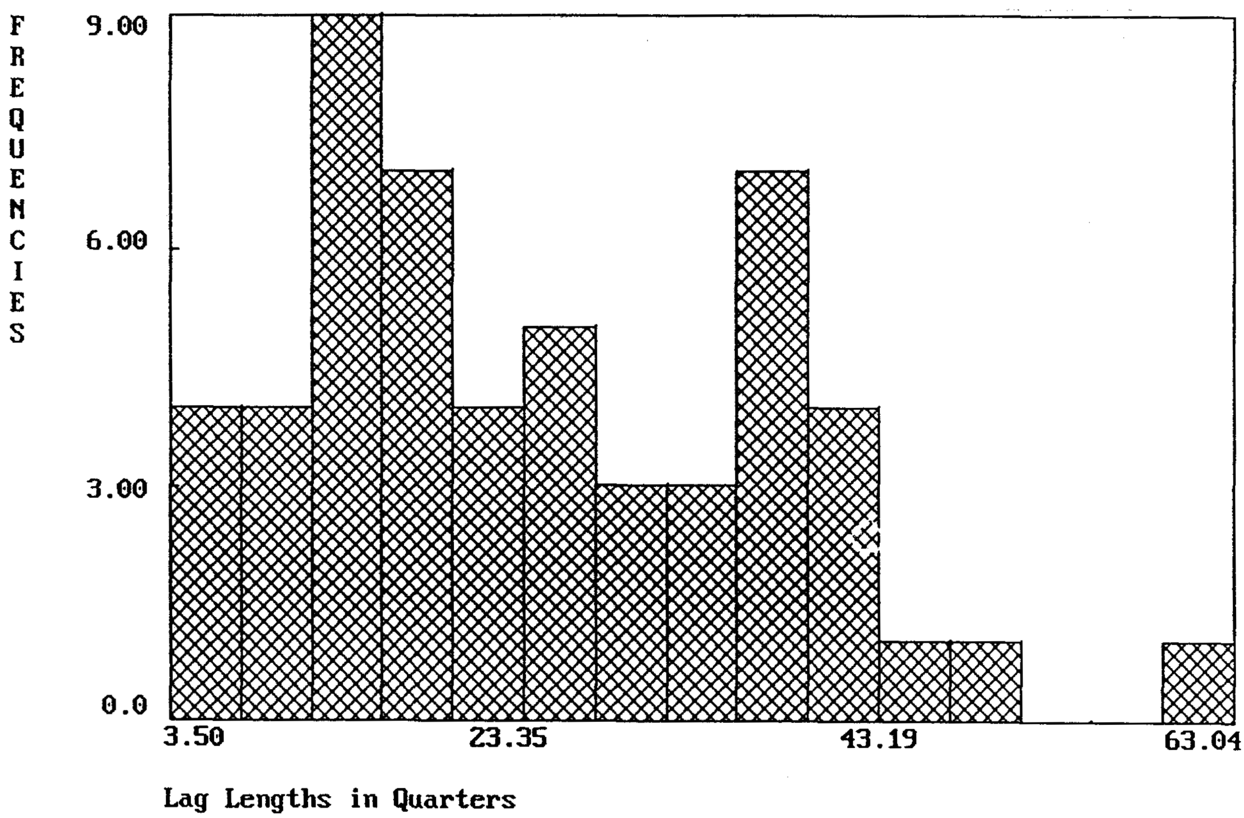

Figure 6: Development Wells Drilled (DEV) and Real Oil Prices (p)

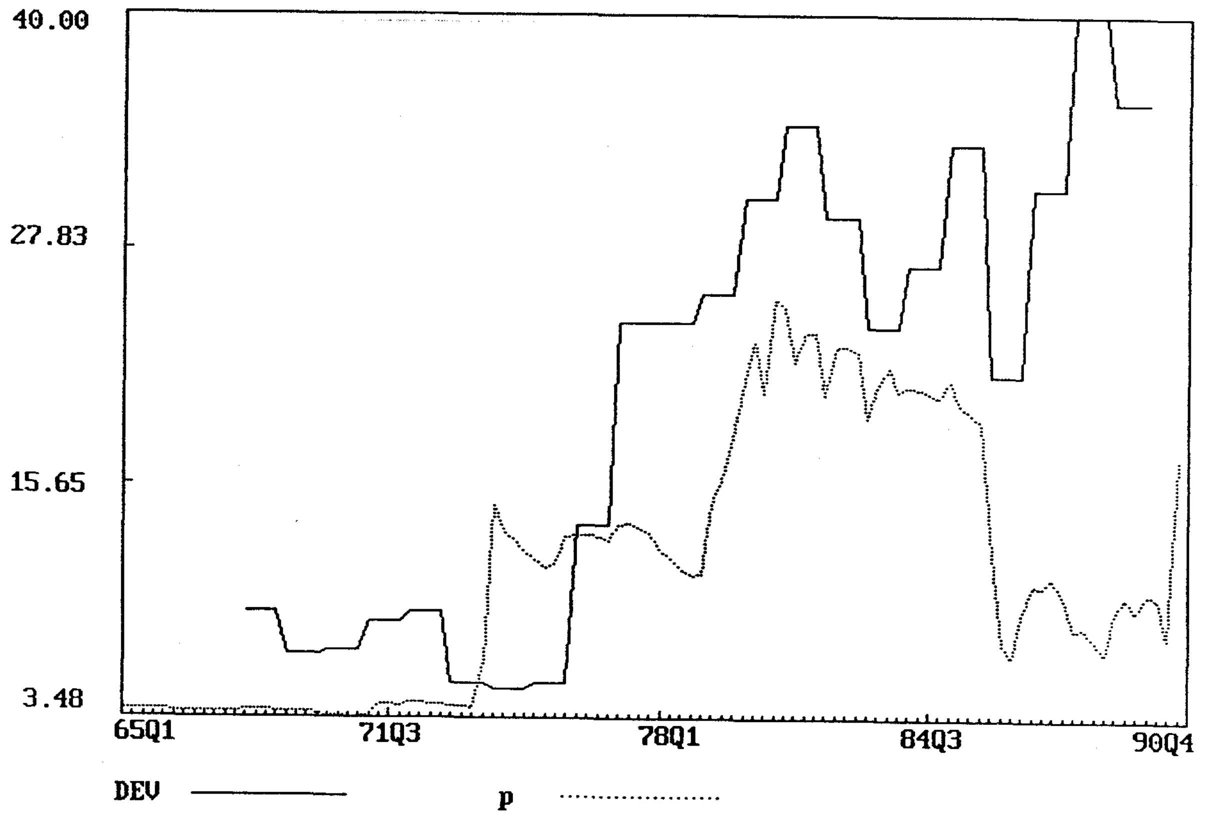

Figure 7: Total Oil Production On The UKCS

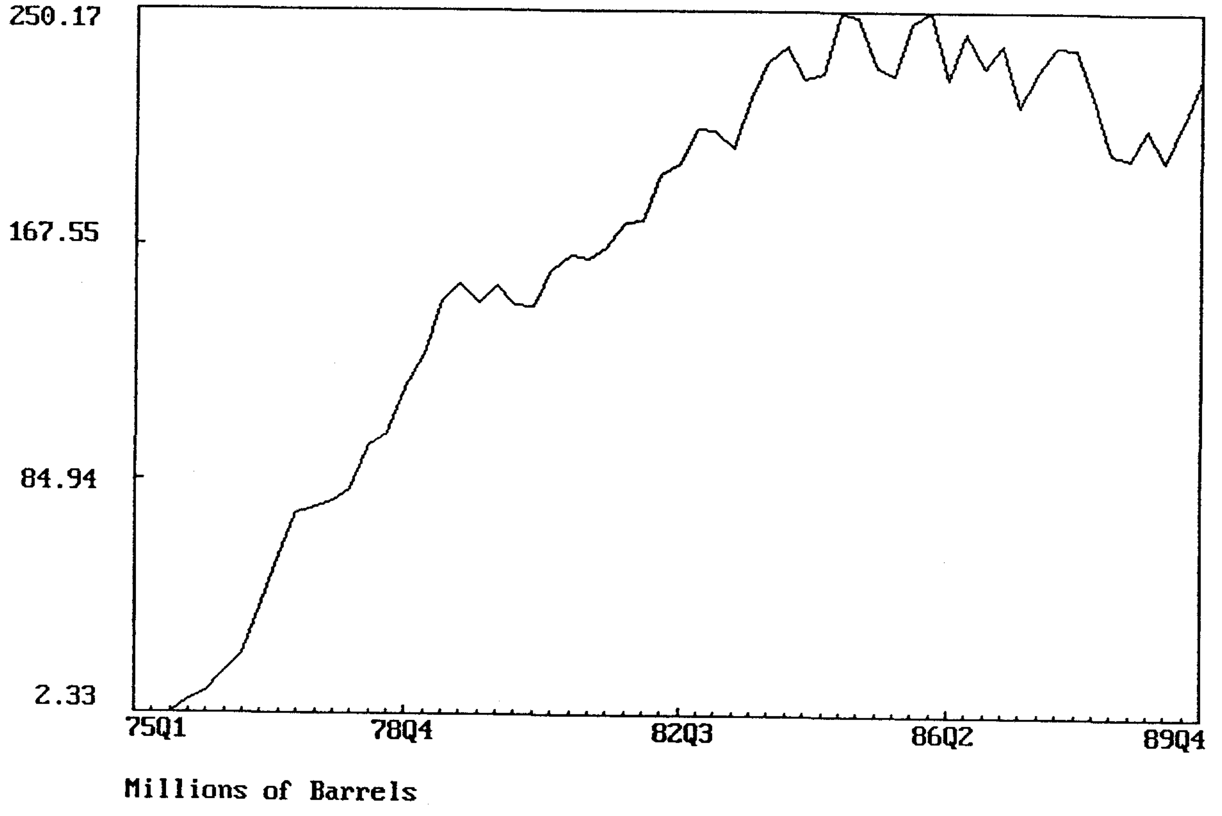

Figure 8: Oil Production Profiles of the Three Large Oil Fields On The UKCS
(Millions of Barrels Per Annum)

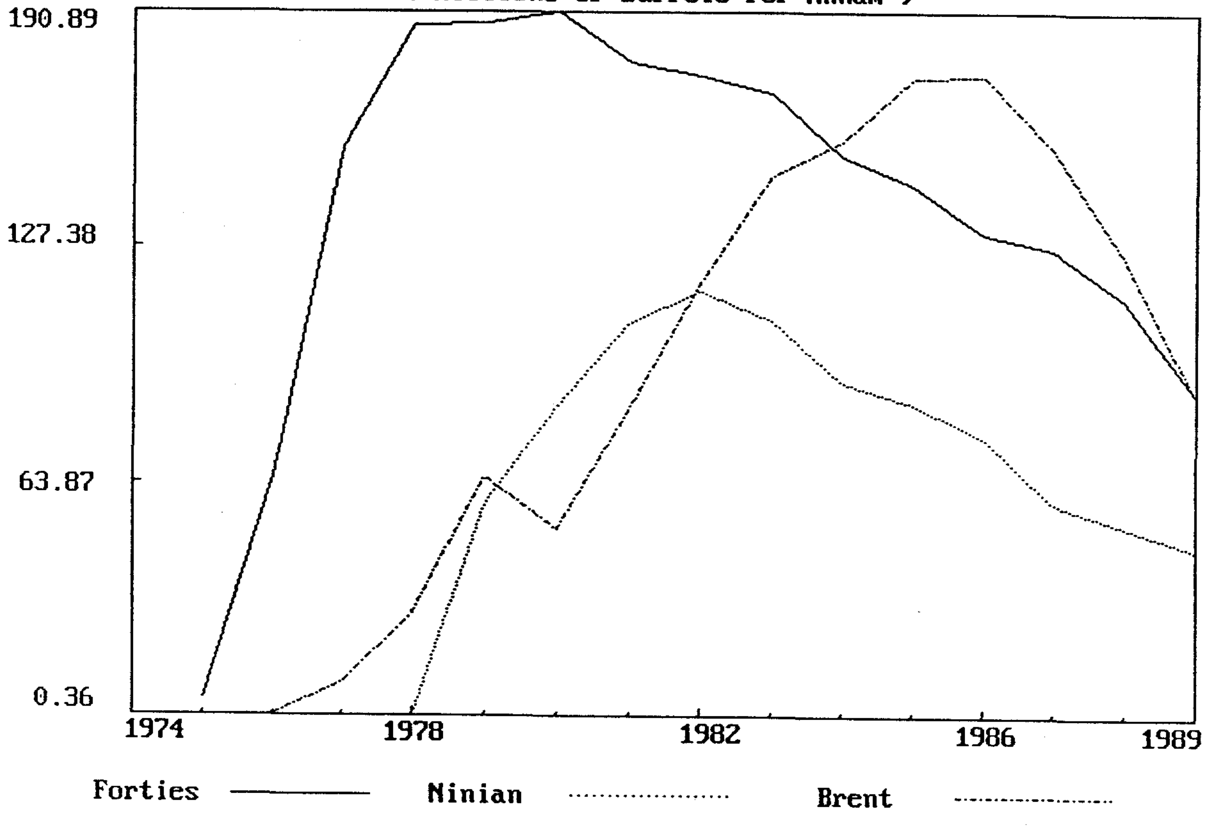

Figure 9: Oil Production Profiles of a Small and a Medium Field On The UKCS
(Millions of Barrels Per Annum)

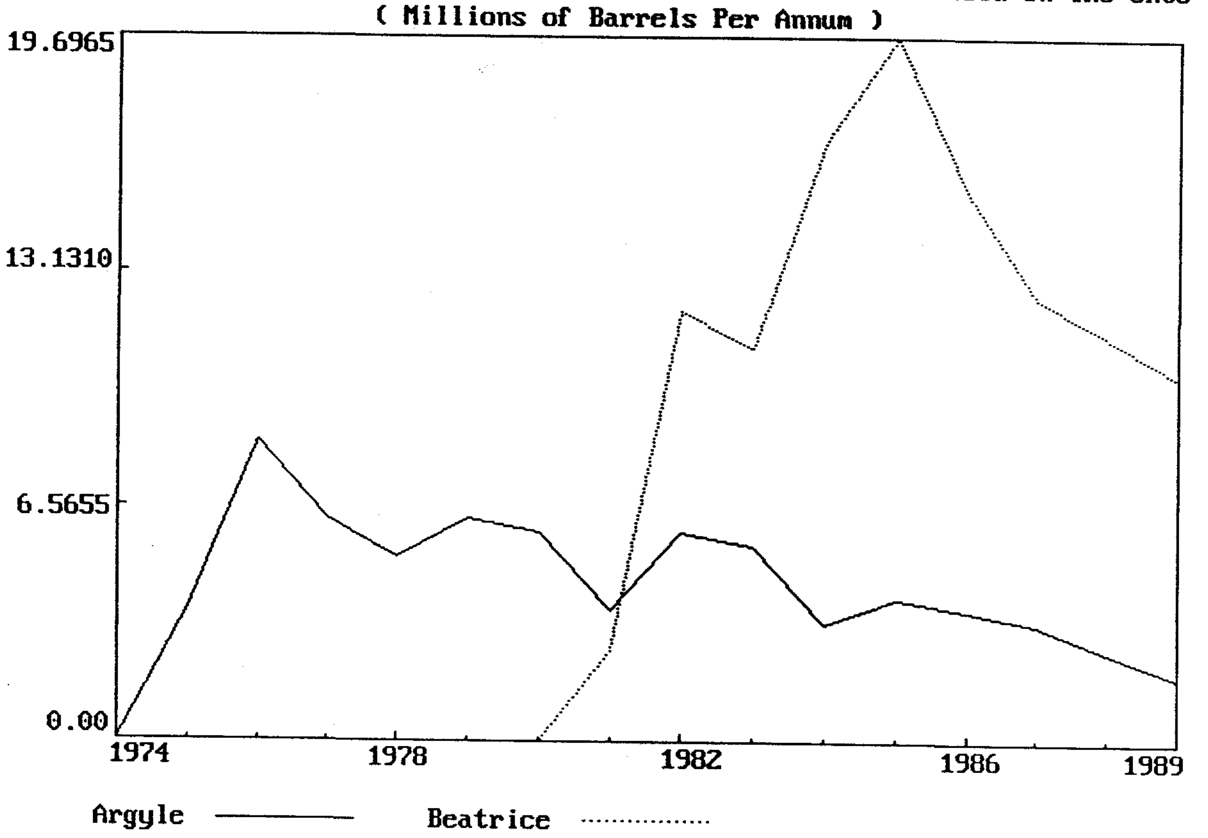

Figure 10: Real Total Operating, Development and Exploration Expenditures

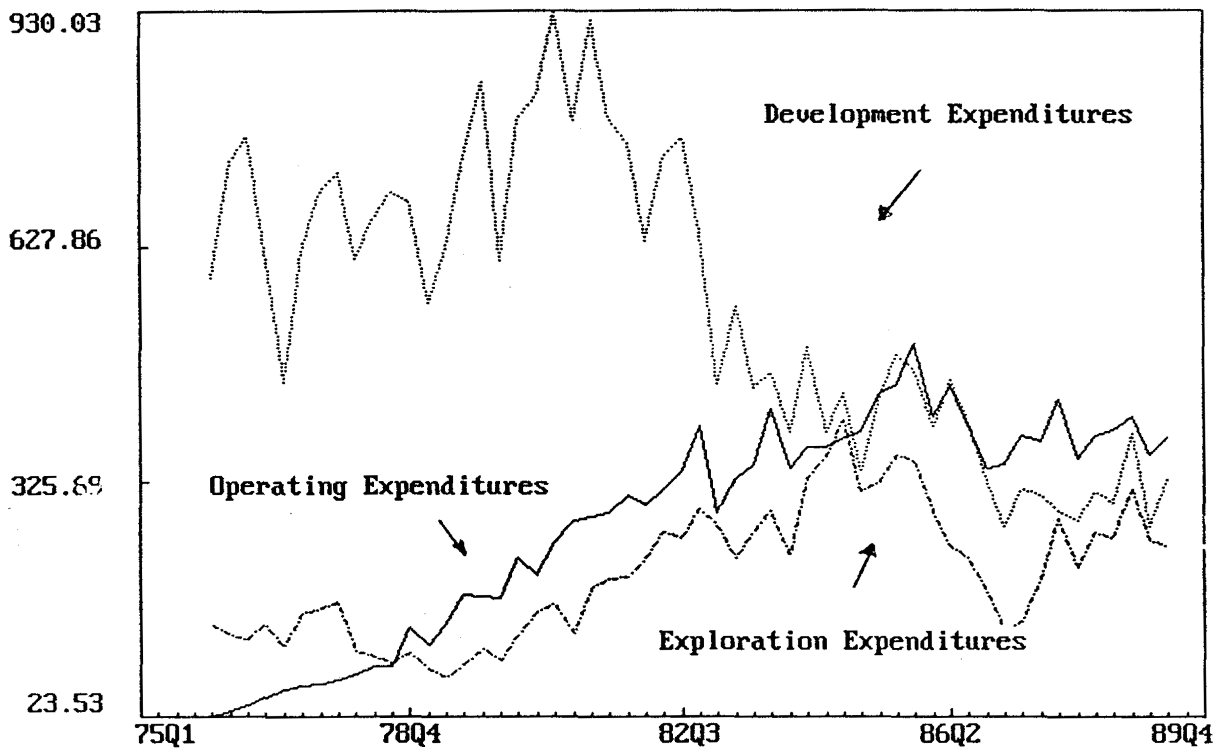

Figure 11: Marginal Extraction Costs - Point Estimates and Confidence Intervals

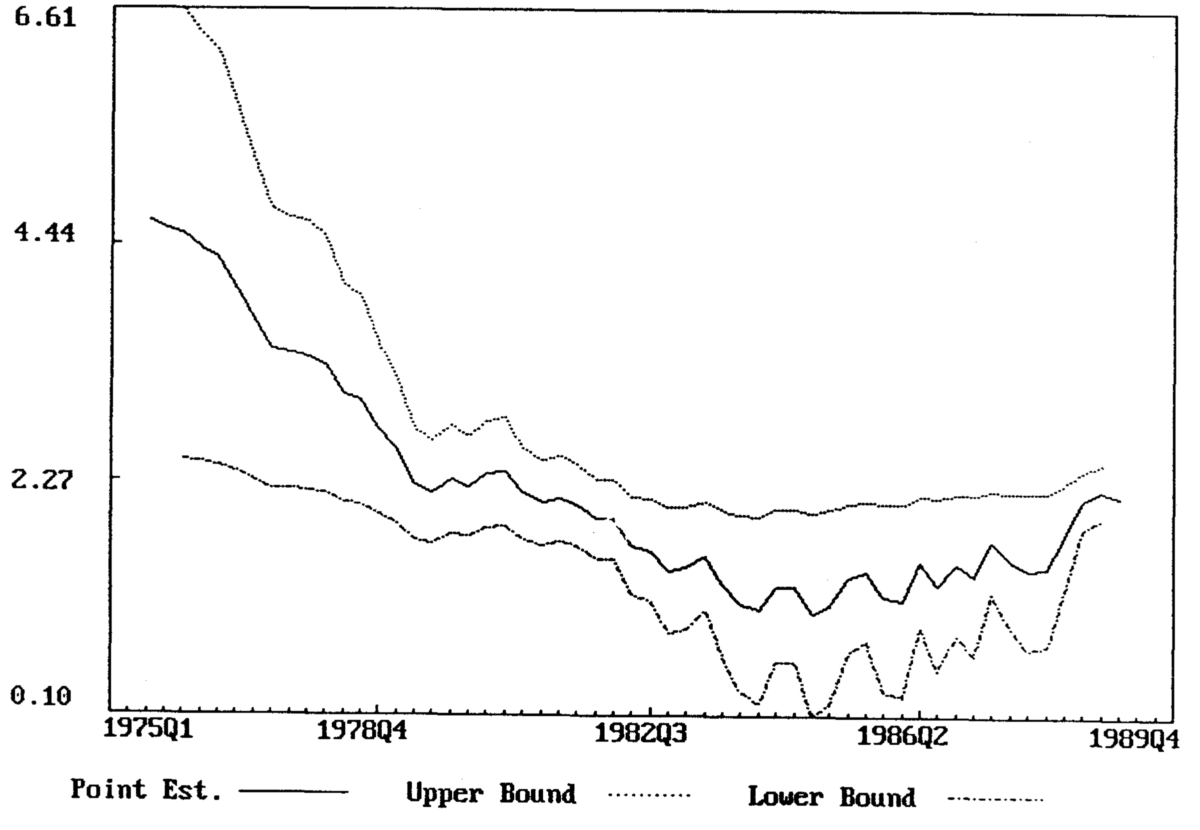

Figure 12: Plot of Actual and Fitted Values for Extraction (Table 1)

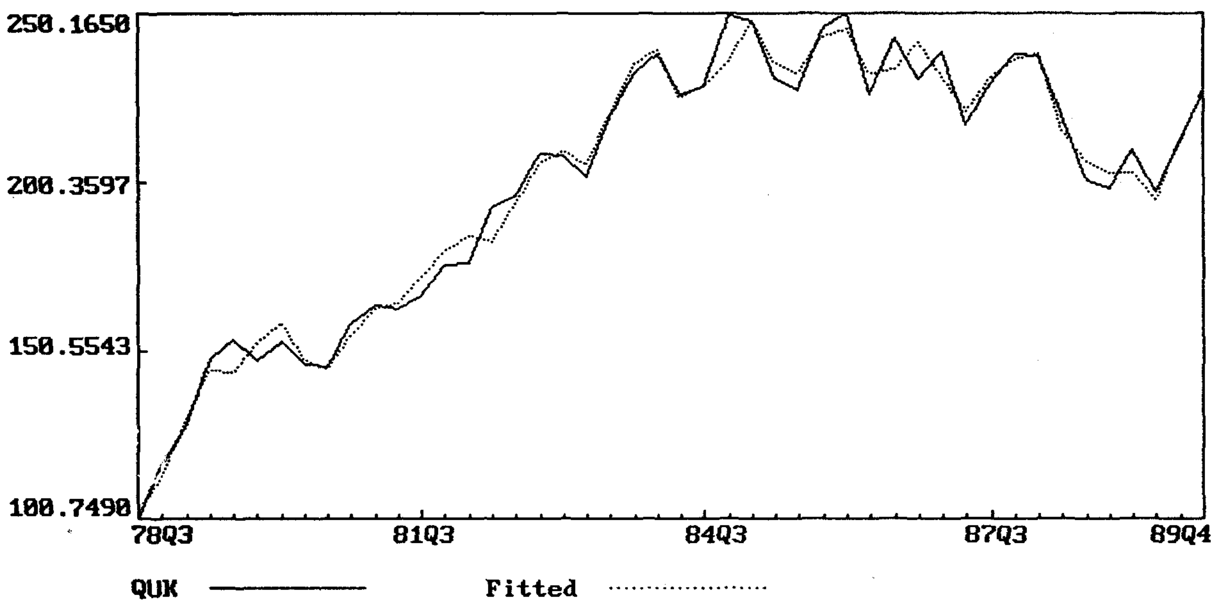

Figure 13: Plot of Actual and Fitted Values for Development (Table 3)