Asymmetry and uncertainty in capital formation: an application to oil investment

by

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Abstract

Theories of irreversible investment suggest a negative relation between investment and uncertainty, and non-linear adjustment costs open for asymmetries in the adjustment of fixed capital. We propose an econometric modelling approach to estimate and test the key predictions of modern investment theory, including asymmetric dynamics and various uncertainty indicators. Our application on a data set from the oil industry offers empirical support for both asymmetric dynamics and uncertainty in oil and gas investment.

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1. Introduction

Modern theories of irreversibility, uncertainty and investment suggest a negative link between risk and capital accumulation (e.g. Dixit and Pindyck, 1994). As noted already by Bernanke (1983), investment irreversibility and uncertainty represent important sources of business cycle fluctuations. With irreversible investments and uncertainty, a volatile business framework would be bad for both investment and economic growth (Ramey and Ramey, 1995; Serven, 1996). In a macroeconomic context, it introduces an argument for policies to secure a stable business framework.[1] We propose an econometric framework for to test the relevance of uncertainty and asymmetry in investment behaviour. Our empirical application is based on data from the oil and gas industry, but the general mechanisms of our model have an explanatory potential also for other types of investment, other industries – and even on a macroeconomic level.

As the oil price surge towards new record heights, economists and policy-makers are not only occupied with the macroeconomic impact of the high oil price (e.g., Jimenez-Rodriguez and Sanchez, 2005), but also with the sustainability of the current price level (e.g., Krugman, 2008). At the core of this discussion is the muted response in oil investment and supply to the sharp oil price increase. Concerns have been raised among consumer interests about the security of supply. The “Peak Oil”[2] debate is growing increasingly popular, the IEA warns of investment shortage (IEA, 2005), and politicians adjust their strategic energy policies to reduce the dependency on oil. Studying the interaction between oil companies and financial markets, Osmundsen et al (2006a, b) note that oil investment fell sharply after the 1998 oil price shock. On the other hand, oil investment was more sluggish in adjusting to the subsequent oil price increase. The present study offers and exploration of theoretical

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[1] Based on micro-econometric studies of investment dynamics under uncertainty, Bloom et al. (2007) also argue that irreversible investment introduces a link between uncertainty and the speed of policy transmission, with slower policy response in the private sector when uncertainty is high.

[2] The idea stems from the geophysical approach initiated by Hubbert (1962), who argued that oil production can be described in terms of logistic growth, with subsequent bell-shaped trajectories for reserves and production. Today “Peak Oil” refers to the popular discussion of when world oil production will actually peak.

and econometric explanations for the conjectured one-sidedness of oil investment to changes in financial, geological and policy variables.

Our contribution is twofold. First, we propose an econometric approach to test the predictions of modern theories of investment, in a model specification including asymmetric dynamics and various uncertainty indicators. We demonstrate how an error-correction model framework may be adjusted to capture relevant perspectives of uncertainty and asymmetry – in accordance with modern investment theory. Second, we establish an empirical role for both oil price volatility and underground risk in oil and gas exploration investment. In this context, we also demonstrate an empirical asymmetry in the relation between exploration activity on one hand, and the oil price and other explanatory variables on the other. OPEC's claimed interest in price stability may therefore be questioned, as price fluctuations and uncertainty will dampen the growth in non-OPEC oil and gas reserves, according to our findings.

In terms of specific results, we find that the level of oil exploration efforts is negatively linked to oil price volatility and underground risk. These findings are supportive of the theoretical literature of irreversible investments (cf. Dixit and Pindyck, 1994), whereby a negative link between investment and uncertainty is established. Our results also offer empirical insights concerning the "bad news principle" from the literature on irreversible investments (Bernanke, 1983). More specifically, the estimated exploration response to a drop in the oil price is significant, whereas the corresponding response to an oil price increase is negligible. We also find asymmetric short-term effects of other explanatory variables. Compared to a symmetric specification, the magnitude of the estimated coefficients increases, and the statistical quality improves. The suggested specification of investment behaviour can be useful in other petroleum regions, as well as in other empirical studies of producer and investment behaviour.

The paper is organized as follows. Section 2 offers a brief survey of previous studies of investment, asymmetry and uncertainty, as well as a review of empirical studies of oil and gas exploration. A simple econometric model is specified in Section 3, our data set is presented in Section 4, estimation procedures and results are presented and discussed in Section 5, before concluding remarks are offered in Section 5.

2. Previous research

The role of asymmetry and uncertainty in investment behaviour is typically linked to contemporary extensions of the standard neoclassical model of investment. These modern variants of investment theory are highly relevant for oil and gas investment in general, and for exploration spending in particular. Before we present an econometric framework to test for some of the key predictions of modern investment theory, we offer an overview of recent research, together with a discussion of its assumptions result, as well as its relevance to oil and gas investment.

2.1 Investment and uncertainty

The role of uncertainty in fixed capital investment has drawn interest from theorists and empirical researchers for decades. A traditional view stems from the properties of the neoclassical production technology. Early theoretical contributions (e.g., Oi 1961; Hartman 1972; Abel 1983) stress the implications of convexity of the profit function, implying that any price variation may be exploited for optimization. Accordingly, any increase in uncertainty will raise the marginal valuation of investment, yielding a positive link between capital-accumulation and uncertainty. We refer to this mechanism as the *opportunity effect* of increased uncertainty.

Academic interest in theories of investment behaviour was spurred by theoretical work in the early 1980s, when Cukierman (1980), Bernanke (1983), McDonald and Siegel (1986) studied the implications of irreversibility and waiting options for investment decision-making. Common for these contributions was the idea that investment could not be reversed. This irreversibility provided the firms with a real option to defer investment. Any increase in the uncertainty around future profitability will increase the value of this waiting option. Accordingly, this strand of literature suggests that investment will respond negatively to increased uncertainty. We will refer to this idea as the *risk effect* of increased uncertainty.

The idea of irreversible investment is truly relevant to oil and gas exploration. Huge capital commitments, long investment lags and field-specific sequences of investment decisions involve a series of waiting options. The irrevocable character of investment expenditure is especially salient for exploration activities; Once a well is spudded, there is no way back. Moreover, theory does not provide clear-cut answers for the role of uncertainty in investment behaviour. Consequently, empirical studies are required to clarify the issue.

2.2 Irreversibility and asymmetry

Theoretical models of irreversible investment suggest that the costs of adjustment are asymmetric, although a stable empirical consensus is yet to be established through the required variety of econometric studies. Dixit and Pindyck (1994) illustrate that irreversible investment imply an asymmetry in the adjustment cost structure, due to the option value of delay. These models typically introduce threshold values of expected project profitability, determining regions whereby companies shift their behaviour between investment, inaction and disinvestments. Moreover, these trigger values of profitability are typically not symmetric around zero, due to the option value implied by irreversibility of investment. Bernanke (1983) was one of the first studies to stress the asymmetry implications of irreversibility in the popular “bad news principle of irreversible investments – that of possible future outcomes, only the unfavourable ones have a bearing on the current propensity to undertake a project” (Bernanke 1983, p. 91).

The bad news principle reflects the fact that the decision to invest is made in such a way as to expose the company to good outcomes and reduce exposure to bad outcomes. An appealing application can be made to oil and gas investment. For exploration activities, this theory would imply that news about oil price increases is irrelevant for the value of the option to wait. On the other hand, news about oil price reductions will increase the value of this option, and put a restriction on current exploration efforts. This is one of the hypotheses we will test in our econometric model. Specifically, we allow for temporary asymmetry in our explanatory variables, to test if the short-term response to an exogenous shock is dominated by the *bad news effect*.

2.3 Risk aversion and agency issues

Risk aversion is another channel for a negative influence from uncertainty on capital formation. The traditional neo-classical approach assumes risk-neutral investors and perfect markets. Theories of irreversible investments also assume risk-neutral decision-makers. Under such circumstances, risk aversion should also not affect corporate investment policies. This view is challenged by recent contributions within behavioural corporate finance (BCF).[3] Cadsby and Maynes (1998) review several experimental studies where risk preferences are misaligned between managers and shareholders, causing investment behaviour characterised by inertia and potentially also myopic loss aversion. On the other hand, agency theory has also invited studies of overconfident managers (e.g., Malmendier and Tate 2005), who systematically overestimate the expected returns to investment.

Increasing financial market pressures and frequent evaluation of financial results may also give rise to myopic loss-aversion among managers in the oil and gas industry (Benartzi and Thaler, 1995). Osmundsen et al. (2006b) argue that pressures on the oil and gas industry from financial markets caused a redirection of investment spending in the late 1990s, from long-term reserve and production growth to projects that could increase earnings in the short term. With evidence that managers take action to avoid negative earnings surprises (Matsumoto 2002), the BCF literature is therefore supportive of both asymmetric adjustment dynamics and a role for uncertainty in corporate investment policies. Again, however, the ultimate impact of uncertainty on investment is an empirical question.

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[3] See Baker et al. (2005) for a recent survey of the BCF literature.

2.4 Empirical studies of investment and uncertainty

Following path-breaking theoretical studies of irreversible investments in the early 1980s, applications for natural resources emerged promptly (e.g., Brennan and Schwartz 1986). These studies were concerned with valuation of development options (e.g., Ekern, 1988; Paddock, Siegel and Smith, 1988).

In one of the first comprehensive econometric studies, Leahy and Whited (1996) establish a negative link between investment and various uncertainty measures in a panel of US manufacturing firms. According to a survey by Carruth et al. (2000), subsequent studies confirm a quite robust negative link between investment and uncertainty, with somewhat more clear-cut results for studies of micro data than for aggregate data. The availability of modern panel data techniques has also stimulated a variety of new empirical studies, and most of these are supportive of a negative impact of uncertainty on investment. See Bond et al. (2005) for a recent overview.

The theoretical literature on real options and uncertainty suggests that asymmetric adjustment should be incorporated in empirical studies of investment, but very few empirical studies have done so.[4] An exception is Price (1996), who finds evidence of asymmetric responses to uncertainty for UK manufacturing investment. A few econometric studies have addressed oil and gas field development in the context of irreversible investments, but the empirical findings are mixed for the influence of uncertainty. In a study of UK oil and gas fields, Favero, Pesaran and Sharma (1992) conclude that uncertainty plays an important role for the appraisal lag, whereas Hurn and Wright (1994) find no statistical significance of oil price variability in their investment equations for oil and gas fields in the same region. We are not aware of empirical studies of oil exploration that explicitly incorporate irreversibility and uncertainty.

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[4] Econometric applications of asymmetric theory are more common in studies of price transmissions in commodity markets. A number of studies are, surveyed by Meyer and von Cramon-Taubadel (2004), and even more recently by Grasso and Manera (2006).

2.5 Empirical studies of oil and gas exploration

There is an extensive empirical literature on the economics of oil and gas exploration, dating back to the early 1960s. A pioneering reference is Fisher (1964), who estimates drilling rates, success rates and discovery rates on US regional data 1946-1955. A series of subsequent studies are based on revisions and updates of the Fisher framework, and is surveyed by Dahl and Duggan (1997). In the early 1990s, a few studies were also published based on data from the United Kingdom Continental Shelf (e.g., Pesaran 1990; Favero and Pesaran 1994).

The validity of dynamic optimisation and intertemporal model specifications for exploration behaviour has been questioned in recent years (e.g., Farzin 2001). Several late empirical studies have returned to a simplified period-by-period optimisation framework (Iledare 1995; Iledare and Pulsipher 1999). Ringlund et al. (2007) also apply this behavioural assumption in a comparative assessment of oil rig activity in a panel of non-OPEC countries. At the same time, their econometric specification is truly dynamic. Our approach will follow a similar line of thought. Contributions from the last ten years are scanty, and exploration behaviour in the aftermath of the oil price drop in 1998 has therefore not been researched thoroughly.

3. Econometric model specification

The key differentiating factor of the production technology among oil and gas companies is the reserve concept, which represents a crucial input in the production process. Oil and gas companies have to invest in risky exploration activities, to sustain production over the longer term. Before the decision to develop the field is taken, exploration acreage must be acquired, exploration wells have to be drilled, and appraisal activities must be undertaken. Oil and gas producers maximise profits not only from production activities, but also from reserve generation. The outcome from this optimisation problem is an optimal plan for reserve additions (cf. Mohn and Osmundsen 2007). Reserve additions from exploration (H_t) may be seen as a combined result of actual drilling activity (Y_t) and drilling efficiency (Z_t): $H_t = Y_t \cdot Z_t$, where Z_t represents average contribution of new reserves per exploration well.[5] The focus of our study is on drilling efforts, and for the remainder of the paper we therefore focus our attention on the Y_t variable as the reserve-generating factor. Following Iledare (1995) and Mohn and Osmundsen (2007), we apply a supply function approach to reserve generation, stating exploration drilling (Y_{jt}) as:

$$Y_{jt} = K_j \prod_i X_{ijt}^{\beta_i} e^{\gamma T + \varepsilon_{jt}} . \qquad [1]$$

Footscript j is introduced to indicate variation across the three regions of our data set,[6] K is a constant term, and α, β_i and γ represent coefficients to be estimated. P_t is the oil price. The set of explanatory variables (X_{ijt}) includes the oil price, state variables of policy and geology, and two indicators of underground and oil price uncertainty. All explanatory variables are described in closer detail in section IV. We also include a time trend (T), along with an error term ε_{jt}. Taking logarithms on both sides of Equation [4], we arrive at a log-linear, econometric specification:

$$y_{jt} = k_j + \sum_i \beta_i x_{ijt} + \gamma T + \varepsilon_{jt} . \qquad [2]$$

Small-caps indicate natural logarithms and the coefficients resemble those of Equation [4]. The persistent equilibrium of our model is represented by Equation [2], which should be seen as a long-term, fundamental relation between exploration activity and the explanatory variables.

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[5] More precisely, drilling efficiency is the product of the success ratio and average discovery size.

[6] Our data set contains regional-specific information for discoveries and licensed exploration acreage, whereas our proxy for the marginal value of new resources is the same across the three regions. We allow for regional variation in the constant term. At the same time, our model implicitly excludes any variation in economic effects across regions, as the coefficients are assumed to be the same for the three regions involved. In practice, a quite stable group of oil and gas companies have had comparable access to the three regions of our data set over the sample period. We therefore assume that the underlying economic behaviour represented by our data set does not vary across regions.

The next step is to nest our long-term relationship in a dynamic modelling framework. Our data set is a panel for 3 regions on the Norwegian Continental Shelf over 40 years. The time series properties are therefore important, and our specification must be adjusted accordingly. With non-stationary variables in Equation [5], direct estimation of the parameters will produce inefficient coefficient estimates, and neglect the dynamics of the data-generating process. On the other hand, if the variables in our equilibrium relation [2] are integrated of degree 1 (*I(1)*), their difference will be stationary (*I(0)*). Generally speaking, if a stationary trend is produced by a linear combination of non-stationary variables, their coefficients define a co-integrating vector (Engle and Granger 1987; Hendry and Juselius 2000). Assuming that such a vector is defined by our Equation [2], the following equilibrium-correction specification is appropriate:

$$\Delta y_{jt} = a_{0j} + \sum_i a_i \Delta x_{ijt} + \lambda y_{jt-1} + \sum_i b_i x_{ijt-1} + cT + u_{jt} \quad , \qquad [3]$$

where u_{jt} is an error term with the usual white noise characteristics. Equation [3] implicitly describes a gradual correction towards a long-term equilibrium relation, as defined by Equation [2]. This equilibrium-correction process is continuously disturbed by shocks. The a_i coefficients capture the short-term response to these shocks, whereas any persistence is closely related to the b_i and c_i coefficients. λ is the equilibrium-correction coefficient, describing the speed of adjustment towards the long-term structural equilibrium. Following Bårdsen (1989), the underlying long-term parameters of [2] can be derived directly from [6] as:

$$\beta_i = \frac{b_i}{\lambda}, \quad \gamma = -\frac{c}{\lambda} \quad . \qquad [4]$$

Standard estimation procedures may now be applied on [6] to obtain unbiased and efficient estimates for short-term dynamics and the long-term structure of our model. Casual observation suggests that oil and gas companies have been fast to cut back on their exploration expenditures when oil prices have fallen. On the other hand, the exploration response to increased oil prices has typically been sluggish. This kind of asymmetric response may also apply to other explanatory variables. Awards of new exploration acreage may have effects on exploration activity that differ from the effects of license expiry. The short-term stimulus to exploration drilling from a major discovery is probably different from the effect of gradual resource decline through production. As recommended by Bloom (2000), we restrict the asymmetry to the short-term response in our model.[7] To test for short-term asymmetry in the explanatory variables, each of these variables is split in two new variables:

$$\Delta x_t^+ = \begin{cases} \Delta x_t & if \ \Delta x_t \geq 0 \\ 0 & if \ \Delta x_t < 0 \end{cases} \quad , \quad \Delta x_t^- = \begin{cases} \Delta x_t & if \ \Delta x_t < 0 \\ 0 & if \ \Delta x_t \geq 0 \end{cases} \quad . \qquad [5]$$

With a corresponding redefinition of $\Delta\sigma_t$, Equation [6] is modified to:

$$\Delta y_{jt} = a_0 + \sum_i a_i^+ \Delta x_{ijt}^+ + \sum_i a_i^- \Delta x_{ijt}^- + \lambda y_{t-1} + \sum_i b x_{ijt-1} + cT + u_{kt} \quad . \qquad [6]$$

For the oil price, this formulation allows us to estimate one short-term effect from an oil price increase (a_p^+), and another for a drop in the oil price (a_p^-). Symmetric investment response to oil price changes implies H_0: $a_p^+ = a_p^-$. Rejection of the null is supportive of asymmetric investment behaviour in the short term. For the oil price, a significant estimate for a_i^- will indicate the presence of a *bad news effect* (Bernanke, 1983) for variable *i*.[8] If theory suggests the presence of asymmetry, corresponding tests can be designed for all relevant variables. The reduction of Equation [6] to a symmetric specification requires equality among all sign-specific short-term effects (H_0: $a_i^+ = a_i^- - i$).

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[7] In preliminary estimations, we also tested for corresponding asymmetries in the structural relationship. However, the estimated asymmetric coefficients varied only marginally for positive and negative changes for the respective structural parameters, both in terms of magnitude and statistical significance. We interpret this as additional support for our specific approach, as long-term asymmetries would be at odds with both theory (Bloom 2000) and with desired stationarity properties of the residual in our long-term equilibrium relation [2].

[8] Following Grasso and Manera (2007), we have also tested the symmetry of the error-correction mechanism (λ). However, in our preliminary two-step estimation procedures, we found no significant difference in the speed of adjustment following positive vs. negative shocks.

4. Data

The key regulatory instrument for exploration and production on the NCS is the production license, providing an exclusive right for exploration and production of oil and gas within a specified area, usually referred to as a *block*. Production licences on the NCS are awarded through licensing rounds, and licensees retain ownership for the produced petroleum. A specific number of blocks is announced by government, and the companies prepare applications based on published criteria. The Ministry of Petroleum and Energy (MPE) decides on a partnership structure for each license, and an operator is appointed to take responsibility for the day-to-day activities under the terms of the license. Typically, a production license is awarded for an initial exploration period that can last up to 10 years. However, specified obligations regarding surveying and/or exploration drilling must be met during the license period. At completion of this kind of obligations, licensees generally retain up to half the area covered by the licence for a specified period, in general 30 years. Our data set contains information on drilling activities, discoveries and exploration acreage for three Norwegian offshore regions over the period 1966-2004 (cf. Figure 1). We are not aware of previous econometric exploration studies that have covered such a long time span. Summary statistics for key variables are presented in Table 1.

Insert Table 1 approximately here

Insert Figure 1 approximately here

Our dependent variable (Y_{jt}) is the annual number of exploration wells, or the sum of wildcat wells and appraisal wells.[9] The first explanatory variable is the oil price (P_t), as illustrated by the left-hand panel of Figure 1.[10] Our choice is a real USD-denomination of Brent blend, the standard reference for North Sea crude oil.[11]

Our second explanatory variable is a proxy for the pool of recoverable oil and gas reserves (R_{jt}), defined as cumulated discoveries net of production. Changes in this variable from one year to another will represent signals of exploration success, with potential feedback to subsequent exploration activities. Over the longer term, the evolution of this reserve variable should capture the gradual depletion of the NCS as a petroleum province. In the right-hand panel of Figure 1, we see how historical discoveries have contributed to the accumulation recoverable oil and gas reserves on the Norwegian Continental Shelf. Strong resource growth was provided by huge discoveries during the 1970s and 1980s, but over the last 15 years, the total reserve base has stagnated, due to falling drilling activity and poor exploration results. At the same time, the pool of reserves is gradually depleted by solid production rates. These are typical symptoms of a maturing oil and gas province.

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[9] According to the Norwegian Petroleum Directorate (2007), a wildcat well is an exploration well drilled to find out whether petroleum exists in a prospect, whereas an appraisal well is a well drilled to determine the extent and size of a petroleum deposit that has already been discovered by a wildcat well. Mohn and Osmundsen (2007) present specific models for each well type for the symmetric case. The focus of this study is on asymmetry and uncertainty issues, and for that purpose we have retained the activity measure that provides the best statistical fit.

[10] Following Iledare (1995), we have also tested the properties a variety of more sophisticated unit cash-flow variables, as well as the adaptive expectations hypothesis for the oil price. These variables are typically put together in relations like: $mvr_t^e = p_t^e(1-c_t)(1-\tau_t)$, where mvr_t^e is a proxy for the expected marginal value of reserves, p_t^e is the expected oil price, c_t is a unit cost variable and τ_t is a unit tax. However, none of the measures that incorporate price expectations, unit costs and tax payments were able to outperform the simple oil price variable in our model. The same was true for variety of representations of the adaptive expectations hypothesis. Consequently, we stay with our plain formulation.

[11] USD denomination is an intuitive choice, as contracts and companies on the Norwegian Continental Shelf are largely focused on USD values. Statistical inference was another criterion for the selection. We have looked at the explanatory power of various model versions, and how different oil price variables interfered with the quality of the other coefficient estimates of the model. Based on these considerations, the real USD denomination was selected for our preferred versions of the model.

The total area of open exploration acreage (E_{jt}) is our proxy for available exploration opportunities on the NCS. [12] Ahead of the initial opening of the NCS for exploration activities back in 1965, 42,000 km2 were awarded in the 1st licensing round – limited to the North Sea (cf. Figure 1). A number of licenses were handed back to the Government in the mid 1970s, reducing the inventory of available acreage. As The Norwegian Sea and the Barents Sea were opened for oil and gas exploration in 1980, new licensing rounds added new frontier acreage. Over the last few years, licensing policies have been adjusted to spur exploration activity, and large areas became available both in mature and frontier areas in 2003 and 2004.[13]

Carruth et al (2000) survey the variety of approaches to risk in empirical investment studies. For the oil and gas industry, the most important variable for earnings and company valuations is the oil price. As our primary indicator of cross-industry uncertainty, we therefore focus on oil price volatility based on historical data.[14] Based on monthly price data for the brent blend quality for the full 40-year period, we calculate annual standard errors of the monthly changes (Δp_{kt}, $k = 1, 2 \,.\,.\, 12$):

$$\sigma_t = \sqrt{\frac{1}{12}\sum_{k=1}^{12}\left(\Delta p_{kt} - E(\Delta p_{kt})\right)^2}, \qquad [7]$$

where the average monthly change in each year is used as a proxy for $E(\Delta p_{kt})$. This is according to financial market practice, and in line with previous studies (e.g., Paddock et al. 1988, Hurn and Wright 1994).

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[12] With uniform exploration acreage and non-dynamic technology, exploration acreage and resource growth may be seen as two sides of the same coin. In practice, however, the quality of licensed acreage depends on state, place and time (due to policy concerns, technological progress, and learning-by-doing). Our approach follows Mohn and Osmundsen (2007), whereby resource growth is an indicator of exploration success. Following this line of thought, licensed acreage should be seen as an input to the production function of exploration, or as a state variable of the oil companies' opportunity set.

[13] When companies play a decisive role in the licensing process, acreage awards and drilling decisions are determined (almost) simultaneously, thereby questioning the exogeneity properties of the acreage variable. However, we regard that this is no threat with the level of company influence in the NCS licensing system (Ministry of Petroleum and Energy 2006). In addition, the acreage variable is lagged by one year in the econometric model, and exogeneity properties should therefore be ensured.

[14] An alternative is to apply an estimate from an ARCH specification of oil price volatility. However, the quality of such measures depends crucially on the validity of that empirical model (Engle, 1983).

As pointed out by Chungcharoen and Fuller (1999), there are two major geological uncertainties that play a key role in the exploration process: the field size and the number of possible fields. Our combined measure of underground risk incorporates both of these aspects. [15] We have no details on geological qualities, and have to rely on more aggregate indicators than Hurn and Wright (1994), who use a range of field-specific characteristics as proxies for underground risk. Drawing on Stauffer (2002), we look at observed derivatives of these characteristics. First, high (low) exploration risk means low (high) discovery rates. Second, to compensate for high exploration risk, the expected reward in terms of discovery size will have to be high, to trigger the required exploration investments (Walls and Dyer 1996). Thus, exploration risk is a positive function of average discovery size, and negatively related to the success rate.[16] Combining these measures, an aggregate proxy for exploration risk (G_{jt}) is the ratio of average discovery size (M_{jt}) to the average discovery rate (S_{jt}).[17] Consequently, an increase in our indicator of underground risk G_{jt} could be caused either by falling discovery rates or by increasing average discovery size. Recalling that $g_{jt} = \ln G_{jt}$, we capture underground risk by the following explanatory variable:

$$g_{jt} = \ln\left(\frac{M_{jt}}{S_{jt}}\right). \qquad [8]$$

As argued by Quirk and Ruthroff (2006), a maturing petroleum province – typically characterised by increasing discovery rates and decreasing discovery sizes – will experience a reduction in exploration risk.

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[15] See Suslick and Schiozer (2004) for a survey of literature related to risk analysis in petroleum exploration and production.

[16] These assumptions are reasonable for the Norwegian Continental Shelf, but not necessarily for all other oil and gas provinces. As pointed out by one of the referees, historical evidence from other parts of the world suggests that lower quality prospects with relatively high extraction costs have been associated with larger discoveries. This would complicate the relation between average discovery size, success rates and exploration risk.

[17] Average discovery size (M_{jt}) is defined as the total annual reserve addition (H_{jt}) divided by the annual number of discoveries (D_{jt}): $M_{jt} = H_{jt}/D_{jt}$. The average discovery rate (S_{jt}) is calculated as the annual number of discoveries (D_{jt}) divided by the annual number of exploration wells (Y_{jt}): $S_{jt} = D_{jt}/Y_{jt}$.

5. Estimation, testing and results

A requirement for the validity of the equilibrium-correction specification is that our structural equilibrium is indeed characterized by co-integration. Our data set is a panel – consisting of three time series over 40 years. A consensus is yet to be reached on how to test for co-integration in heterogeneous panel data. Procedures have been developed for balanced panels (e.g., Levin and Lin, 1993; Banerjee, 1999), but challenges remain unsettled for our type of data set, due to varying starting points and several gaps. We therefore test the stationarity properties of all our variables separately for each of the three regions, applying the augmented Dickey-Fuller test.[18] Results are presented in Appendix 1. We are unable to reject the null of non-stationarity for 27 out of 28 time series from the *level* specification of the model, including estimated residuals for Equation [5]. This suggests that the variables of our model are indeed co-integrated. With one exception, the null of non-stationarity is rejected on a 99 per cent significance level for all the *change* variables of our model. We take these results as support for our modelling approach.

When Phillips Petroleum discovered the first huge oil field (Ekofisk) on the NCS back in 1969, estimates for recoverable oil and gas reserves on the Norwegian Continental Shelf were multiplied 15 times from one year to another. With the log of cumulative discoveries as one of our explanatory variables, the Ekofisk discovery creates a disturbing outlier in our data set. We have therefore introduced a dummy variable (d_t^r) that takes the value 0 for years before 1970, and 1 for all years after 1970. The lagged change in this variable (Δd_{t-1}^r : . . 0, 0, 0, 1, 0, 0, 0, . .), takes a

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[18] Dickey and Fuller (1981) introduced a popular procedure to test that a variable follows a unit-root process. The null hypothesis is that the variable is contains a unit root, with a stationary data-generating process as the alternative. With the augmented Dickey-Fuller test, a regression is run of the differenced variable on its lagged level, as well as its lagged differences (sometimes also with a time trend):

$$\Delta x_t = \gamma_0 + \gamma_1 x_{t-1} + \sum_j \gamma_{2j} x_{t-j} + v_t \ .$$

A significant negative parameter estimate for γ_1 will be supportive of stationarity in Δx_t, implying that the variable expressed in levels (x_t) is integrated of degree 1 ($I(1)$). The Dickey-Fuller test accounts for serial correlation by use of additional lags of the first-difference variable.

highly significant parameter estimated in our models, and it also improves the quality both on other parameter estimates and general model diagnostics.

Following the econometric model specification in Equations [6] and [9], we now regress the change in drilling activity (Δy_t), against changes and lagged levels of the explanatory variables, including the oil price ($\Delta p_t, \Delta p_t^+, \Delta p_t^-, p_{t-1}$), cumulated discoveries net of production ($\Delta r_{jt-1}, \Delta r_{jt-1}^+, \Delta r_{jt-1}^-, r_{jt-2}$),[19] open exploration acreage ($\Delta e_{jt-1}, \Delta e_{jt-1}^+, \Delta e_{jt-1}^-, e_{jt-2}$), oil price volatility ($\Delta \sigma_t, \sigma_{t-1}$), and underground risk ($\Delta g_{jt-1}, g_{jt-2}$). Regional variation is available for all variables except the oil price (p_t) and oil price volatility (σ_t). A time trend (t) was included in preliminary estimations, but turned out with insignificant parameter estimates for all model versions, and is therefore skipped in the table of results. Note that theory does not suggest asymmetries for the uncertainty variables. Based on preliminary estimation, symmetry could not be rejected for our uncertainty indicators. Consequently, our preferred models imply a balanced response to changes in uncertainty, both in the short run and in the long run.

Underground risk (g_{jt-1}) and open exploration acreage (e_{jt}) not have statistically significant persistent effects in any of the preferred models, and the corresponding lines of the table are therefore left out. All estimations are performed with fixed-effects procedures, whereby regional dummy variables are included and suppressed through normalization around sample unit means.[20]

For each of the four model variants, our estimation strategy follows a general-to-specific approach. We have tested for a variety of lag specifications, and the variables of our preferred models are those that that could defend a position based on statistical inference and general model diagnostics. Variables that have been eliminated in our general-to-specific approach are marked with a hyphen (–) in Table

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[19] Observe that this variable is equivalent to the inventory of recoverable oil and gas reserves.

[20] Our approach is a dynamic econometric model for a panel data set, with large T and small N. Modern estimation procedures for dynamic panel data models often involve the GMM estimators introduced by Arellano and Bond (1991). However, as pointed out by Bond (2002), fixed-effects least squares estimates are consistent in the case of large T panels.

2. Overall results for the preferred models are presented in Table 2. We apply robust standard errors due to strong evidence of heteroskedasticity, as indicated by the Breusch-Pagan (BP) test statistics.[21]

Insert Table 2 approximately here

Column 1 presents the traditional model, with no asymmetric effects, and no uncertainty indicators. Column 2 introduces asymmetric short-term effects for the oil price ($\Delta p_t^+, \Delta p_t^-$), resource accumulation ($\Delta r_{jt}^+, \Delta r_{jt}^-$) and acreage evolution ($\Delta e_{jt}^+, \Delta e_{jt}^-$). Uncertainty indicators are added to the traditional, symmetric model in Column 3, whereas Column 4 integrates the uncertainty indicators in a model with asymmetric short-term effects.

Underground risk (g_{jt-1}) and open exploration acreage (e_{jt}) do not have persistent effects in any of the preferred models, and the corresponding lines of the table are therefore left out. The basic symmetric model captures 50 per cent of the variation in our data set, or 43 per cent for adjusted R^2. Allowing for asymmetry improves the explanatory power by 5 percentage points (4 percentage points for adjusted R^2), as illustrated in Column 2 of Table 1. In a fully specified version of this asymmetric model, a joint test for equality across our asymmetric parameters (H_0: $a_i^+ = a_i^-$ $\forall\ i = p, r, e$) is clearly rejected ($p = 0.04$). In specific tests for each of the variables, symmetry is rejected for the oil price (H_0: $a_p^+ = a_p^-$; p-value = 0.06) and for the resource variable (H_0: $a_r^+ = a_r^-$; p-value = 0.04). For the acreage variable, we are not able to reject symmetry in the fully specified model. Still, an implication of our results is that the reduction of Model 2 to the symmetric Model 1 is not justified on statistical grounds.

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[21] Estimated standard errors are based on the so-called Huber-White or Sandwich variance estimator (Huber, 1967; White, 1984).

Including the uncertainty parameters in the basic symmetric model increases the explanatory power to 56 per cent, and another two percentage points are added when we allow for asymmetric effects. Tests for joint significance are highly significant, with a p-value below 0.001 for all four models. The retained variables are largely significant in statistical terms, and they all take plausible signs and values. Table 1 also provides further support for cointegration, as the equilibrium-correction coefficient takes the correct sign, and is highly significant in all models. The implicit speed of adjustment is rapid, with equilibrium-correction coefficients around 0.8.

The estimated models contain statistically significant economic effects, but their magnitude is rather small. The influence from oil price variation on drilling activity is not very robust in statistical terms. Oil price elasticities range from 0.20 to 0.63, suggesting that exploration drilling on the NCS is less responsive to oil price variation than found in previous studies of oil and gas provinces elsewhere in the world. Compared to Dahl and Duggan's (1997) survey of oil price elasticities in US exploration studies, this suggests that the exploration response to price changes is lower in a regulated, high-tax environment like the Norwegian than for USA. In a recent study of exploration activity on the UKCS, Kemp and Kasim (2006) also find the oil price influence on exploration efforts to be modest. Ringlund et al. (2004) estimate error-correction models for rig activity in six global regions. Their results indicate that oil price elasticities of oil and gas exploration vary inversely with the degree of regulation.

With short-term elasticities of 0.31-0.49, our results also illustrate how new acreage awards ($\Delta e_{jt-1} > 0$) stimulate exploration drilling in the short term. On the other hand, there is no persistence in the stimulus from new acreage awards. Exploration success ($\Delta r_{jt-1} > 0$) has an invigorating effect on subsequent exploration drilling, as lagged resource growth (Δr_{jt-1}) takes a significant elasticity close to unity.

As illustrated by the transition from Column 1 to Column 3 in Table 1, the introduction of uncertainty indicators provides an improved econometric explanation of our data. The explanatory power increases by 6 percentage points to 56 per cent, and the F-test for joint significance of model parameters also increases slightly. Moreover, this model version implies a negative short-term effect on exploration activities from changes in both oil price volatility ($\Delta\sigma_t$) and underground risk (Δg_{jt-1}). Our results suggest a negative relation between exploration efforts and uncertainty. One interpretation is that the *opportunity effect* of increased uncertainty (Oi, 1961; Hartman, 1972; Abel, 1983) is dominated by the *risk effect* (Cukierman, 1980; Bernanke, 1983; Dixit and Pindyck, 1994) even in the short run. At the same time, the long-term effects of these uncertainty indicators are negligible. Even though its parameter is insignificant, we retain oil price volatility in the structural part of the Uncertainty model (Column 3), besides underground risk, whose parameter is significant. The reason is that the inclusion improves on other parameter estimates, as well as the overall quality of the model. We see these results as modestly supportive of a role for uncertainty in of oil and gas exploration activity.

Our setup can also be applied to test for the existence of asymmetric short-term effects, as described in the review of theory above. The bad news principle reflects the fact that the decision to invest is made in such a way as to expose the company to good outcomes and reduce exposure to bad outcomes. The implication is a different investment response to oil price decline than to oil price decline. For this purpose, we introduce asymmetric short-term effects according to the formal representation in Equations [5]-[6].

The combination of asymmetry and uncertainty effects is presented in Table 1, Column 4. An eye-catching result is that oil price increases do not stimulate exploration drilling in the short term. On the other hand, a drop in the oil price of 1 per cent will cause an instantaneous drop in exploration activity of 0.63 per cent. These results indicate that it takes more to convince the oil and gas companies that an oil price change is persistent when the oil price increases than when the oil price falls. We take this as evidence of a *bad news effect* on exploration activity from short-term oil price fluctuations. Empirical studies of the interaction between companies and financial markets (e.g., Osmundsen et al. 2006a, b) also suggest that increasing pressures for strict capital discipline among oil and gas companies have reduced their willingness to invest for long-term reserves and production growth.

Our preferred model also includes asymmetric effects for exploration success ($\Delta r_{jt-1} > 0$). Significant discoveries may serve as door-openers or initial footholds in frontier exploration areas, they may trigger learning-by-doing effects, they may confirm/reject specific exploration plays, and they may lower the entrance costs for neighbouring prospects. As an oil and gas province matures, depletion mechanisms may reduce future discovery prospects. In our model, this mechanism is captured by the level variable r_{jt}, and also by the coefficient on negative changes in our reserve variable ($\Delta r_{jt-1} < 0$), which becomes relevant only in the phase where resource growth from new discoveries is dominated by annual production.

Finally, the combined model in Table 1, Column 4 suggests that new licensing rounds ($\Delta e_{jt-1} > 0$) have a significant, but modest temporary effect. On the other hand, exploration activity is not negatively affected when exploration acreage is reduced ($\Delta e_{jt-1} < 0$), i.e. when licenses are handed back to the government on expiry. The magnitude of this effect is modest, but its sign and impact is according to expectations. Additions of new exploration acreage provide a temporary stimulus to exploration drilling. But the validity of the opposite effect is more doubtful.

Observe also that the small short-term effect of oil price volatility slips when we allow for asymmetric short-term effects in the oil price. This suggests an interaction between our asymmetric specification of the oil price and oil price volatility. Oil price volatility is still highly relevant, as our estimated model implies a negative link between oil price volatility and accumulated exploration efforts. The role for our indicator of underground risk is also maintained in the combined model, confirming the short-term negative influence from uncertainty on exploration spending. Our uncertainty indicators do not justify a role in the structural part of the model, and we therefore conclude that the role of uncertainty is largely related to the short-term dynamics of exploration spending.

Insert Figure 2 approximately here

The left-hand panel of Figure 2 compares post-sample estimates for the traditional symmetric model (Model 1) against the asymmetric specification with uncertainty variables (Model 4). As we can see, Model 4 captures the volatility of observed drilling activity slightly better than Model 1. The recent decline in exploration activity is also better explained by the asymmetric model than by the symmetric specification. The main reason for this difference is that the asymmetric effect of oil price changes allows for a more abrupt negative impulse from the 1998 oil price shock, whereas the effect of the subsequent oil price increase is sluggish. This is also illustrated in the right-hand panel of Figure 2, where the marginal impulse response of oil price changes is depicted. As we can see, a 10 per cent drop in the oil price produces an instantaneous drop in exploration activity of 6.3 per cent, before a gradual correction towards the persistent effect of 1.9 per cent is introduced. On the other hand, an oil price increase has no immediate effect, but only a gradual adjustment towards the long-term effect, initiated with a one-year lag.

The estimated error-correction models establish a negative link between uncertainty and exploration activity. Even if the oil price volatility variable does not take a significant coefficient, an inverse relationship between oil price variability and accumulated exploration efforts is secured by the asymmetric short-term oil price elasticity. For underground risk, the link is explicitly supported by the negative and significant coefficient for our underground risk indicator.

6. Conclusions and caveats

A rich empirical literature on exploration economics developed in the three decades after Fisher (1964) opened the field. Unfortunately, the flow of new contributions has dwindled over the last 15 years, whereas general theory of investment behaviour has progressed extensively. At the same time, the market environment for oil and gas has grown increasingly dynamic, with massive industrial restructuring, record-high oil prices, weak exploration results, and widespread security-of-supply concerns. Understanding the economics of oil and gas exploration is therefore more important than ever.

Modern economic theory suggests a role for uncertainty and asymmetry issues in investment behaviour. A key result from the literature on irreversible investment is that an increase in uncertainty will cause a reduction in investment, due to an increase in the option value of delay. This view has replaced the traditional neoclassical approach, whereby the convexity of the profit function implies a “desirability of price instability” (Oi 1961). Traditional neo-classical models are symmetric in terms of price response. On the other hand, modern theories of irreversible investment do suggest asymmetries in the investment response to changes in economic variables. This kind of behaviour is also supported by recent developments of agency theory and behavioural finance. We provide a formal framework of estimation of these mechanisms, as well as testing procedures for the role of asymmetry and uncertainty in oil and gas exploration activities.

Our econometric model of exploration efforts provides an appealing augmentation of previous empirical studies of oil and gas exploration. In a formalized statistical framework, we establish an empirical role for both oil price volatility and underground risk. We also demonstrate that the response in exploration behaviour to changes in explanatory variables depends on the sign of these changes. Our asymmetric specification outperforms the symmetric model in statistical terms. The explanatory power improves, the magnitude of the estimated coefficients increase, and the coefficients of the asymmetric model are more precisely estimated.

According to our results, oil and gas exploration efforts adjust instantaneously to a drop in the oil price, whereas the reaction to an oil price increase is sluggish. One possible interpretation is that falling oil prices effectively coordinates the oil industry on a low exploration level, and that this coordination prevails for some time also when the oil price picks up again. Our results also imply that the impulse to exploration efforts from resource depletion is quite different than for major new discoveries, although both these changes relate to cumulated oil and gas resources in the same way. New licensing rounds provide a stimulus to exploration drilling in the short term, whereas the same effect is not applicable for reductions in exploration acreage due to license expiry.

Our results have a wide range of applications. First, they provide a potential improvement to empirical analyses of oil and gas exploration in terms of both understanding and prediction. Second, our specification may be useful to empirical studies of producer and investment behaviour in other regions – and industries.

Finally, there are interesting policy implications to be made. Specifically, our model lends support to the argument that oil-importing countries would benefit from a stable oil price level. As the immediate reduction in exploration efforts when the oil price falls outweigh the sluggish exploration increases when the oil price picks up again, accumulated exploration efforts are at their highest at stable oil prices. Active management of the US Strategic Petroleum Reserve may therefore be justified on grounds of increasing total exploration efforts over time. On the other hand, we also offer arguments for stabilisation of exploration efforts in oil-producing countries. If temporary oil price drops are allowed to suppress exploration activity, the revival is sluggish. Accordingly, our models provide a case for sequential licensing policies and counter-cyclical policy measures in oil exploration.

On a more general note, modern theories of irreversibility, uncertainty and investment suggest a negative link between risk and capital accumulation. In a macroeconomic context, this raises additional policy concerns for stability, as a volatile business framework would be bad for growth under these circumstances. Our proposed model framework may be applied to test the relevance of these hypotheses on other types of investment, other industries – and even on a macroeconomic level.

This study is limited to efforts of exploration. To capture the full picture of exploration economics, we would have to include equations for exploration efficiency along with our exploration effort equation, preferably in a simultaneous setting. An econometric model of the exploration process should acknowledge the simultaneous interaction between efforts and efficiency, and reveal responses from economic, geological and technological variables in the short term as well as in the long term. More work is also required to identify processes of depletion and technological progress. Unfortunately, such a detailed and refined approach would exhaust the limits of our data set, and therefore has to be left for future research.

Another topic for further research would be to formulate a dynamic theory of exploration behaviour to support our empirical model more rigorously. Such a theory should preferably also include the trade-off between various types of investment among the oil and gas companies, as well as explicit transmission mechanism for uncertainty and asymmetric adjustment costs.

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Appendix 1: Tests for Stationarity

Augmented Dickey-Fuller (ADF) test ratios computed in Stata.

Level variables (cf. Equation [5])

	Total NCS	*North Sea*	*Norwegian Sea*	*Barents Sea*
y_{kt}	-1.87	-2.44	-2.63	-4.26^{**}
p_t	-1.98	-1.98	-1.98	-1.98
r_{kt}	-2.19	-2.58	-2.02	-1.84
e_{kt}	-2.65	-2.12	-3.12	-2.46
σ_t	-3.13	-3.13	-3.13	-3.13
g_{kt}	-3.11	-2.95	-2.58	-2.71
$\hat{\varepsilon}_t$	-2.75^{***}	-3.14^{***}	-4.49^{***}	-2.37^{**}

H_0: Non-stationarity.

*) H_0 rejected at 90, **) 95 and ***) 99 per cent confidence level, respectively.

Change variables (cf. Equation [6])

	Total NCS	*North Sea*	*Norwegian Sea*	*Barents Sea*
Δy_{kt}	-6.90^{***}	-6.10^{***}	-5.90^{***}	-4.99^{***}
Δp_t	-5.96^{***}	-5.96^{***}	-5.96^{***}	-5.96^{***}
Δr_{kt}	-5.03^{***}	-4.97^{***}	-2.79^{*}	-5.97^{***}
Δe_{kt}	-5.69^{***}	-5.36^{***}	-4.29^{***}	-4.93^{***}
$\Delta \sigma_t$	-10.12^{***}	-10.12^{***}	-10.12^{***}	$-9{,}09^{***}$
Δg_{kt}	-9.62^{***}	-9.60^{***}	-8.06^{***}	-9.37^{***}

H_0: Non-stationarity.

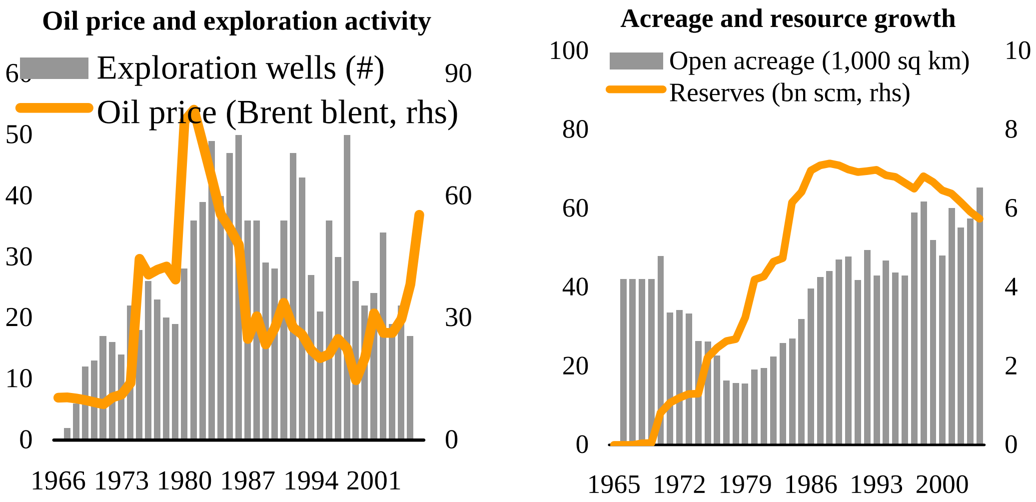
*) H_0 rejected at 90, **) 95 and ***) 99 per cent confidence level, respectively.

Table 1. Descriptive statistics for data sample

	Obs.	*Mean*	*St. dev.*	*Min.*	*Max.*
Y_{jt}	84	12.857	10.270	0.0000	40
P_t	40	31.201	19.180	8.8000	81.200
R_{jt}	120	1470.7	1988.9	0.0000	5891.6
E_{jt}	120	13134	12913	0.0000	47985
G_{jt}	120	204.00	414.04	0.0000	2955.9
σ_t	40	7.7375	7.1269	0.0232	36.300

Source: Norwegian Petroleum Directorate (Y_{kt}, R_{kt}, E_{kt}, G_{kt}), ReutersEcowin (P_t, σ_t).

Figure 1. Key variables of the data set



Sources: Oil price: ReutersEcoWin (http://www.ecowin.com). All other numbers: Norwegian Petroleum Directorate.

Table 2. Estimated error-correction models of exploration drilling

	Traditional Model	*Asymmetric (A) Model*	*Uncertainty (U) Model*	*A&U Model*
Estimated coefficients [a)]				
Intercept	0.51^{*} (0.07)	0.44 (0.18)	0.48^{**} (0.03)	0.31 (0.13)
Δp_t	0.20 (0.18)		0.26^{*} (0.10)	
Δp_t^{+}		–		–
Δp_t^{-}		0.54^{*} (0.06)		0.63^{**} (0.03)
Δr_{kt-1}	0.88^{***} (0.00)		0.90^{***} (0.00)	
Δr_{kt-1}^{+}		0.93^{***} (0.00)		0.97^{***} (0.00)
Δr_{kt-1}^{-}		–		7.60^{**} (0.02)
Δd_{t-1}^{r}	-1.90^{***} (0.00)	-1.97^{***} (0.00)	-1.97^{***} (0.00)	-2.30^{***} (0.00)
Δe_{kt-1}	0.31^{*} (0.10)		0.33^{*} (0.07)	
Δe_{kt-1}^{+}		0.44^{*} (0.08)		0.49^{**} (0.03)
Δe_{kt-1}^{-}		–		–
$\Delta \sigma_t$			-0.01^{**} (0.05)	–
Δg_{kt-1}			-0.04^{**} (0.02)	-0.04^{***} (0.01)
y_{kt-1} (λ)	-0.84^{***} (0.00)	-0.83^{***} (0.00)	-0.74^{***} (0.00)	-0.76^{***} (0.00)
p_{t-1}	0.21^{**} (0.03)	0.16^{*} (0.10)	0.16^{*} (0.10)	0.15^{*} (0.09)
r_{kt-2}	0.10^{*} (0.09)	0.15^{**} (0.03)	0.13^{*} (0.10)	0.18^{**} (0.05)
σ_{t-1}			-0.01 (0.27)	–
Model diagnostics				
R^2	0.50	0.55	0.56	0.58
R^2 (adj.)	0.43	0.47	0.46	0.50
F(k, n-k)	14.52	14.13	15.17	10.41
BP (LM)[b]	5.06^{**}	7.65^{***}	3.86^{**}	10.01^{***}
Obs. (#)	70	70	70	70
Derived structural coefficients (cf. Equation [5])				
p_t	0.25^{**} (0.03)	0.19 (0.12)	0.21^{*} (0.09)	0.20^{*} (0.10)
r_{t-1}	0.12^{*} (0.06)	0.18^{**} (0.02)	0.18^{*} (0.08)	0.24^{**} (0.03)
σ_{t-1}			-0.01 (0.28)	

*) Significant at 90, **) 95 and ***) 99 per cent confidence level, respectively.

a) p-values in brackets.

b) Breusch-Pagan LM test for heteroscedasticity (H_0: Homoscedasticity).

Figure 2. Post-sample prediction and marginal effects