Investment Behaviour in the International Oil and Gas Industry

Essays in empirical petroleum economics

PhD Thesis by

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To Trude, Agnes Marie, and Håkon Mathias

Preface

My interest in econometric modelling of producer behaviour was triggered when I started as a freshman at the Research Department of Statistics Norway in the early 1990s. However, drawn by the waters of Western Norway, I left Statistics Norway already in 1994 to pursue a career with economic research, strategy and communication in the finance and petroleum industries. Since then, a silent day-dream of mine has been to return to the ivory tower at some point later in life, to pursue my research ambitions one step further. Starting in 2005, a 3-year grant of leave from Statoil made that day-dream come true. This dissertation represents the outcome of my endeavours.

The original idea behind my PhD project was to combine academic interests with experience and data from the industry to shed new light on investment behaviour and market interaction among international oil and gas companies. To the extent that I have succeeded, it is because I have been standing on the shoulders of giants – and not only in the purely scientific context.

StatoilHydro has been the primary champion of this project. My gratitude therefore goes out to all the people in StatoilHydro who have shown interest in my academic aspirations. Without the generous support from my superiors and the keen interest from my colleagues, this project could not have been accomplished.

The research behind this thesis has been carried out at the University of Stavanger, under the excellent supervision of professor Petter Osmundsen, who also provided the inspiration and hospitality which was critical to make me take on the challenge of a PhD project. I am also thankful to my co-adviser Knut Einar Rosendahl from the Research Department at Statistics Norway. Knut Einar has rendered a range of valuable comments and suggestions for the papers of this thesis, and also provided me with opportunities to present and discuss my work with his competent colleagues at Statistics Norway.

Contents

Summary

High growth and welfare aspirations will require massive energy investment in the years ahead of us, especially in the non-OECD area. With more than 60 per cent of primary energy supply, oil and natural gas play a dominant role in today's global energy market. Even with high ambitions to contain greenhouse gas emissions and arrest global warming, petroleum is likely to remain an important source of energy in a 20-year perspective. A good understanding of the investment process among oil and gas companies is important to grasp the full picture of oil and gas supply. Insights from oil and gas investment studies may translate into policies to improve the security of energy supply, to promote energy efficiency and economic growth, and to pull people out of poverty through the extension of affordable energy.

In petro-states like Norway, oil and gas investments play an important role for macroeconomic fluctuations in the short to medium term. A proper understanding of investment behaviour in the oil and gas industry is therefore useful for economists, market analysts, policy-makers, and everyone who takes an interest in economic and financial market fluctuations. Moreover, strategies for resource management become important for any country rich in petroleum resources. In this context, the links between exploration, reserve accumulation, field development and production become important both to corporate strategists and to policy-makers.

Profit maximisation is the key behavioural assumption for international oil and gas companies, as for most other industries. However, some features are specific to oil and gas production. The reserve concept is unique to non-renewable resource industries, and so is exploration activity. High capital intensity, imperfect competition, and extensive political attention are some other distinguishing characteristics. Industry-specific methods and tailored analyses are therefore required. Combining industry-specific theories of investment behaviour with the best statistical methods available, this thesis adds new empirical insights on issues of capital formation and interaction between companies and markets in the international oil and gas industry.

1

Efforts and efficiency in oil and gas exploration is the subject of Part 1. Empirical studies are conducted on a data set for the Norwegian Continental Shelf. In the first study, an econometric model of exploration and appraisal drilling is specified and estimated. Explanatory variables include the oil price, cumulative discoveries and open exploration acreage. The dynamic model accounts explicitly for sluggishness and short-term adjustments in exploration drilling. We find robust long-term oil price effects on exploration activity, whereas the short-term response is muted. On the other hand, the temporary influence on exploration drilling from licensing rounds for new exploration acreage is significant, and so are the feedback effects from historical exploration success. At the same time, the longer-term impact of these variables is more moderate.

Drilling efforts have been subject to a wide range of econometric studies since the mid 1960s, especially for the US. Less attention has been paid to the success and efficiency of oil and gas exploration, not to mention the interaction between efforts and efficiency. Important gaps of the previous literature are bridged by the second paper of this thesis, where three components of reserve growth are examined simultaneously in an integrated and novel modelling approach. Departing from a simple theory of exploration, modern techniques of time-series econometrics are applied to estimate three simultaneous equations for drilling activity, success rates and average discovery size.

An increase in the oil price of 1 per cent produces a persistent increase in annual reserve-generation of 1 per cent, according to the results. However, the oil price exerts a negative influence on the discovery rate and a positive influence on average discovery size. This suggests that overall exposure to exploration risk in the oil and gas companies is positively linked to the oil price. The proposed modelling approach illustrates that policy measures need not and should not be limited to the regulation of drilling activity. With reserve additions as the ultimate target, the potential gains from measures to stimulate the success rate or average field size may well exceed the direct importance of drilling activity in itself (i. e. number of spudded wells). Second, my results suggest that annual reserve additions are procyclical, due to a strong positive link between the oil price and average discovery size. If the government interest is to stabilise reserve growth over time, this result provides a case for countercyclical licensing policies.

Standard theory of irreversible investment and real waiting options suggest that the relationship between investment and uncertainty is negative.

However, recent contributions to the theory of strategic investment point out that investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. Increased uncertainty has the potential to increase the value of both these types of real options. Thus, the theory of compound options may give rise to a positive relationship between investment and uncertainty. Empirical studies are therefore required to settle the question.

This forms the basis for the paper in Chapter 4. Based on data for 170 companies over the period 1992-2005, we estimate various models of investment, with robust results for the uncertainty variables. Our results suggest that industry-specific uncertainty (oil price volatility) has a stimulating effect on investment rates, as suggested by modern theory of strategic investment and real options. On the other hand, overall uncertainty (stock market volatility) represents a bottle-neck for investment and capital formation. Based on recent contributions to the theoretical investment literature, our results offer a valuable supplement, as we offer empirical support to the idea that strategic investments with real options may give rise to a positive relationship between investment and uncertainty.

Recent developments in the oil and gas industry suggest that investment behaviour is not necessarily changeless over time. In the paper of Chapter 5, we propose a micro-econometric procedure to investigate the stability of investment behaviour. Based on a data set for 253 oil and gas companies over 14 years, we estimate dynamic models of capital formation, accounting explicitly for sluggishness and partial adjustment.

Our results provide robust evidence for two distinctly separated historical regimes of investment behaviour in the international oil and gas industry over the last 15 years; one from 1992 to 1997, and one from 1998-2005. The late rise in oil price and cash-flows has had a far smaller impact on investment rates than what was typical before 1998, suggesting that financial market pressures in the aftermath of the Asian economic crisis have caused tightened capital discipline in recent years. Moreover, the early 1990s were characterised by a negative relationship between investment and uncertainty, whereas the recent increase in oil price volatility seems to have spurred investment over the last few years. This result is at odds with the vast majority of previous studies of investment and uncertainty, but well in line with recent development of theories of compound options structures, imperfect competition and strategic investment behaviour.

3

The last part of this thesis deals with the interaction between companies and investment behaviour on the one hand, and external oil and financial market dynamics on the other. In the paper of Chapter 6, we explore a hypothesis that a change in investment behaviour among international oil companies (IOC) towards the end of the 1990s had long-lived effects on OPEC strategies, and on oil price formation. Coordinated investment constraints were imposed on the IOCs through financial market pressures for improved short-term profitability in the wake of the Asian economic crisis. Clustering of attention on short-term profitability gave rise to a coordinated equilibrium of reduced investment. This tacit collusion had a dampening effect on production growth, and was also supportive of the subsequent increase in the oil price.

A partial equilibrium model for the global oil market is applied to compare the effects of these tacitly collusive capital constraints on oil supply with an alternative characterised by industrial stability. Our results suggest that even temporary economic and financial shocks may have a long-term impact on oil price formation. Specifically, we find that the curb on IOC investments in the late 1990s caused an increase in the oil price of 10 per cent in the long run. Both OPEC and non-OPEC producers have gained from this development, whereas the cost is carried by oil-importers and consumers.

The interaction between capital markets and company behaviour is also subject to scrutiny in the last paper of this thesis. To assess important drivers of company valuation, a simple econometric model is specified and estimated on market and accounting data for 14 major oil and gas companies from 1990 to 2003. Company-specific valuation multiples are regressed against a number of financial indicators, as well as the oil price.

A key result is that short-term accounting returns (RoACE) are not supported as an important value-driver in our estimated model. On the other hand, valuation multiples respond negatively to an increase in the oil price, implying that oil and gas companies are priced at mid-cycle oil prices. The estimated model suggests a robust and material influence on market valuations from oil and gas production. This suggests that company size and reputation still plays an important role in the valuation process. The study elucidates some of the weaknesses of RoACE for company valuation purposes. Our primary focus is on inter-company comparisons and relative stock market valuation. However, within the individual companies, a consistently normalised RoACE may still prove useful for internal efforts to improve operational and financial performance over time.

Sammendrag

Høye forventninger om vekst og velstand vil kreve store energiinvesteringer verden over i årene som kommer. Med mer enn 60 prosent av energiforsyningen har olje og naturgass en dominerende rolle i dagens globale energimarked. Store ambisjoner om å begrense utslipp av drivhusgasser og begrense den globale oppvarmingen kan neppe forhindre at petroleum vil forbli blant verdens viktigste energibærere selv i et 20-års perspektiv. Investeringer og kapitalakkumulasjon blant olje- og gasselskapene er en viktig del av tilbudssiden i energimarkedet generelt, og i olje- og gassmarkedene spesielt. Studier av olje- og gassinvesteringer kan gi verdifull ny kunnskap, med politikk-implikasjoner som kan bedre forsyningssikkerheten i energimarkedet, fremme økonomisk vekst og løfte mennesker ut av fattigdom gjennom bedre tilgang til energi.

I Norge spiller olje- og gassinvesteringene også en viktig rolle for den makroøkonomiske utviklingen både på kort og lang sikt. God oversikt over mekanismene bak olje- og gassinvesteringene er dermed nyttig for økonomer, markedsanalytikere, offentlige myndigheter og alle andre med interesse for svingninger i konjunkturer og kapitalmarkeder. Alle land med store olje- og gassforekomster vil i tillegg ha interesse av å utvikle gode strategier for ressursforvaltningen. I så måte vil sammenhengene mellom leteaktivitet, ressursutvikling, feltutbygging og produksjon være sentrale både for selskaper og myndigheter.

Til grunn for atferden blant internasjonale olje- og gasselskaper ligger en målsetning om å maksimere den økonomiske inntjeningen, på samme måte som i andre næringer. Enkelte trekk er imidlertid særegne for olje- og gassnæringen. Det gjelder for eksempel påvisning og utvikling av olje- og gassreserver, som er en kritisk forutsetning for selve produksjonsaktiviteten. Høy kapitalintensitet, ufullkommen konkurranse og stor politisk oppmerksomhet er eksempler på andre næringsspesifikke særtrekk. De økonomiske standardmodellene for produsentatferd krever derfor spesialtilpasning, og skreddersøm er påkrevd for analyseverktøyet når olje- og gassindustrien står i søkelyset. Industrispesifikk økonomisk teori for

investeringsatferd kombineres i denne avhandlingen med moderne metoder for statistisk analyse. Resultatet er ny innsikt om kapitaldannelse og samhandling mellom selskaper og markeder i den internasjonale olje- og gassindustrien.

Aktivitet og effektivitet i oljeselskapenes letevirksomhet er temaet i den første delen av avhandlingen. I kapittel 2 spesifiserer vi en teoretisk modell for leting etter olje og naturgass, som deretter tallfestes med utgangspunkt i historiske data fra norsk kontinentalsokkel. Som forklaringsvariabler bruker vi oljepris, historiske funnresultater og tilgang til leteareal. Modellen tar hensyn til tregheter og kortsiktige tilpasninger av samlet leteboring. Resultatet innebærer at oljeprisen har en viss betydning for leteaktiviteten, men tilpasning til endringer i oljeprisen tar tid, og den kortsiktige responsen er beskjeden. For de kortsiktige svingningene i leteaktiviteten spiller lisenspolitikk og funnresultater en langt viktigere rolle. Til gjengjeld tyder resultatene på at verken lisenstildelinger eller funnsuksess kan påvirke leteaktiviteten på vedvarende basis.

Leteaktivitet har vært gjenstand for en rekke analyser innenfor økonomiforskningen, spesielt når det gjelder data fra USA. Faktorer og mekanismer bak resultatene av leteaktiviteten er ikke like godt utforsket. Viktige mangler ved litteraturen på området adresseres i kapittel 3, hvor reservetilveksten blir dekomponert og kartlagt i en integrert og nyskapende empirisk modell. Nærmere bestemt anvendes moderne teknikker for tidsserieøkonometri i en simultan tallfesting av tre ligninger for leteaktivitet, funnsuksess og gjennomsnittlig funnstørrelse.

Resultatene tyder på at en økning i oljeprisen på 1 prosent bidrar til en økning av samme størrelsesorden for den årlige reservetilveksten. Dette skyldes ikke bare at høyere oljepris gir høyere leteaktivitet, men også at leteresultatene blir bedre når oljeprisen stiger. Vi finner riktignok tegn på at funnratene faller når oljeprisen stiger. Men enda viktigere er det at en økning i oljeprisen gir en betydelig økning i gjennomsnittlig funnstørrelse. Dette indikerer at oljeselskapene tar større risiko i leteaktiviteten når oljeprisen er høy, noe som gir utslag i lavere funnrater, men også flere store funn.

Denne analysen illustrerer tydelig at myndighetenes oppmerksomhet bør strekke seg lengre enn til selve leteaktiviteten. Med reservetilvekst som endelig mål for letevirksomheten kan tiltak for å heve funnrater og gjennomsnittlige funnstørrelser gjerne gi større uttelling enn en økning i antallet letebrønner. Videre antyder analysene av letevirksomheten at

tilveksten i reservene svinger i takt med oljeprisen. Dersom myndighetene er opptatt av en jevn tilvekst av nye utbyggingsmuligheter tilsier dette at letepolitikken bør inneholde motsykliske elementer.

Økonomisk teori tar hensyn til at bedriftenes investeringer i mange tilfeller er irreversibel. Når ledelsen har tatt beslutningen om å bygge ut et olje- eller gassfelt er det ingen vei tilbake. Slike mekanismer medfører at økt usikkerhet vil gi reduserte investeringer, fordi verdien av å vente med å investere blir større når usikkerheten øker. Nyere forskningsbidrag påpeker imidlertid at investeringsbeslutningen ikke bare medfører et tap av muligheten til å vente, men også at selskapet blir kompensert i form av nye muligheter for framtidig vekst og videreutvikling. Med slike modifikasjoner gir ikke teorien noen entydig sammenheng mellom investeringer og usikkerhet. For å avklare spørsmålet trenger man derfor analyser av data fra virkeligheten.

Olje- og gassinvesteringer under usikkerhet danner utgangspunktet for artikkelen i kapittel 4. Ulike investeringsmodeller tallfestes her ved hjelp av data for 170 olje- og gasselskaper gjennom en 14-årsperiode. Her finner vi at økt generell usikkerhet skaper en flaskehals for investeringene, mens økt industrispesifikk usikkerhet (oljeprisvolatilitet) har en stimulerende effekt. I lys av nyere teori for investeringer under usikkerhet åpner disse resultatene for at særtrekk ved olje- og gassindustrien gjør at den empiriske sammenhengen mellom oljeinvesteringer og usikkerhet ikke er i tråd med tradisjonell økonomisk teori.

Utviklingen av olje- og gassindustrien gjennom de siste 10 årene er preget av uro og omveltninger – i markedene rundt selskapene, i forholdet mellom selskapene og internt i hvert av selskapene. Kapittel 5 presenterer et modellopplegg som er utviklet for å undersøke hvorvidt prosessen rundt olje- og gassinvesteringene har vært stabil gjennom de siste 15 årene. Data fra 253 selskaper fra begynnelsen av 1990-tallet og fram til i dag benyttes for å tallfeste dynamiske modeller for kapitaldannelse, med eksplisitte mekanismer for kortsiktig dynamikk og tregheter.

Ved hjelp av moderne statistiske metoder finner vi solide holdepunkt for to tydelig atskilte historiske regimer for investeringsatferden i olje- og gassindustrien; det første regimet fra 1992 til 1997, og et annet fra 1998 og fram til i dag. Resultatene tyder på at den siste oljeprisøkningen har hatt en vesentlig mindre betydning for investeringene enn det som var vanlig før 1998. Dette er en refleksjon av at økt press fra finansmarkedene om

lønnsomhetsforbedring har skjerpet kapitaldisiplinen, og lagt en demper på investeringsviljen blant olje- og gasselskapene de siste 10 årene.

Den siste delen av avhandlingen kretser rundt interaksjonen mellom oljeselskaper på den ene siden, og finans- og oljemarkedet på den andre. I kapittel 6 studerer vi en hypotese om at endringer i investeringsatferden blant internasjonale olje- og gasselskaper har hatt langvarige virkninger på oljeprisen. Et koordinert finansmarkedspress for bedret lønnsomhet på tvers av hele industrien bidro til en implisitt samordning mellom selskapene omkring et lavere investeringsnivå enn man ville fått uten dette presset. Effekten ble den samme som ved et stilltiende samarbeid med OPEC; mye tyder nemlig på at redusert vekst i olje- og gassproduksjonen støttet opp om den påfølgende økningen i oljeprisen.

En partiell likevektsmodell for det globale oljemarkedet anvendes for å tallfeste virkningene på oljeprisen av den forbigående endringen i selskapenes investeringsatferd. Vi finner at selskapenes midlertidige tilbakeholdenhet har gitt en langsiktig økning oljeprisen på 10 prosent. Dette tyder på at selv midlertidige endringer i selskapenes atferd kan få vedvarende virkninger i oljemarkedet. Alle produsenter av olje – innenfor og utenfor OPEC – har tjent på denne utviklingen, mens kostnadene ved oljeprisøkningen blir båret av oljeimportører og forbrukere.

Samspillet mellom kapitalmarkeder og selskaper står også i fokus for avhandlingens siste kapittel. Statistiske metoder benyttes her for å undersøke hvordan aksjemarkedets verdsetting av selskapene påvirkes av finansielle og operasjonelle prestasjonsindikatorer. Et hovedresultat består i at de estimerte modellene ikke gir støtte til regnskapsbaserte lønnsomhetsmål (RoACE) som viktige verdidrivere. Vi finner videre klare tegn på at internasjonale olje- og gasselskaper prises med utgangspunkt i langsiktige oljeprisforventninger, og at størrelse og omdømme spiller en viktig rolle for aksjemarkedets verdsetting. Studien belyser enkelte svakheter ved regnskapsbaserte indikatorer for verdsettingsformål. Innenfor hvert selskap kan likevel konsistente mål for avkastning på sysselsatt kapital likevel være nyttige for å følge opp interne forbedringsprosesser over tid.

Part 1

Overview

Chapter 1

Motivation, methods, and results

1. Motivation and Scope

1.1 Why study oil and gas investments?

With brisk economic growth and high oil prices, issues of energy supply have ascended on the geopolitical agenda. Global oil demand is being fuelled by strong growth, both in the OECD area and in emerging economies – like Brazil, Russia, India and China. Consequently, the sharp increase in the oil price over the last years has raised concerns among consumer interests about the security of supply. To sustain general expectations for global economic growth, IEA (2003) estimates that energy supply will have to be supported by capital expenditures in the amount of USD 16 trillion over the period 2001-2030. Power generation represents some 60 per cent of this requirement, whereas the residual 40 per cent relates to fossil fuels (cf. Figure 1).

Figure 1. World energy investment requirement 2001-2030 (per cent)

Total: 16 trillion dollars
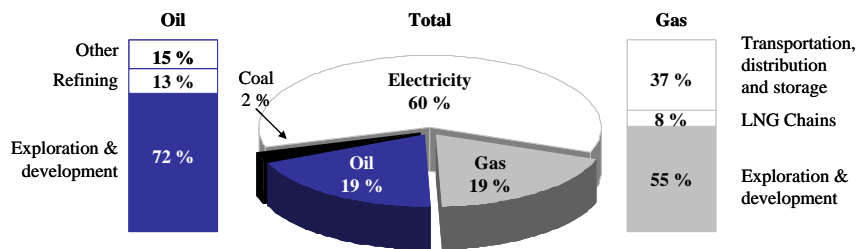
Source: International Energy Agency (2003).

The background for this huge economic commitment is the need to extend the supply of electricity and fossil fuels to new populous groups of consumers in fast-growing emerging economies like India and China (IEA, 2007). The link between economic growth and energy demand is stronger in developing countries than in the OECD. Consequently, the average share of energy investment in GDP seems to vary inversely with economic affluence. However, with high levels of current consumption, the industrialised part of the world will hardly lose their position in the energy market. Although fast-growing energy markets in non-OECD countries play an important role for

the *growth* in energy demand, OECD countries are still expected to account for some 40 per cent of world energy investment over the next 30 years.

The availability of capital to meet future energy requirements is not a matter of course. A range of uncertainties and challenges are involved, for policy-makers, for the oil and gas industry and in terms of fund-raising and financing arrangements. At the overall level, energy-consuming households, companies and countries are concerned with stability and reliability of energy supply. Moreover, a geopolitical concern to reduce global poverty raises policy concerns to spur investment in new energy-supply infrastructure. Last but not least, environmental threats caused by energy consumption may well have implications for both producers and consumers. Ambitions to cut greenhouse-gas emissions will most certainly have an impact on both the level and composition of energy investment. A wild-card in this energy-environment game is technology development, which is important for the penetration of new energy solutions, and therefore also has an important role in future energy investments.

Figure 2. Investment requirement by region and activity

2001-2030, USD bn
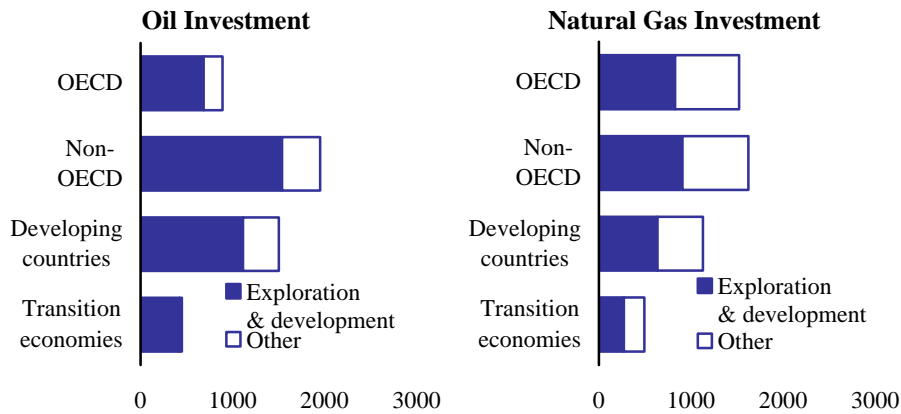
Source: International Energy Agency (2003).

For investments relating to fossil fuels, IEA figures suggest a 50/50 split between oil and gas investments, with exploration and development activities as the most important sources of investment demand. The IEA estimates imply that an annual USD 100 bn of investment is required to meet the needs

and aspirations implied by general economic expectations over the next 30 years. 2/3 of these investments should be absorbed by exploration and development activities, implying a gross capital accumulation of nearly USD 4000 bn in global upstream oil and gas activities over the period.

On the one hand, the effects on energy supply from gradual depletion of reserves and deterioration of infrastructure will have to be arrested through investments in upgrades and new production capacity. More than half of future investments in non-renewable energy supply are required simply to maintain supply at present levels. On the other hand, persistent economic growth and increasing welfare aspirations will entail investments in additional production capacity. This part of energy investment will mainly be directed at the fast-growing markets in non-OECD countries.

Investment behaviour in the oil and gas industry shares several characteristics with general corporate investment behaviour. However, some features are specific to oil and gas production, and industry-specific analyses are therefore required. The reserve concept is unique to non-exhaustible resource industries, and so is exploration activity. Other distinguishing features include cyclical investments, large indivisible investment projects, long investment lags, imperfect competition, extensive political attention, and potential super profits due to exhaustibility and resource rent. Special features of the oil and gas industry will therefore have to be appreciated both in terms of investment behaviour and the selection and impact from various explanatory factors.

Uncertainty and risk for oil and gas investments are also related to overall uncertainties and risks for (energy) investment, but all sources of uncertainty are not necessarily the same. At one level, the global and regional reserve potential is affected by geological uncertainty (below-ground risks). At another level, there is uncertainty concerning the availability and access to remaining reserves, regulatory and market conditions (above-ground risks). To a large extent, these risk factors are specific to oil and gas investments, and therefore also have to be addressed explicitly in empirical assessments. The reserve situation today is that market-oriented oil and gas provinces like USA, Canada, United Kingdom and Norway are faced with progressing depletion. The vast majority of global oil and gas reserves are located outside the OECD area, and exploration and development activities are now gradually being redirected towards these resource-rich regions of the world (e.g. Russia, Latin America, and the OPEC countries), introducing a range of new risk factors for Western oil and gas companies.

These resource-rich countries are typically quite different from the market-oriented systems that Western oil and gas companies have been used to from oil and gas provinces in Europe and North America. Oil and gas resources often play a national strategic role, strong national oil companies are common, and so are restrictions on foreign investment. Licensing, fiscal and commercial terms are subject to negotiations and special restrictions may even apply to marketing arrangements. Additional risks and uncertainty around future investment relate to widespread corruption, weak control and legal systems, political and military unrest, human rights issues and a variety of operational risk factors relating to local operation (e. g., Karl 1997).

As all fossil fuels are non-renewable, access to producible reserves is a special and critical issue. Unless oil and gas production volumes are replaced through successful exploration efforts, the basis for future production will be undermined. Consequently, an important strategic challenge for the oil industry currently relates to reserve replacement. Empirical studies of the exploration process may thus shed light on the fundamentals of oil and gas supply, as well as the potential for policy measures to influence investment and energy supply. Such studies may reveal insights that carry interest not only from an academic perspective, but also for strategists and policy-makers.

To recapitulate, empirical studies of the investment process among oil and gas companies are both necessary and important to understand the economics of oil and gas supply. Insights from such studies may translate into policies to improve the security of energy supply, to promote energy efficiency and economic growth, and to pull people out of poverty through the extension of affordable energy.

From a domestic Norwegian perspective, there are additional reasons to be interested in oil and gas investment. Since the first discovery in the late 1960s, Norway has rapidly developed into one of the largest oil exporter worldwide. The development of a domestic oil and gas industry has been a strategic objective shared by a stable majority of political parties. Consequently, the oil and gas industry plays an important role in the Norwegian economy today. As illustrated in Figure 3, the petroleum sector represents approximately 25 per cent of the gross domestic product (GDP). Oil and gas revenues represent more than 50 per cent of total export, and every third unit of government revenue can be attributed to oil and gas activities.

For macroeconomic policies, oil and gas investments are especially important. The reason is not their quantity (approx. 6 per cent of mainland GDP), but

their volatility. With an import share of approx. 1/3, a 50 per cent reduction in oil and gas investments from one year to another will represent a direct impulse to mainland GDP at approx. 2 percentage points, before any repercussions.[1] Consequently, oil and gas investments play an important role for macroeconomic fluctuations in the short to medium term. A proper understanding of investment behaviour in the oil and gas industry is therefore useful for economists, market analysts, policy-makers, and everyone who takes an interest in economic and financial market fluctuations.

Figure 3. The position of the Norwegian oil and gas industry
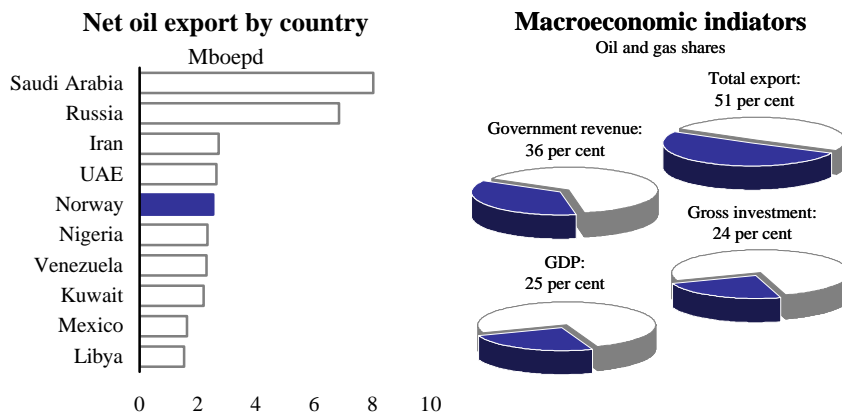
Source: (Norwegian) Ministry of Petroleum and Energy (MPE 2007).

At the same time, strategies for resource management become important for any country rich in petroleum resources. In this context, the links between exploration, reserve accumulation, field development and production become important not only to corporate strategists, but also to policy-makers. Empirical studies of oil and gas investment improve our understanding of the various stages of the oil and gas production process, and how these activities are affected by geological, economic, and policy-related factors. As an example, a smooth growth rate in production on the national level requires not only a stable level of field developments, but also a steady supply of new discoveries. The efficiency of public licensing policies therefore depends on a thorough understanding of company behaviour in the exploration process.

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[1] Based on employment in Norwegian oil and gas activities, Cappelen et al. (2003) suggest a short-run macroeconomic multiplier around 2, and a long-term multiplier above 3. In other words, 1000 new jobs in the oil and gas industry will encourage the employment of another 2000 persons in the rest of the economy over a 5-year period.

Figure 4. Key figures for the Norwegian continental shelf

Exploration and production
1966-2006

Investment allocation
1985-2012 (NOK bn; USD/bbl)
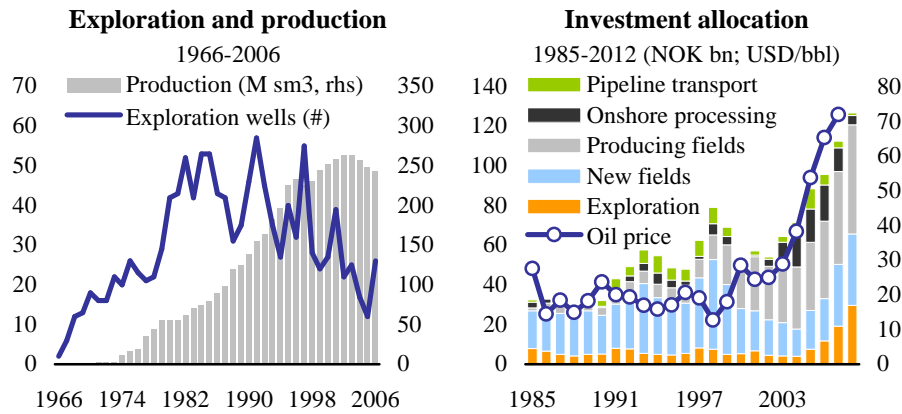
Source: Ministry of Petroleum and Energy (MPE 2006).

A range of perspectives is available to justify more work on empirical studies of oil and gas investment behaviour. At the international level, interest is motivated by economic growth concerns, by income distribution, and by environmental issues. In petro-states like Norway, oil and gas investments are important for the macroeconomic business cycle, and for the design of strategies and policies for national resource management. As we will see, oil and gas investment behaviour is not fully explored by previous academic research. Recent developments in general investment theory and econometrics leave room for valuable and interesting applications on data from the oil and gas industry.

1.2 Overall scope and research ideas

International oil and gas companies combine capital, labour and other inputs to produce oil and natural gas from natural deposits. The development and production of oil and gas reserves is a capital-intensive activity. Investment behaviour and the process of real capital formation is therefore of special interest in the oil and gas industry.

Profit maximisation is the key behavioural assumption for international oil and gas companies, as for studies of most other industries. Consequently, investment behaviour in the oil and gas industry shares several characteristics with general corporate investment behaviour. However, as mentioned above, some features are specific to oil and gas production, and industry-specific

analyses are therefore required. One of these features is related to the non-renewable nature of the output. The reserve concept is unique to non-renewable resource industries, and so is exploration activity. Oil and gas reserves may be seen as inputs to the production of oil and natural gas. These reserves are not readily available in well-functioning input markets, like the case is for traditional inputs. Rather, oil and gas companies have to invest in risky exploration activities, to maintain and grow the base of oil and gas reserves, and to sustain subsequent production activity over the longer term. At the same time, reserve additions are the result of a production process of its own, and both the efficiency of this process and the implied accumulation of oil and gas reserves contribute significantly to the value of an oil company.

Reserve replacement is currently an important strategic challenge both for companies and countries. New empirical insights in the economics of oil and gas exploration should therefore be of interest both for company managers and policy-makers. Consequently, one of my research ideas is to apply modern econometric techniques to time series data from the NCS, to shed light on exploration activity in a partly mature, and highly regulated oil and gas province.

Figure 5. Efforts and efficiency in NCS exploration
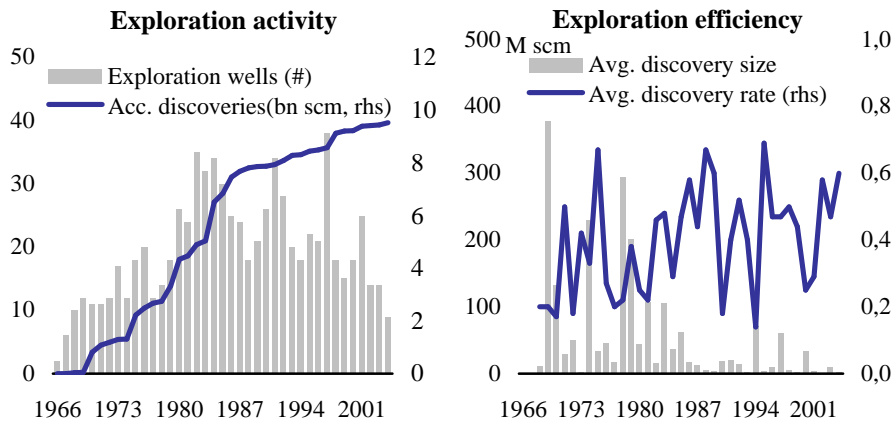
Source: Norwegian Petroleum Directorate (NPD 2007).

Exploration drilling efforts have been subject to a wide range of econometric studies since the mid 1960s, especially for the US (Dahl and Duggan, 1998). Less attention has been paid to the success and efficiency of oil and gas exploration, not to mention the interaction between efforts and efficiency.

Modern co-integration techniques of time series econometrics are also yet to be applied to oil and gas exploration data. Finally, only a few empirical exploration studies cover more than one oil price cycle. To bridge these gaps in the literature, another research idea of this project has been to address three components of reserve growth simultaneously in a co-integration framework. This approach allows the oil price and other explanatory variables to influence reserve growth not only through exploration activity, but also via the (ex post) success rate and average field size.

Non-renewable properties of oil and gas resource extraction can hardly be neglected in studies of exploration behaviour, and especially not when applications are designed on aggregate time series data. Drawing on recent advances in panel data econometrics, an alternative approach is to investigate data for a range of individual companies. Each oil and gas company holds a portfolio of assets at various stages of development, maturation and depletion. Moreover, typical panel data sets cover a shorter time span than time series data. With this perspective on oil and gas investments, non-renewable properties become less apparent than in field-specific data and regional time series data. Panel data studies of company accounts may therefore rely on a neo-classical investment model as the theoretical point of departure. However, the estimated investment models may still reveal insights for oil and gas investment which are quite different from other (manufacturing) industries (e. g., Lamont, 1997).

Figure 6. Investment indicators in the international oil and gas industry
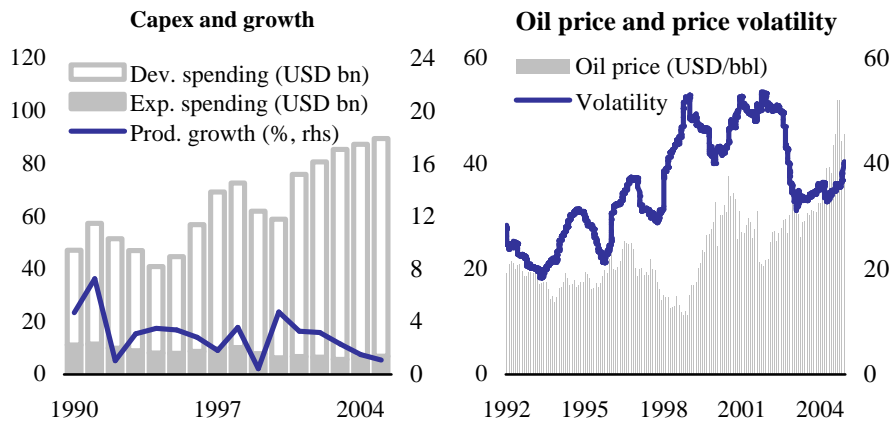
Oil price volatility: Annualised standard deviation of daily price change (250 days rolling data window).
Sources: Investment indicators: Deutsche Bank (2005), oil price and stock market data: Reuters Ecowin (http://www.ecowin.com).

With a powerful panel data set at hand, two ideas are particularly interesting in terms of empirical oil and gas investment research. First, recent developments in the oil and gas industry suggest that investment behaviour is not necessarily changeless over time. Shifts and shocks in prices, liquidity and uncertainty may carry over to management mentality. Moreover, substantial changes in the economic environment of the firm may also induce changes in the underlying models of investment behaviour. We will therefore investigate how the process of capital formation at the firm-level might be affected by a period of far-reaching industrial upheaval and restructuring. One striking example in this respect was manifested by the wave of mergers the international oil and gas industry in the aftermath of the Asian economic crisis towards the end of the 1990s (e.g., Weston, Johnson and Siu, 1999).

Second, the role of uncertainty in empirical investment models has attracted increasing interest from empirical researchers over the last decade (Carruth et al., 2000). In the standard theory on irreversible investments, the option value of waiting to invest is positively influenced by an increase in uncertainty. Consequently, this real-options approach to investment suggests a negative relation between investment and uncertainty (Dixit and Pindyck, 1994). However, investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development and growth options. Increased uncertainty will increase the value of both waiting and growth options. A reconciling study by Abel et al. (1996) illustrates how both these perspectives can be accommodated in modern theories of investment. Adding future put options of contraction to the traditional call options of deferral, ambiguous results are produced for the sign of the investment/uncertainty relationship. Consequently, empirical studies are required to settle the issue. Based on company data for a range of international oil and gas companies, the idea is therefore to estimate and test the role of uncertainty in oil and gas investment.

Spending on exploration and physical capital accumulation can be financed through retained earnings, but also from debt and equity markets (Reiss, 1990). In consideration of competition, strategies, targets and costs, the total capital budget is allocated to various types of capital expenditure – like exploration, field development, operational upgrades, and/or acquisitions of assets or businesses. In practice, corporate investment is also affected by specific return targets and planning assumptions for input and output prices (wages, interest rates, exchange rates, oil and gas prices). As fixed assets, real capital is employed in production activities of the firms. The return from these individual assets may be enhanced through measures for revenue support and

cost suppression along the entire value chain. Moreover, corporate investment returns are managed through portfolio optimisation, involving acquisitions, divestitures and swap transactions. Finally, cash-flow from operations is distributed by management decisions, for reinvestment, debt payments and accommodation of shareholders (dividends or share buybacks).

Figure 7. Growth, profitability and returns
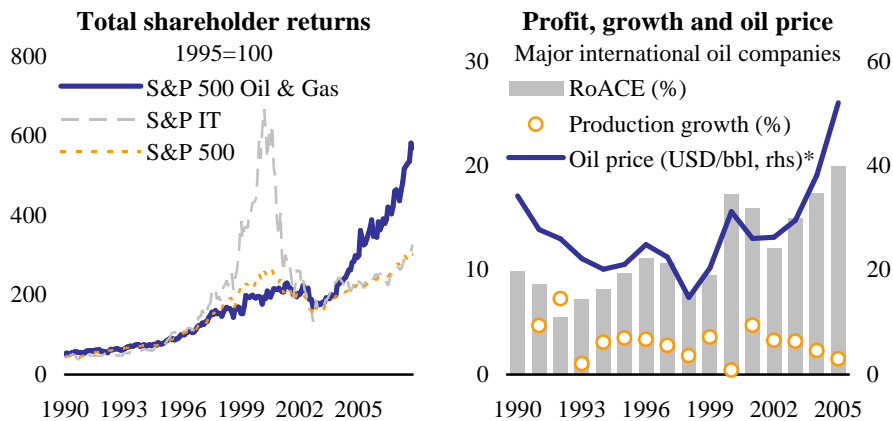
* in real terms (at 2004-prices).
Source: http://www.ecowin.com (stock market data), Deutsche Bank (2004; industry data).

Access to capital markets is influenced by corporate results and performance, strategies, financial structure, management and control systems. Consequently, the cost of capital is also influenced by these variables. At the same time, financial markets serve as an important intermediary for communication between investors and companies. Investment advice and company valuation in the equity market is decisive in this respect, and therefore it becomes important to develop and maintain good relations with the capital market (e.g., Boone, 2001). Over the last 10 years, oil and gas companies have been subject to increasing financial market pressures (e. g., Weston et al, 1999; Osmundsen et al., 2007). During this period, stock market analysts focused increasingly on simplistic indicators of short-term accounting returns in their valuation analyses (Antill and Arnott, 2000, 2002; UBS Warburg, 2003; Deutsche Bank, 2004). The most important of these indicators was Return on Capital Employed (RoACE; cf. Figure 7).[2]

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[2] RoACE is defined as net income adjusted for minority interests and net financial items (after tax) as a percentage ratio of average capital employed, where capital employed is the sum of shareholders' funds and net interest-bearing debt.

Score-cards of financial and operational targets were pursued by corporate managers, under the surveillance of analysts and investors. Companies who failed to deliver, were mentioned systematically in negative terms, in the financial press, in analyst reports, and in the investment community. This pressure instigated an increase in capital discipline in the oil and gas industry, which in turn put a lid on long-term capacity growth and reserve development.

One of the research ideas for this project has been to study how oil and gas investment behaviour is influenced by the interaction between financial markets on one hand, and oil and gas markets on the other. A key hypothesis is that the described pressures from financial markets have repressed investment and production growth in the international oil and gas industry. In turn, this development may also have had implications for global oil and gas supply, and for oil price formation. Econometric techniques can be applied to estimate the relation between performance and stock market valuation. With access to a full model for the global oil market (e. g., Aune et al. 2005), it is also possible to quantify the oil market implications of increased capital discipline in the oil and gas industry.

2. Methodology

2.1 Theory of investment behaviour

The perceived mystery of capital accumulation and its role in business fluctuations has a long history. Already in his *General Theory*, Keynes (1936) noted:

"*Most, probably, of our decisions to do something positive, the full consequences of which will be drawn out over many days to come, can only be taken as the result of animal spirits – a spontaneous urge to action rather than inaction, and not as the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities.*"

Since the path-breaking 1930s, the investment decision of the firm has attracted broad academic interest from researchers in corporate finance,

industrial organisation, public economic and macroeconomics. Based on early theoretical contributions from pioneers like Haavelmo (1960), Jorgenson (1963) and Tobin (1969), empirical interest in investment behaviour also has a long tradition in applied economic research.

The process of investment and capital formation is inherently dynamic. The capital stock of the firm is augmented by investment, and debased through technological and economic depreciation. These characteristic features are appreciated by economic theory, and models of corporate investment usually depart from some sort of dynamic optimisation problem. The standard workhorse of applied investment research dates back to Jorgenson (1963) and Tobin (1969), and is derived from the neoclassical company's intertemporal profit maximisation problem.[3]

Jorgenson (1971) provides an overview of early empirical contributions, whereas modelling strategies and results up to the early 1990s are surveyed by Chirinko (1993). Chirinko's comprehensive recapitulation reflects the separation between two distinct modelling strategies. On the one hand, econometric models are derived from the first-order conditions of intertemporal maximisation problems, in the neo-classical spirit of Tobin (1969) and Jorgenson (1971). On the other hand, a range of accelerator models are based on general autoregressive distributed lag (ADL) forms, and estimated without the stringent connection to maximising behaviour of economic theory (e.g., Mayresse, Hall, and Mulkay, 1999; Bond et al., 2003). Structural models should be preferred on theoretical grounds, but tend to underperform the more flexible (accelerator) models in terms of prediction. Here lies a fundamental trade-off in modern empirical investment research: "the applied econometrician must choose between distributed lag models that are empirically dependable but conceptually fragile and structural models that have a stronger theoretical foundation but an unsteady empirical superstructure" (Chirinko, Fazzari, and Meyer, 1999). This present thesis includes applications of both these groups of models.

During the 1970s, the role of options in financial markets was studied by a range of prominent scholars (e.g., Merton, 1973; Black and Scholes, 1973; Cox and Ross, 1976). However, it was not until the early 1980s that further academic interest in theories of fixed business investment behaviour was spurred by the material equivalent to financial options – the real options approach. Cukierman (1980), Bernanke (1983), Brennan and Schwartz

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[3] A formal derivation of the neo-classical investment model is offered in Appendix 1.

(1986), McDonald and Siegel (1986) study the implications of irreversibility and waiting options for real investment decision-making.[4] 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 enhance the value of this waiting option. Consequently, this strand of literature suggests a negative link between investment and uncertainty (Carruth et al., 2000; Bond et al., 2005).

However, the conclusion of a negative investment/uncertainty relationship is relaxed in recent contributions to the literature on strategic investment and real options. The investment decision involves not only the initial waiting option, but also potential future waiting and development options. Abel et al. (1996) argue that investment theories with compound option structures leave the investment/uncertainty relationship unsettled. Recent applications in management and finance (e.g., Kulatilaka and Perotti, 1998; Smit and Trigeorgis, 2004) also stress that investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. Increased uncertainty will increase the value of both waiting and development options. Moreover, the value of waiting options is also eroded by investment lags (Bar-Ilan and Strange, 1996; Pacheco-de-Almeida and Zemsky, 2003), imperfect competition, and strategic investment behaviour (Grenadier, 2002; Aguerrevere, 2003; Akdogu and MacKay, 2007). Empirical studies are therefore required to settle the investment-uncertainty relationship.

Compound options are especially relevant for the oil and gas industry. As illustrated in the left-hand panel of Figure 8, oil and gas developments are characterised by sequential investment decisions and huge capital expenditures for production facilities and infrastructure. Irreversibility therefore becomes an important issue. At the same time, the opening of a new oil and gas area often involves basic investments that may reduce the thresholds for future neighbouring developments. An example is provided in the right-hand panel of Figure 8. The initial development of the Statfjord and Gullfaks fields in the North Sea over the 1980s prepared the ground for the subsequent industrial development of the entire Tampen area. With imperfect competition and first-mover advantages, the value of future development options may dominate the instant value of deferral. All these options are influenced by uncertainty. Again, we see that the role of uncertainty in oil and

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[4] It deserves mentioning that the same irreversibility issues in investment under uncertainty were touched upon even earlier by Henry (1974).

gas investment can not be established without empirical investigations. Based on company data for the international oil and gas industry, two of the papers in this thesis provide new empirical results and insights concerning the investment/uncertainty relationship.

Figure 8. Compound options in oil and gas development

Decision tree

Footholds, hubs and satellites
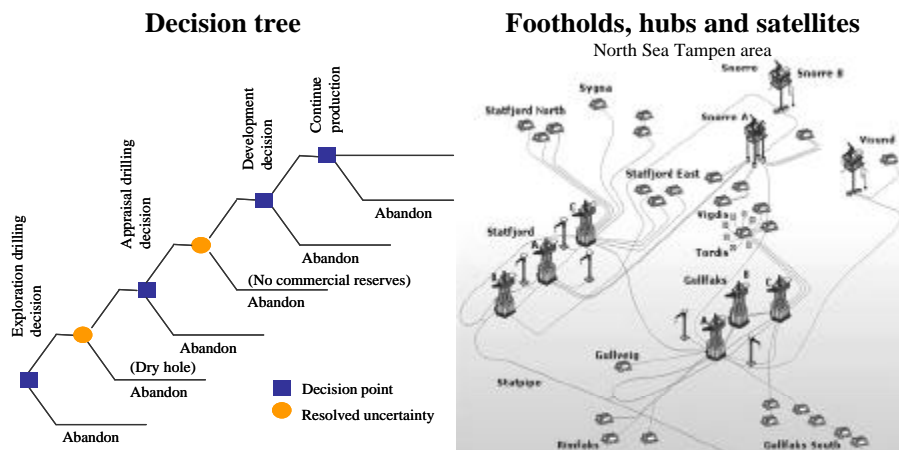
Based on Smit and Trigeorgis (2004).   Source: Statoil.

Another strand of the investment literature is concerned with theories of capital market imperfections. With this point of departure, several contributions in econometric investment research have extended the neo-classical framework to test for the presence and importance of financial frictions (e.g., Fazzari, Hubbard, and Peterson, 1988; Schiantarelli, 1996; Hubbard 1998). A number of applications conclude that changes to net worth (cash-flow) plays a significant role for investment behaviour, which is not consistent with the "financial irrelevance" theorem of Modigliani and Miller (1958). However, recent contributions suggest that these results may be tainted by measurement error (e. g., Erickson and Whited, 2000) and model specification problems (Kaplan and Zingales, 1997; Gomes, 2001), leaving room for additional research to conclude the issue. One of the papers of this thesis explores the role for cash-flow variables in oil and gas investment, suggesting a new link between uncertainty and financial frictions in the process of capital formation.

2.2 Econometric method

In terms of empirical methods, most of the early studies of investment behaviour were based on aggregate time series data. However, recent contributions to time series econometrics have yet to be applied to oil and gas investment. This is especially relevant for studies of oil and gas exploration behaviour. The reason is that the number of contributions to the empirical exploration literature slowed to a trickle some 15 years ago, before the new time series econometrics had reached this field of economic research. Two papers in this thesis apply techniques of co-integration and error-correction to time series data from the Norwegian Continental Shelf.

During the 1970s, common practice in time series econometrics was to estimate simple linear regressions on non-stationary time series data. However, as shown by Granger and Newbold (1974), this estimation strategy is likely to produce spurious relationships between time series variables. If the time series variables of the proposed model are trending, their linear combination may also have a trend. Consequently, the error term of a simple linear model will fail to meet the requirements of standard estimation methods. In that case, direct estimation of the parameters will produce inefficient coefficient estimates, and the validity of statistical inference is therefore problematic. Direct estimation of the structural relation will also not describe the underlying dynamics of the data-generating process properly (Engle and Granger, 1987; Greene, 2003).

However, if the variables of interest are integrated of degree 1 ($I(1)$), their difference will be stationary ($y_t \sim I(1) \implies \Delta y_t \sim I(0)$). A key result from the literature on co-integration and error-correction is that a linear combination of non-stationary variables may produce a stationary error-term. If such a combination is represented by the underlying relationship of our model, the variables are co-integrated, and their set of coefficients will define their co-integrating vector.[5] In this case, we may estimate the dynamics of the process in an error-correction specification. In the error-correction model, the change in the dependent variable is specified as a linear function of changes and levels of both the dependent and the independent variables. The error-term of the error-correction model will now be stationary and well-behaved, provided that a co-integrating vector is indeed identified by our simple model.

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[5] A pioneering reference to the literature on cointegration and error-correcton is Engle and Granger (1987). A useful recent update is provided by Hendry and Juselius (2000, 2001).

In error-correction model specifications, coefficients on changes in exogenous variables may be interpreted as short-term effects, whereas the long-term (structural) parameters can be derived from the coefficients attached to the level variables (Bårdsen, 1989). For single-equation models, standard estimation procedures may be applied directly on the error-correction specification to obtain unbiased and efficient estimates for both short-term dynamics and the long-term underlying structure of our model (Engle and Granger, 1987). For the systems version of the model, maximum likelihood techniques have been developed by Johansen (1988, 1995). A novelty of this thesis is the employment of co-integration and error-correction models in empirical studies of oil and gas exploration. The application to time series and panel data for the Norwegian Continental shelf illustrates a rich and flexible framework with interesting implications. A closely related framework is also applied to microeconomic panel data to estimate an accelerator model with error-correction for total investment among international oil and gas companies (cf. Chapter 5).

Microeconomic data based on company information offers more variance in the cross-section, and therefore represents a powerful point of departure for studies of investment behaviour (Bond and van Reenen, 2007). Complications relating to autoregressive properties of time series data are less apparent for panel data. However, new challenges arise, especially in dynamic panel data models – where the lagged endogenous variable is typically included among the regressors. Nickell (1981) shows that lagged endogenous variables will typically not have the desired exogeneity qualities in dynamic panels. Under these circumstances, both the *OLS* and the *fixed-effects* estimators will be inconsistent (see e.g., Bond, 2002), with an upward bias for *OLS* and a downward bias for the *fixed-effects* estimator. A variety of instrumental variable techniques have been developed to handle this endogeneity bias of dynamic panel data models. Anderson and Hsiao (1981) propose a *2SLS* estimator for a model transformation in differences, with instruments that are correlated with the transformed lagged dependent variable and orthogonal to the differenced error term. Moreover, Anderson and Hsiao propose lagged differences of the lagged dependent variables as instruments to obtain consistent estimates of the dynamic model. In a corresponding first-difference *GMM* framework, Arellano and Bond (1991) show that deeper lags of the dependent variables are also available for the preferred instrument matrix.

A challenge with the original Arellano Bond framework is that lagged differences represent poor instruments for first differences of persistent time series, and especially for variables that are close to a random walk. In meeting

this challenge, Arellano and Bover (1995) demonstrate that additional moment conditions may be provided by the inclusion of the original level equations in the system of estimated equations, with significant efficiency gains. Their estimator is referred to as the *System GMM* estimator, further developed by Blundell and Bond (1998), Blundell, Bond and Windmeijer (2000), and implemented in Stata by Roodman (2006). In Chapters 4 and 5, we take advantage of these developments in the estimation of dynamic panel data models for oil company investment. Bond (2002) offers a nice introduction to these methods. For a more comprehensive modern textbook treatment, see Arellano (2003).

3. Overview of the papers

3.1 Exploration economics in a regulated petroleum province

Oil and gas exploration has been subject to economic research for decades. The attention has largely been concentrated on the US oil and gas industry, with some studies also for the United Kingdom. In this article, we present new insights on the relation between exploration activities and economic variables in the highly regulated industrial environment in Norway.

Starting with the Ekofisk discovery in 1969, a number of subsequent field developments laid the foundations for a new and important industry in Norway, and a significant supplying region for US and European oil and gas markets. The Norwegian government has played an active role in the development of a Norwegian petroleum industry, with a strategy characterised by gradualism. The impact of external market forces has traditionally been subdued by a carefully developed regulatory system, followed up by well-developed institutions and governance systems.

Based on detailed database information from the Norwegian Petroleum Directorate, a unique data set has been developed to cover the 40-year history of three separate regions of the Norwegian Continental Shelf (NCS). This panel data set has not been subject to econometric studies before. A drilling function is derived from a simple theory of exploration, whereby drilling efforts are explained by the oil price, cumulative discoveries and available exploration acreage. We estimate error-correction models that capture sluggishness and short-term dynamics in the data, as well as the longer-term

relations between drilling efforts and the explanatory variables. Finally, we present projections to illustrate how exploration activity is affected by changes in oil prices, licensed exploration acreage and new discoveries.

Our models are estimated for a regulated market regime, and the results reveal new and interesting insights with respect to exploration behaviour. We establish economic effects that are quite robust, but their magnitude is rather small compared to previous studies. The estimated model suggests a robust, long-term impact from the oil price, whereas the estimated short- term effects are rather weak. Our results illustrate how new licensing rounds stimulate exploration drilling in new attractive prospects. Discoveries are also shown to provide additional feedback to exploration drilling, but this drilling response quickly culminates in anticipation of new licensing rounds. Our models are quite successful in accounting for dynamics and sluggishness in the exploration drilling behaviour, and the estimated error-correction models suggest a rapid adjustment process.

3.2 Efforts and efficiency in oil exploration: a VEC approach

Drilling efforts have been subject to a wide range of econometric studies since the mid 1960s, especially for the US. Less attention has been paid to the success and efficiency of oil and gas exploration, not to mention the interaction between efforts and efficiency. Only a few empirical exploration studies cover more than one oil price cycle. Modern techniques of time series econometrics are also yet to be applied to oil and gas exploration data. Finally, the data we observe for efforts and efficiency in oil exploration are produced by simultaneous decisions in each company. This simultaneity should be appreciated also in econometric models of the exploration process.

To bridge these gaps in the economic literature, this study examines three components of reserve growth simultaneously in an integrated and novel modelling approach. A theoretical model for reserve-generation is derived from standard neoclassical behavioural assumptions. A decomposition of reserve growth is then applied to specify annual reserve additions as a result of drilling activity, success rates and average discovery size. Co-integration techniques are applied to estimate a vector error-correction model with three simultaneous equations for drilling activity, success rates and average discovery size. The econometric model also links the three components of reserve-generation to relevant economic, geological and technology variables.

30

The data set covers the full history of oil and gas activity on the Norwegian Continental Shelf (1969-2004). The estimated model gives a breakdown of effects from explanatory variables between these key components of reserve-generation, as well as a systematic separation between short-term (temporary) effects and long-term (persistent) effects in the exploration process. Estimated long-term elasticities are illustrated in Figure 9.

Figure 9. Decomposed elasticities of reserve generation

Estimated partial and total elasticities by explanatory variable (per cent) [*]
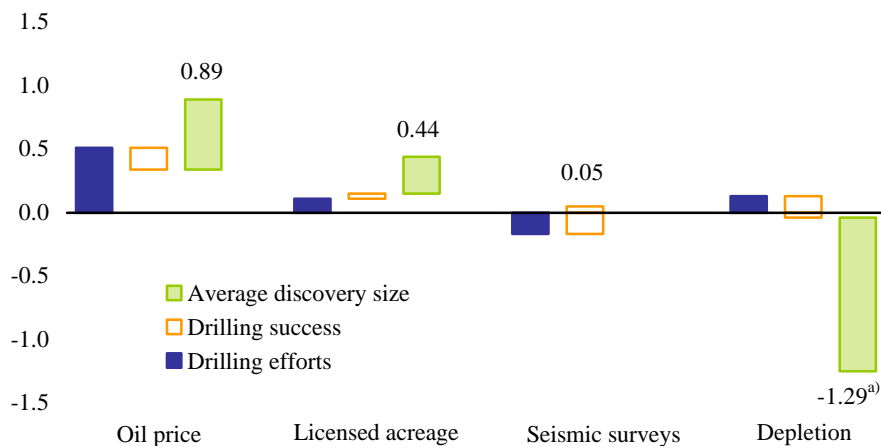
[*] FIML estimates obtained with Stata 9.0 (see Chapter 3).
[a] Semi-elasticity: percentage change in dependent variable from absolute change in depletion indicator.

An increase in the oil price of 1 per cent produces a persistent increase in annual reserve-generation of 0.89 per cent, according to our results. More precisely, a negative influence from the oil price on the discovery rate is dominated by a positive influence on average discovery size. On impact, this suggests a pro-cyclical pattern for reserve-growth. The proposed modelling approach illustrates that policy measures need not and should not be limited to the regulation of drilling activity. With reserve additions as the ultimate target, the potential gains from measures to stimulate the success rate or average field size may well exceed the direct importance of drilling activity in itself (i. e. number of spudded wells). Second, our results suggest that annual reserve additions are procyclical, due to the strong positive link between the oil price and average discovery size. If the government interest is to stabilize reserve growth over time, this result provides a case for countercyclical licensing policies.

3.3 Investment and uncertainty in the international oil and gas industry

Standard theory of irreversible investment and real waiting options suggest that the relationship between investment and uncertainty is negative. However, recent contributions to the theory of strategic investment point out that investment imply not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. Increased uncertainty has the potential to increase the value of both these types of real options. Thus, the theory of compound options may give rise to a positive relationship between investment and uncertainty. Empirical studies are therefore required to settle the question. With highly strategic investments and an abundance of real options, the oil and gas industry offers an especially appropriate application.

The combination of investment theory, modern econometric procedures and panel data offers a robust framework to study the impact of industry uncertainty on total investment expenditures. Applying System GMM estimators on a data set covering 170 companies over the period 1992-2005, we draw on recent empirical research of the relation between investment and uncertainty in manufacturing industries. However, our scope is different, and so are our results.

Our results suggest that industry-specific uncertainty (oil price volatility) has a stimulating effect on investment rates, as suggested by modern theory of strategic investment and real options. On the other hand, overall uncertainty (stock market volatility) represents a bottle-neck for investment and capital formation. A negative relationship between investment and uncertainty is the standard result of modern theories of irreversible investment. The majority of empirical studies in the field are also in support of this hypothesis. Based on recent contributions to the theoretical investment literature, our results offer a valuable supplement, as we offer empirical support to the idea that strategic investments with real options may give rise to a positive investment/ uncertainty relationship.

Over the last 15 years, international oil and gas companies have gone through a period of industry upheaval, restructuring and escalating market turbulence. Easily accessible oil and gas reserves in market-oriented economies like USA, Canada and United Kingdom are faced with depletion. Oil and gas investments are now gradually redirected in a rat race for increasingly scarce oil and gas resources. Our results should therefore be interpreted in the context of strategic investments (Bartolini, 1993; Smit and Trigeorgis, 2004).

3.4 Shifting sentiments in company investment

Recent developments in the oil and gas industry suggest that investment behaviour is not necessarily stable over time. Changes and shocks in prices, liquidity and uncertainty may carry over to management mentality. Moreover, substantial shifts in the economic environment of the firm may also induce changes in the underlying models of investment behaviour, among managers as well as investors. We propose a micro-econometric framework to assess how the process of capital formation at the firm-level might be affected by a period of far-reaching industrial upheaval and restructuring.

Based on accounting information for 253 companies over the period 1992-2005, we specify the process of capital formation as an accelerator model with error-correction, whereby investment is explained as a continuous adjustment process towards a long-term equilibrium relation between capital and output. The error-correction process is disturbed by temporary shocks, and by variation in a set of financial and operational control variables. Based on the industrial restructuring of the late 1990s, we apply a flexible dummy-variable (GMM) procedure to test for the presence of a structural break in oil and gas company investment.

Our results provide robust evidence for two historical regimes of investment behaviour in the international oil and gas industry over the last 15 years; one from 1992 to 1997, and one from 1998-2005. The late rise in oil price and cash-flows has had a far smaller impact on investment rates than what was typical before 1998, suggesting that financial market pressures in the aftermath of the Asian economic crisis have caused tightened capital discipline in recent years. Moreover, the early 1990s were characterised by a negative relationship between investment and uncertainty, whereas the recent increase in oil price volatility has spurred investment over the last few years. This result is at odds with the vast majority of previous studies of investment and uncertainty, but well in line with recent development of theories of compound options structures, imperfect competition and strategic investment behaviour (e.g., Smit and Trigeorgis, 2004).

Industrial leaders and their companies respond continuously to changing political and market environments. Their models and ways of thinking may be stable for periods. However, from time to time their mindset is also challenged by external forces, and sometimes these pressures bring about deeper behavioural changes. Our study demonstrates that such a change took

place in the oil and gas industry in the 1ate 1990s, in response to external economic shocks and massive pressure from financial markets.

3.5 Financial market pressures, tacit collusion and oil price formation

Ever since the oil price shocks of the early 1970s, the Organisation of Petroleum Exporting Countries (OPEC) has been followed with massive interest from the public, reflecting the vital significance of the oil price to industry, households and financial markets. The special structure of the oil market has also attracted scholarly interest, with numerous studies of OPEC's role and strategy in various models of producer behaviour under imperfect competition. Less attention has been given to the role of producer behaviour in non-OPEC countries. Nevertheless, investment behaviour in the international oil and gas industry is an important part of supply-side dynamics in the oil market, and therefore also an important factor behind the formation of oil prices.

Figure 10. Company valuation and oil market shares
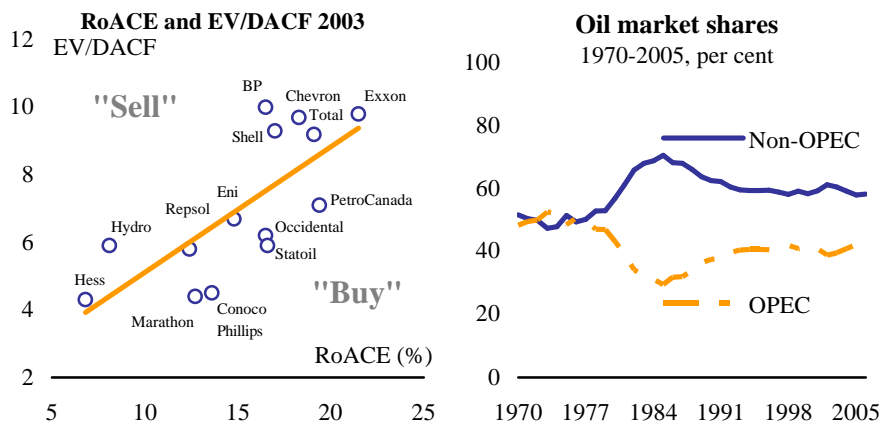
Source: Deutsche Bank (2004), US Energy Information Administration (EIA).

The key hypothesis of this paper is that a strategic redirection of the international oil industry towards the end of the 1990s has had long-lived effects on OPEC strategies – and on oil price formation. Starting in 1998, increased focus on shareholder returns, capital discipline and return on capital employed (RoACE) caused a slowdown in investment rates and production growth among international oil companies. Thus, the emphasis on short-term profitability and financial indicators had the same effect as a coordinated

equilibrium of reduced investment, implicitly representing a tacit collusion to support an increase in the oil price. At the same time, strong growth in oil demand and consolidation in the competitive fringe allowed OPEC to raise their price ambitions significantly at the turn of the century.

The objective of this study is to quantify the oil price impact of these developments. Using an equilibrium model for the global oil market, we examine the effects of the change in investment pattern on oil supply and oil prices, as compared with a situation characterised by industrial stability and unchanged price ambitions within OPEC. The model simulations clearly suggest that enhanced capital discipline caused a temporary slowdown in investment and production growth among international oil companies. Consequently, global exploration activities, investment expenditures and oil production growth were suppressed, allowing OPEC to raise their price ambitions. Our results suggest that even temporary economic and financial shocks may have a long-term impact on oil price formation. Specifically, we find that the curb on IOC investments in the late 1990s caused an increase in the oil price of 10 per cent in the long run. Both OPEC and non-OPEC producers gain from this development, whereas the cost is carried by oil-importers and consumers.

3.6 Valuation of international oil companies

Since the late 1990s, stock market analysts have focused strongly on short-term accounting return measures, like RoACE, for benchmarking and valuation of international oil and gas companies. To assess important drivers of company valuation, a simple econometric model is specified and estimated on market and accounting data for 14 major oil and gas companies from 1990 to 2003. The company-specific valuation multiple EV/DACF is regressed against a number of financial indicators, as well as the oil price. Our models take into account the potential endogeneity challenge in our data for market valuation and company performance.

A key result is that the general perception of RoACE as an important value-driver is not supported by our estimated model. More precisely, the econometric results indicate that the valuation impact of this simple profitability measure is negligible. On the other hand, valuation multiples respond negatively to an increase in the oil price, implying that oil and gas companies are priced at mid-cycle oil prices. The estimated model also suggests a robust and material influence on market valuations from oil and gas

production. This suggests that company size and reputation still plays an important role in the valuation process. Finally, reserve replacement ratios contribute positively to stock market valuation, but the effect is quite modest, and the significance is marginal.

The study elucidates some of the weaknesses of RoACE for company valuation purposes. Our primary focus is on inter-company comparisons and relative stock market valuation. However, within the individual companies, a consistently normalized RoACE may still be a useful key indicator in their internal efforts to improve operational and financial performance over time.

This paper represents an early attempt to substantiate the links between market valuation and financial and operational indicators in the international oil and gas industry. The results are interesting, but preliminary. Our belief is that profitability and returns on invested capital is linked to company valuations. However, our RoACE variable does not establish this link. Future research should explore alternative measures of underlying financial performance, to overcome the weaknesses of RoACE.

4. Unresolved issues/suggestions for future research

4.1 Econometrics of effort and efficiency in oil and gas exploration

Efforts of oil and gas exploration on the Norwegian Continental Shelf (NCS) are addressed in the econometric study of Chapter 2 of this thesis. In addition to exploration efforts, resource growth will depend on exploration success and average discovery size. This challenge is met by the vector-error-correction analysis of Chapter 3. Both these studies leave room for further sophistication. First, recent trends in oil and gas exploration activity indicate that companies respond swiftly to any oil price drop, whereas the reaction to an oil price increase is typically sluggish. An interesting avenue for further research would therefore be to allow this kind of asymmetry in the econometric model specification. A modelling approach is proposed for exploration activity by Mohn and Osmundsen (2007), but how these asymmetries may relate to success rates, field size and reserve growth remains an issue for further research.

To grow and develop their base of reserves, oil and gas companies have at least two strategies at their disposal. Exploration drilling is important, but for maturing oil fields, efforts to increase oil recovery (IOR) also yield substantial results in terms of reserve additions. Consequently, oil and gas companies balance their drilling efforts between exploration and production drilling. An interesting topic for further research would therefore be to study how production drilling has contributed to reserve growth on the NCS, and at best, to analyse total drilling efforts in a combined framework of investment behaviour.

More work is also required to identify processes of depletion and technological progress. A problem with data dominated by the time series dimension is that these variables tend to correlate. We have included both time trends and depletion variables in our estimated models. However, it is hard to claim that either of these proxies represents exact measures of the underlying processes we would like to uncover. Data sets with more cross-sectional variation would probably offer more opportunities in this respect. Unfortunately, such a detailed and refined approach would exhaust the limits of our data set, and therefore has to be left for future research. Panel data studies of fields, regions, or countries should therefore be pursued to grasp the full picture of technological progress and depletion mechanisms in oil and gas exploration.

Finally, we have based our study on the empirical failure of traditional dynamic optimisation models of exploration behaviour. The theoretical point of departure for the exploration studies of this thesis is a static, discretionary approach to the process of exploration. 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.

4.2 Microeconometric studies of oil and gas investments

Based on micro data for international oil and gas companies, we explore issues of investment behaviour also in a generalised panel data setting. In Chapter 4, the role of various types of uncertainty is explored in a simple Q model approach, whereas shifting sentiments and structural breaks are addressed in Chapter 5. These studies reveal specific and interesting new

insights on oil and gas investments, with especially thought-provoking results for the role of uncertainty. Nonetheless, these papers should be regarded as introductory exercises, as they raise a number of new questions in addition to the ones they answer.

The uncertainty indicators of our study apply to overall uncertainty like general stock market volatility and oil price volatility. The analysis should therefore be augmented or replicated with company-specific risk variables to test the robustness of our results. The straightforward variable choice for this purpose is share price volatility. However, another potential allegation against our approach is that our uncertainty measures are historical rather than forward-looking. This choice is a conscious one, and well in line with specific forms of expectations formation (e.g., adaptive expectations). Still, alternative measures of forward-looking uncertainty should also be explored. Candidates include uncertainty indicators from survey data, analyst forecasts, implied volatility from option markets, and estimated volatility based on ARCH specifications.

The application of micro data in studies of oil and gas investment is unprecedented. The statistical power of these data sets represents a world of opportunities for further sophistication. A well-established modelling strategy in similar studies is related to sample splits. Companies can be grouped according to special characteristics, and regressions are run on each of the groups separately. In the same way, the data set can be grouped according to special values or intervals for the explanatory variables, and regressions may then be run on each of the sub samples. This technique can be applied not only to address cross-sectional variations, but also to study asymmetries in investment behaviour.

Finally, we should bear in mind that our studies of oil and gas investment do not solve the fundamental conundrums of contemporary empirical investment research. Chapter 4 offers an application of the neo-classical q model of investment to a panel of international oil and gas companies. Although we correct our market-to-book ratio for potential measurement error, the fundamental problem of model specification is still unsolved. In Chapter 5, we propose an approach to study how companies across an industry may move from a situation of financial flexibility to financial friction. However, the general role of financial variables in theoretical and empirical investment models remains unclear. More work should therefore be done on oil and gas company data to help resolve the big issues of modern investment research.

4.3 Oil company investment and market interaction

The presented study of company valuation represents an early attempt to substantiate the links between market valuation and financial and operational indicators in the international oil and gas industry. The results are interesting, but preliminary. Our original hypothesis was that company valuations are linked to profitability and returns on invested capital. However, our RoACE variable does not establish this link. Future research should explore alternative measures of underlying financial performance, to overcome the weaknesses of our RoACE measure. By including the oil price, we try to isolate the oil price effect on RoACE, and to pick up variation in short-term profitability that can not be attributed to oil price variation. An interesting direction for future research would be to correct the company RoACE measures for oil price variation in each company, to establish a more precise indicator of underlying financial performance. Such an indicator is more likely to have a robust influence on company valuations than our reported RoACE measure.

A weakness with the present valuation study also concerns the quality of the data set. With 14 companies over 14 years, the number of observations is limited. Moreover, our data set contains information only for large multinational companies. A larger set of company data for a wider range of companies would increase the statistical power of the econometric analysis, and shed better light on the general process of company valuation. A richer data set would also make it possible to study variation across (groups of) companies in greater detail. In this context, an interesting direction for future research would also be to study the stability of the valuation process more carefully. Modern econometric techniques may reveal more exact information on how the process of capital formation in the oil and gas industry was altered in the late 1990s, as demonstrated for business fixed investment in Chapter 5 of this thesis.

Potential implications of financial market pressures for oil price formation are explored in Chapter 6 of the thesis. The study explores the dynamics of the oil and gas industry, and illustrates potential implications in terms of OPEC behaviour and total oil supply in an interesting way. However, our broad model analysis leaves room for improvement as well as further research. Ideally speaking, our assertion that financial market pressures implicitly led to tacit collusion in terms of reduced investment should be explored further in a theoretical framework, with the development of an appropriate theoretical model of strategic investment. Moreover, the role and formation of oil price expectations deserves a more careful treatment, both for IOC investment

behaviour and for OPEC's investment decision. The exact form of OPEC's preferred oil price trajectory should also be modelled with more rigour. Last but not least, there are producers outside OPEC who do not comply with our neoclassical assumption of profit maximisation and standard competitive investment behaviour. More comprehensive studies are therefore justified for the ascending role of countries like China and Russia in global oil and gas supply.

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Part 1

Efforts and efficiency
in oil and gas exploration

Chapter 2

Exploration economics in a regulated petroleum province: The case of the Norwegian Continental Shelf

By Klaus Mohn and Petter Osmundsen

Abstract[1]

Reserve replacement remains a key challenge for the international oil and gas companies. As market-oriented oil and gas provinces are maturing, exploration activity is shifted towards the resource-rich, regulated regimes outside the OECD. Regulated oil and gas provinces remain under-explored also in econometric terms. In this paper, we specify and estimate an econometric model of exploration and appraisal drilling for the highly regulated Norwegian Continental Shelf (NCS) over the period 1965 to 2004. Explanatory variables include the oil price, cumulative discoveries and open exploration acreage. Estimated error-correction models account explicitly for sluggishness and short-term adjustments in exploration drilling. We find robust long-term oil price effects on exploration activity, whereas the short-term response is muted. On the other hand, the temporary influence on exploration drilling from licensing rounds for new exploration acreage is significant, and so are the feedback effects from historical exploration success. At the same time, the longer-term impact of these variables is more moderate.

JEL classification: C22, G31, Q38

Key words: Oil exploration, Reserve generation; Industrial economics: Econometrics

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1. Introduction

exploration drilling from licensing rounds for new exploration acreage is significant, and so are the feedback effects from historical exploration High oil prices and "Peak Oil" concerns make investment behaviour and supply side dynamics in the oil and gas industry more interesting than ever.[2] Several commentators and analysts link the current high oil prices to the lack of investments in the oil sector, as oil and gas exploration throughout the world has failed to respond to increasing oil prices over the last years (Osmundsen et al. 2005a, b). At the same time, oil and gas reserves in market-oriented economies like USA, Canada and United Kingdom are faced with depletion. Oil and gas investments are therefore gradually redirected towards resource-rich regions of the world (e.g. Russia, Latin America, and the OPEC countries), where the degree of regulation and government intervention is far higher than Western oil and gas companies have been used to.

Oil and gas exploration has been subject to economic research for decades. The attention has largely been concentrated on the US oil and gas industry, with some studies also for the United Kingdom. In this article, we present new insights on the relation between exploration activities and economic variables in the highly regulated industrial environment in Norway,[3] the third largest net oil exporter in the world. Based on detailed database information from the Norwegian Petroleum Directorate, a unique data set has been developed to cover the 40-year history of three separate regions of the Norwegian Continental Shelf (NCS). This panel data set has not been subject to econometric studies before. A drilling function is derived from a simple theory of exploration, whereby drilling efforts are explained by the oil price, cumulative discoveries and available exploration acreage. We estimate error-correction models that capture sluggishness and short-term dynamics in the data, as well as the longer-term relations between drilling efforts and the explanatory variables. Finally, we present projections to illustrate how exploration activity is affected by changes in oil prices, licensed exploration acreage and new discoveries.

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[2] The "Peak Oil" idea stems from Hubbert's (1962) idea 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.
[3] For an overview of the regulatory regime in the Norwegian oil and gas industry, see Glomsrød and Osmundsen (2005).

The Norwegian Continental Shelf (NCS) is a relatively young oil and gas province. The first discovery was made in 1969, and the Ekofisk field was put on stream two years later. A number of discoveries were made in subsequent years, and laid the foundations for a new and important industry in Norway, and a significant supplying region for US and European oil and gas markets. In 2005, total petroleum production came in at 257 M scm (4.4 mmboepd). Figure 1 illustrates the role of the NCS in the international oil market. The Norwegian government has played an active role in the development of a Norwegian oil and offshore industry. The strategy for resource management and industrial development has been characterised by gradualism. The impact of external market forces has traditionally been subdued by a carefully developed regulatory system, followed up by well-developed institutions and governance systems. For an industry and policy overview of the NCS, see Ministry of Petroleum and Energy (2005).

Several resource-rich countries outside the OECD show interest for the Norwegian Model for resource management and industrial development. Our study of exploration behaviour should be of interest not only to the governments in regulated oil and gas provinces worldwide, but also to companies who aim at developing new business in the expanding resource-rich regions outside the OECD area.

Figure. Oil production and net export by country

Oil production by country
(mmbopd, 2004)

Country	Value
Russia	9.2
Saudi	9.0
USA	7.6
Iran	4.0
Mexico	3.8
China	3.5
Norway	3.2
Canada	2.6
Venezuela	2.6
UAE	2.4

Net oil export by country
(mmbopd, 2004)

Country	Value
Saudi A.	7.0
Russia	6.5
Norway	2.9
Iran	2.5
Venezuela	2.1
Nigeria	2.0
UAE	2.0
Kuwait	2.0
Mexico	1.8
Iraq	1.5
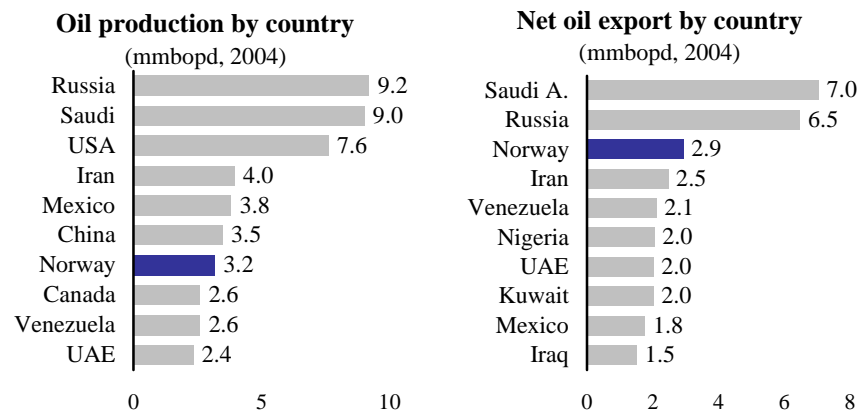
Source: Petroleum Economics Ltd.

The paper is organised as follows. A brief survey of previous related research is offered in Section 2, before a simple theory of exploration based on producer behaviour and duality principles is outlined in Section 3. The

52

empirical specification is derived in Section 4 and our data set is presented in Section 5. Econometric results are presented and discussed in Sections 6 and 7, respectively, before some concluding remarks are offered in Section 8.

2. Previous research

The combination of geological and economic variables in empirical models of exploration dates back some 40 years. By many, Fisher (1964) is claimed to have opened this field of research with his seminal econometric studies of US oil and gas exploration. Fisher (1964) estimate equations for the drilling rate, success rate and the discovery rate for different US Petroleum Administration Defence Districts (PADD) over the period 1946-1955. Explanatory variables include oil prices, seismic crews and proxy variables for drilling costs. Based on extended versions of the same data set, updates and extensions of the Fisher framework were presented in a range of papers for the US oil and gas industry over the following 15 years.

Erickson and Spann (1971) expand the set of explanatory variables and detected a connection between technological ability and success rates. Concentrating on gas exploration, Pindyck (1974) estimates a similar model on a broader data set, with quite different results from those of Fisher (1964) and Erickson and Spann (1971). Pindyck (1978) was the first to open for the aspects of intertemporal maximisation, as he introduced the interest rate in his drilling equation. Kolb (1979) concentrates on oil-prone districts in a slightly more disaggregated approach. These early Fischer models had a simple structure that largely could be justified based on economic fundamental principles. However, the theoretical foundation was gradually improved, as dynamics and uncertainty were introduced explicitly in the producer's optimisation problem.

The geological approach to exploration and production modelling emphasises the importance of physical factors like cumulative production and technological conditions, whereas economic factors are typically not accounted for. The key reference to this approach is Hubbert (1962), who argues that cumulative production evolves according to a logistic growth model. A standard result of this literature is that the success rate from exploration will depend on the maturity of the petroleum province in question. Since the mid 1970s (Bouhabib 1975), cumulative measures of reserves, drilling efforts and discoveries have typically been included in the econometric exploration models. The role of these variables has been to

53

account for the dampening depletion effects on exploration success and consequent reserve additions. Moroney and Berg (1999) illustrate that model diagnostics and forecasting performance of simple Hubbert models improve when economic and policy variables are included.

A requirement for theory-based econometric research on the oil and gas industry is that the data set is generated in an industrial environment guided by commercial principles. The quality of the data will usually increase, the longer the history of the actual activity. This explains why most of the empirical work on exploration behaviour is done in USA. A survey of empirical exploration models for the US oil and gas industry is offered by Dahl and Duggan (1998). Into the 1990s, some studies also emerged for the exploration and production of oil and natural gas on the United Kingdom Continental Shelf (e.g., Pesaran 1990; Favero and Pesaran 1994). Based on an integrated, dynamic optimisation problem, these studies produce plausible, estimated equations for exploration, development and production. However, they fail to produce robust estimates in support of intertemporal maximisation. Later studies, especially for the US oil and gas industry, have therefore relaxed the assumption of intertemporal behaviour, and several have returned to the period-by-period optimisation approach (e.g., Iledare 1995; Iledare and Pulsipher 1999; Farzin 2001). This behavioural assumption is also applied by Ringlund et al. (2004). Still, their econometric specification of oilrig activity for a panel of non-OPEC countries is indeed dynamic. Our approach will follow a similar line of thought.[4]

Over the last 15 years, general depletion mechanisms have been supplemented with theories for infant-industry cumulative scale economies, stemming from learning-by-doing effects in exploration activities (Quyen 1991). One of the few attempts to incorporate this kind of industrial dynamics in empirical models is represented by Hendricks and Porter (1996), who apply game theory to study the impact of information externalities on drilling behaviour in the Gulf of Mexico. Rehrl and Friedrich (2005) also account for both learning and depletion effects in an applied logistic growth framework for long-term analysis of production and price formation in the oil market.

Three different perspectives have been applied to study exploration economics. One approach is to see exploration behaviour from the company's perspective, and base the econometric models on micro data (e.g., Ghouri

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[4] To test the validity of this assumption, interest rate variables were included in the preliminary estimation of our model. However, we were unable to establish plausible and robust estimates of their coefficients.

1991). An alternative is to consider individual oil and gas fields as the principal economic unit, focusing specifically on the life-cycle dynamics and vintage issues of oil and gas production (e.g., Iledare 1995). The most common perspective is based on aggregate data for regions, countries or groups of countries. All the above articles except Ghouri (1991) and Iledare (1995) fall into this category, and so does our study.

3. A simple model of exploration behaviour

Our theoretical point of departure is a simple model for the technology structure associated with the development of oil and gas reserves. Abstracting from acquisitions and divestitures, there are two primary sources of organic reserve growth. First, the companies may engage in exploration drilling. Traditionally, this activity has offered great rewards for the successful companies, but the associated risks are also high. Second, the companies may invest capital and efforts to increase the recoverable reserves in producing fields. Techniques for active reservoir management have come far, and include carefully planned drilling of new production wells, various injection techniques and other IOR measures to increase recovery and maximise the economic value of reservoirs in production and their associated infrastructure.[5] The risks associated with this type of investments are generally lower than for exploration activities, but so are also the expected rewards.

Oil and gas producers maximise profits from production and reserve generation, as illustrated in Figure 2. As the markets for oil and gas reserves, license shares and other petroleum assets have matured, exploration for oil and gas reserves has developed into an autonomous profit-generating activity among integrated international oil and gas companies. Exploration decisions do not necessarily require future development and production. Rather, any discovery is evaluated on its own merit, and a range of strategies is available for further value optimisation.

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[5] IOR (Increased Oil Recovery) is the usual concept for measures to extend reserves in NCS reservoir management. In other provinces, the EOR (Enhanced Oil Recovery) concept is more common. Essentially, these concepts are synonyms. However, their actual content may vary marginally across different provinces, according to regional variation in type of efforts and techniques.

Figure 2. Stylised production structure in an oil and gas company
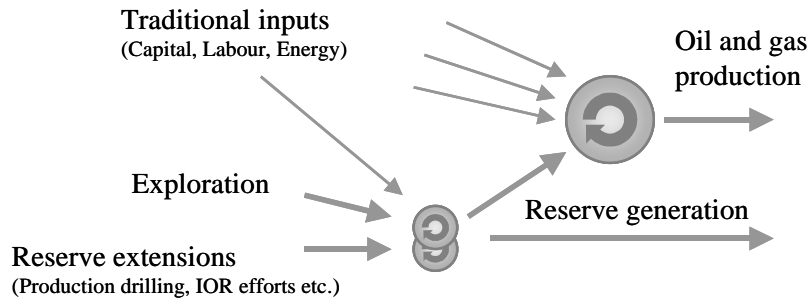
Oil and gas companies employ exploration staff for the long term. A standby capacity is maintained over the business cycle, almost independent of fluctuations in the oil price and exploration activity from year to year. Seen from the oil and gas companies on the NCS, exploration activities are not very capital-intensive, as all capital equipment are hired for specific activities. We therefore hypothesise a subordinate role for traditional inputs like capital and labour in decisions concerning exploration activity. This means that fluctuations in exploration activity from one year to another is driven mainly by the oil price, and by the availability and quality of exploration opportunities.

The role of traditional inputs (capital and labour) is also not well explained by empirical studies of exploration behaviour (Dahl and Duggan 1997). Attempts have been made to include interest rates and user-costs of capital (e.g. Pindyck 1978; Pesaran 1990), but their role is generally not justified by econometric evidence. Interest rate variables are therefore normally not included in modern empirical exploration studies (e.g., Iledare and Pulsipher 1999; Farzin 2001; Ringlund et al. 2004). The strongest argument for this simplification is that dynamic optimisation is not well supported by previous attempts to explain the economics of oil and gas exploration, especially not in Europe.[6] Human capital and learning-by-doing has drawn some interest in theoretical studies (e.g. Quyen 1991; Hendricks and Porter 1996), but so far, no clear role is established for labour and labour costs in empirical models of exploration behaviour. Based on these results and our own preliminary

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[6] See Farzin (2001) for a thorough discussion of the failure of interest-rate variables and intertemporal maximisation hypotheses in empirical exploration models.

findings[7], we therefore assume that costs associated with capital and labour stem from a standby capacity, and that they are insensitive to fluctuations in exploration activity from one year to another. Accordingly, the cost of traditional inputs is treated as constant. This means that oil and gas companies evaluate their exploration activity from year to year based on the opportunity set offered by oil and gas market developments, accumulated underground experience and current regulatory conditions – given a fixed capacity of labour and capital.

In technical terms, the production technology of exploration is described by a well-behaved production function $y_t = f(z_t, x)$, where y_t is annual reserve generation, z_t is a vector of state and policy variables and traditional inputs (x) are treated as fixed. Candidates for the z_t vector include licensed exploration acreage, cumulative oil and gas discoveries, seismic activity and variables to capture technological progress.[8] The following revenue function ($r(p_t, z_t)$) now summarises the income side of our crude model of exploration behaviour:[9]

$$r = r(p_t, z_t) = \max_y \left\{ p_t \cdot y_t \right\} \ s.t. \ f(z_t, x) \geq y_t \ . \qquad [1]$$

p_t is the oil price, our proxy variable for the marginal value of oil and gas reserves.[10] The corresponding profit function is given by:

$$\boldsymbol{p} = \boldsymbol{p}(p_t, z_t, x) = \max_y \left\{ r(p_t, z_t) - c(x) \right\} \ s.t. \ f(z_t, x) \geq y_t \ , \qquad [2]$$

where c represent the fixed capacity costs discussed above.

---

[7] We allowed for general wage and interest rate variables in the early stages of our estimation process. Based on statistical evaluation, none of these variables could justify a position in the preferred empirical models.

[8] For studies focusing explicitly on technological progress in the exploration process, see Forbes and Zampelli (2000, 2002) and Managi et al. (2005).

[9] See Livernois and Ryan (1989) for a discussion of non-jointness and separability issues in oil and gas exploration technologies.

[10] Following Iledare (1995), we have also tested the properties of 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: $v_t^e = p_t^e(1-c_t)(1-\boldsymbol{t}_t)$, where v_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 $\boldsymbol{t}_t$ is a corresponding 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, and we therefore stay with our plain formulation.

Applying Hotelling's lemma to the profit function of Equation [2], we have for the optimal supply plan for new reserves:

$$y_t^*(p_t, z_t) = \frac{\partial \boldsymbol{p}(p_t, z_t, x)}{\partial p_t} = \frac{\partial r(p_t, z_t)}{\partial p_t}.$$ [3]

An asterisk is added to y_t^* to distinguish optimal reserve generation from the actual or observed activity. Positive changes to the oil price are expected to stimulate reserve additions – and drilling efforts, whereas the marginal impact of changes to the state variables (z_t) will depend on the specific nature of these variables.

Price expectations and/or adjustment lags in the impact of the explanatory variables may cause exploration activity to differ from the desired level defined by Equation [3]. The data-generating process may well be characterised by sluggishness and dynamics, even if the data is not the result of an intertemporal optimisation process. The exploration process may be disturbed by contractual obligations, leads and lags in the exploration technology, uncertainty about future prices, as well as regulatory constraints. We assume that any deviation from the optimal rate of reserve generation is adjusted by a constant fraction each year:

$$\frac{y_t}{y_{t-1}} = \left(\frac{y_{t-1}^*}{y_{t-1}}\right)^{\boldsymbol{l}} ,$$ [4]

where an asterisk is appended to separate the optimal reserve requirement (r_t^*) from the observed level (r_t). $0 < \boldsymbol{l} < 1$ specifies the speed of adjustment. The following logarithmic form will have its parallel in our empirical specification:[11]

$$\ln y_t - \ln y_{t-1} = \boldsymbol{l} \, (\ln y_{t-1}^* - \ln y_{t-1}) .$$ [5]

---

[11] As pointed out by one of the referees, an alternative could be to let the deviation from current optimal reserve additions (y_t^*/y_{t-1}) determine the pace of adjustment instead of the lagged deviation (y_{t-1}^*/y_{t-1}). However, the information set for y_t^* is not known with certainty before the end of period *t*. Consequently, y_t^* can also not be determined with certainty before the end of in period *t*. We therefore assume that the underlying adjustment is based on the lagged equilibrium error – in an econometric specification that encompasses the adaptive-expectations hypothesis for the dependent variable (cf. Mizon and Richard 1986).

Our empirical specification will support partial adjustment in exploration efforts. Further, our empirical model allows for a separation between immediate short-term price responses on the one hand, and the long-term price effects on the other – driven by gradual adjustment of drilling activity and price expectations.[12]

4. Empirical specification

We need a specification of the profit function in [1] that can be estimated by econometric methods, taking proper account of the characteristics of the data-generating process. A simple and tractable point of departure is a Cobb-Douglas specification for the revenue function in Equation [2]:

$$r(p_t, z_t) = K p_t^{\boldsymbol{d}} \prod_{i=1}^{n} z_{it}^{\boldsymbol{b}_i} e^{\boldsymbol{g}T}, \qquad [6]$$

where k is a constant term, and $\boldsymbol{d}$ and $\boldsymbol{b}_i$ represent elasticities of revenue with respect to the oil price (p_t) and state and policy variables (z_{it}), respectively. We also include a time trend (T), to capture the effect on profit from potential technological progress ($\boldsymbol{g}$). Differentiation of [6] with respect to p_t now yields the following expression for the desired supply of oil and gas reserves:

$$\frac{\partial r(p_t, z_t)}{\partial p_t} = y^*(p_t, z_t) = K\boldsymbol{d} p_t^{\boldsymbol{d}-1} \prod_i z_{it}^{\boldsymbol{b}_i} e^{\boldsymbol{g}T}, \qquad [7]$$

Letting $k = \ln(K\boldsymbol{d})$ and $\boldsymbol{a} = \boldsymbol{d}\text{-}1$, we now obtain the following (log) linear relation between exploration activity and explanatory variables:

$$\frac{\partial r(p_t, z_t)}{\partial p_t} = \ln y^*_t(p_t, z_t) = k + \boldsymbol{a} \ln p_t + \sum_{i=1}^{n} \boldsymbol{b}_i \ln z_{it} + \boldsymbol{g}T, \qquad [8]$$

---

[12] Previous empirical studies of exploration behaviour have generally been in favour of the adaptive-expectations hypothesis for oil prices (e.g., Farzin 2001). With our error-correction approach, we present estimates for the gradual adjustment of exploration activity. A potential source of delayed response is the gradual adaptation of price expectations, but we do not estimate this process explicitly. See Prat and Uctum (2001) for a discussion of modelling strategies for oil price expectations.

Reserve additions from exploration (r_t) may be seen as a combined result of actual drilling activity (d_t) and drilling efficiency (e_t): $r_t = d_t \cdot e_t$, where e_t represents drilling efficiency, or average contribution of new reserves per exploration well.[13] The focus of our study is on drilling efforts, and for the remainder of the paper we therefore focus our attention on the d_t variable as the reserve-generating factor.

As indicated by the partial adjustment mechanism for exploration activity and the adaptive expectations hypothesis for prices, there is reason to believe that the data-generating process is dynamic by nature. In econometric terms, both the dependent and the independent variables in [8] are likely to be non-stationary. If these variables have a trend, their linear combination may also have a trend, and the error term will fail to meet the requirements of standard estimation methods. In that case, direct estimation of the parameters will produce inefficient coefficient estimates, and the validity of statistical inference is therefore problematic. Direct estimation of the structural relation will also not describe the dynamics of the data-generating process properly.

However, if the variables in Equation [8] are integrated of degree 1 (*I(1)*), their difference will be stationary ($y_t \sim I(1) \implies \Delta y_t \sim I(0)$). A key result from the literature on co-integration and error-correction is that a linear combination of non-stationary variables may produce a stationary error-term. If such a combination is represented by [6], the variables are co-integrated, and their set of coefficients defines the co-integrating vector.[14] In this case, we may estimate the dynamics of the process in an error-correction specification. We now expand our z_t vector to include cumulative oil and gas discoveries (res_t),[15] licensed exploration acreage (acr_t) and a time trend (T) to capture technological progress. This yields for the equation to be estimated:

$$
\begin{aligned}
\Delta \ln d_{kt} = a_{0k} + a_2 \Delta \ln p_t + a_3 \Delta \ln res_{kt} + a_4 \Delta \ln acr_{kt} \\
+ \boldsymbol{1} \ln d_{k\,t-1} + b_1 \ln p_{t-1} + b_2 \ln res_{k\,t-1} + b_3 \ln acr_{k\,t-1} + b_4 T + u_{kt}
\end{aligned}
\qquad [9]
$$

---

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

[14] A pioneering reference to the literature on cointegration and error-correcton is Engle and Granger (1987). For a recent survey, see Johansen (2006).

[15] Another candidate for historical exploration success is simply lagged exploration efficiency – or discovered resources per exploration well (e_t). Both these variables have been tested in various econometric specifications. Models with lagged efficiency as a proxy for historical exploration success generally show weaker statistical performance than the specification in Equation [9]. On this background, we conclude that the most relevant information about historical exploration success is captured by the evolution of our resource variable (res_t).

where a_i and b_j are the coefficients to be estimated. Footscript k is introduced to represent variation across the three regions of our data set, and u_{kt} is an error-term with the usual white noise characteristics. Equation [9] states the change in the dependent variable as a function of lagged changes in independent variables and the lagged deviation from the underlying structural equilibrium, as defined by [8]. The error-term will now be stationary and well-behaved, provided that a co-integrating vector is indeed identified by [8]. The short-term dynamics of the model is now described by the set of a-coefficients. These coefficients may be interpreted as instantaneous and temporary effects on the dependent variables from changes in the explanatory variables. l represents the speed of adjustment, or the error-correction coefficient. The long-term structural relationship is established when the changes in all variables approach zero. Following Bårdsen (1989), estimates for the underlying structural parameters of [8] can therefore be derived directly from [9]. Eliminating all change variables in [9], and solving for d_{kt} yields for the long-term structural relation:

$$d_{kt} = k + \boldsymbol{a} \ln p_t + \boldsymbol{b}_{res} \ln res_{kt} + \boldsymbol{b}_{acr} \ln acr_{kt} + \boldsymbol{g}T \quad , \qquad [10]$$

where the structural coefficients are derived from [9] as:

$$k = -\frac{a_0}{l}, \ \boldsymbol{a} = -\frac{b_1}{l}, \ \boldsymbol{b}_{res} = -\frac{b_2}{l}, \ \boldsymbol{b}_{acr} = -\frac{b_3}{l}, \ \boldsymbol{g} = -\frac{b_4}{l} \qquad [11]$$

Standard estimation procedures may now be applied directly on [8] to obtain unbiased and efficient estimates for both short-term dynamics and the long-term underlying structure of our model.

5. Data set and variables

Our data set is retrieved from the data bases of the Norwegian Petroleum Directorate, who has collected and processed information and statistics on Norwegian oil and gas activities since the early 1970s. We have time series for all variables over the period 1965-2004, split between the three major offshore regions on the Norwegian Continental Shelf.[16] The upper bound for the number of observations in our panel is 40x3 = 120. However, observations are missing for some of the regions in some of the years. For example, the

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[16] The North Sea, The Norwegian Sea and The Barents Sea, cf. map in Appendix 1.

Norwegian Sea and the Barents Sea were not opened for exploration drilling before 1980.

Figure 3. Key variables of the data

Oil price
USD/bbl, 2004 prices

Exploration and appraisal wells

Exploration and appraisal wells

Acreage and discoveries
USD/bbl, 2004 prices

Open acreage (1,000, sq km)
Acc. discoveries (bn scm, rhs)

Barents Sea
Norwegian Sea
North Sea
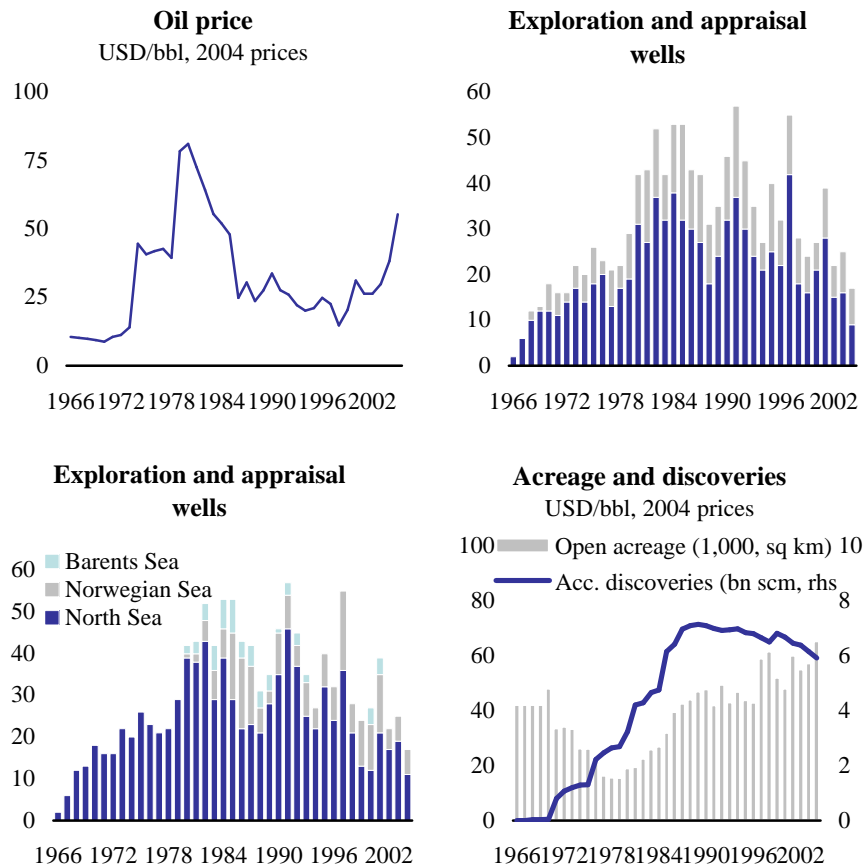
Sources: Oil price: http://EcoWin.com. All other numbers: The Norwegian Petroleum Directorate.

Our data set contains regional-specific information for discoveries and licensed exploration acreage, whereas our proxy for the marginal value of new reserves 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. The political and regulatory regime is also the same for the three regions, producing a unified business framework. We therefore assume that the underlying economic behaviour represented by our data set does not vary across regions.[17]

Our choice of number of wells as the dependent variable is a result of tests and comparisons of a variety of activity measures. An econometric appraisal of various activity measures in NCS exploration reveals that a model explaining drilling activity in terms of number of wells outperforms specifications with alternative activity measures, including drilling footage, annual number of drilling days and annual exploration expenditures. Annual well-count is a simple and plain activity measure, has an easy interpretation, and agrees well with our theoretical specification. The two top panels of Figure 3 illustrate how exploration drilling on the NCS has been on a downward trend over the last 10 years, in spite of the recent increase in oil prices. NPD's data base system provides characteristics of 3840 wells over the period 1965-2004. 30 per cent (1201) of these wells relate to exploration. Further, exploration wells are split between wildcats (844) and appraisal wells (367). Some exploration wells are oil-prone and others are gas prone, but the ex ante uncertainty is very large when it comes to expected type of hydrocarbons that is likely to be found. A typical feature for decision concerning exploration activities on the NCS is that no clear distinction is made between exploration wells for oil and exploration wells for natural gas. Consequently, specific data for oil- or gas-targeted exploration is not available. We therefore regress the total sum of exploration wells, as well as the two specific subgroups (wildcats and appraisal wells), against the explanatory variables.

The first explanatory variable is the oil price, as illustrated by the left-hand bottom panel of Figure 3. Our choice is Brent blend, the standard reference for North Sea crude oil. Preliminary estimations were run on both NOK and USD denominations for the oil price, and we have tested the properties of nominal versus the real price. Based on these tests, we have come to prefer a real USD denomination.[18] The result is the oil price series illustrated Figure 3.

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[17] Ringlund et al. (2004) demonstrate that the oil price sensitivity of exploration drilling may vary across regions in an international context. However, they also argue that regulatory heterogeneity across countries is the most likely explanatory factor behind the regional variation in the economics of the exploration process.

[18] Statistical inference was the key criteria for this selection. However, we also looked at the explanatory power of the 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

We would also like to include a variable for the cumulation of oil and gas resources. Based on various econometric specifications and definitions, we arrived at NPD's estimate for total oil and gas resources on the NCS net of undiscovered resources and historic production as the best suited resource variable for our modelling purpose. In other words, our resource variable (res_t) include estimates for recoverable resources in fields and discoveries as defined by the NPD. Resource estimates for fields include reserves and contingent resources, where contingent resources also include estimates for IOR potential. Based on alternative sources, we find that changes in our resource variable closely resemble the history of discoveries on the NCS.[19] The development of our measure of cumulated discoveries (net of production) is illustrated in the bottom right-hand panel of Figure 3. Strong resource growth was provided by huge discoveries during the 1970s and 1980s, but over the last 15 years, the stock oil and gas resoures has stagnated, due to falling drilling activity and poor exploration results. At the same time, solid production rates now contribute to gradual depletion. These are typical symptoms of a maturing oil and gas province.

Finally, the bottom right-hand panel of Figure 3 illustrates how exploration acreage (acr_t) has been regulated by the Norwegian Government. Some 42,000 km^2 were awarded in the 1st licensing round in 1965, ahead of the opening of the Norwegian Continental Shelf. Licenses that were handed back to the Government towards the mid 1970s reduced the cumulative open exploration acreage, before new licensing rounds added new frontier acreage in the Norwegian Sea and in the Barents Sea from 1980. Licensing policies have been adjusted over the last few years to spur exploration activity, and large areas were awarded in mature areas and frontier areas both in 2003 and 2004.

6. Estimation and testing

As described in Section 5, our econometric model consists of two parts. First, we have the long-term structural relation between drilling efforts and the

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model. Our choice of oil price denomination also secures consistency of measurement in our econometric model – as the left-hand variable is a true volume term.

[19] This resource estimate has been subject to revisions (including re-statements), due to technological progress, new information and changes in economic conditions. However, the NPD does not provide detailed historical information on these revisions. We therefore have to rely on the most recent estimates, including their updated historical records.

explanatory variables, as represented by Equation (6). Second, we have the econometric specification of the error-correction model, to capture short-term dynamics and sluggishness. This approach allows a separation between temporary and persistent (structural) effects, as well as an explicit representation for the adjustment process towards the structural equilibrium. All estimations are performed with fixed-effects panel data procedures, whereby regional dummy variables are included and suppressed through normalisation around sample means (DVLS).[20] Further, our estimation strategy follows a general-to-specific approach, starting out with a full-blown model, including all explanatory variables. We have tested for a variety of lag specifications, and have retained variables and lags that could justify a position in the model based on estimated coefficient qualities and more general model diagnostics.

Before we present the estimates for the structural and dynamic models, we include a note of caution with respect to co-integration. Our hypothesis is that the structural equilibrium of our exploration model can be described as a cointegrating vector, and we would like to specify a dynamic representation of the relationship as an error-correction model. A critical requirement in this respect is that our structural equilibrium is indeed characterised by co-integration.

Strictly speaking, 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. Some tests have been developed (e.g., Levin and Lin 1993; Banerjee 1999) for balanced panels, but challenges remain unsettled for our data set due to varying starting points for our time series, as well as several gaps.[21] We have therefore tested the stationarity properties of all our explanatory variables separately for each of the three regions, applying both Dickey-Fuller and Phillips-Perron procedures and test statistics.[22]

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[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 involves 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.

[21] For the first 15 years of our data period (1965-1979), regular drilling took place only in the North Sea. In the Norwegian Sea, exploration wells have been drilled every year since the opening of the area in 1980. The Barents Sea was also opened in 1980, but since 1994, exploration activities in this northern region have been interrupted by both voluntary and regulated interludes (cf. upper right-hand pan in Figure 3).

[22] 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

Detailed results from these stationarity tests are presented in Appendix 2, including results also for the aggregate series for the total NCS. The null of non-stationarity is rejected on a 99 per cent significance level for all dependent variables (well categories) in all the three regions, as well as for the respective aggregate series for the total NCS. Non-stationarity is also rejected for the explanatory variables, on a 99 per cent significance level in 11 out of 12 cases. These results suggest that we have the necessary support for our specification of error-correction models for NCS exploration efforts.

We now regress the change in drilling activity ($\boldsymbol{D}\ln d_t$) against the change in the oil price ($\boldsymbol{D}\ln p_t$), lagged discoveries ($\boldsymbol{D}\ln res_t$), lagged changes in available exploration acreage ($\boldsymbol{D}\ln acr_t$), as well as lagged levels of all explanatory variables (cf. Equation [7]). Full-blown estimated versions of Equation [7] with all explanatory variables are presented in Appendix 3. A time trend was also included in our initial estimations (cf. Appendix 3). However, a position for this variable could not be justified in our preferred models.[23]

In our general-to-specific estimation approach, the models have been narrowed down, based on parameter inference and general model diagnostics. Preferred estimates for the error-correction models are presented in Table 1, with p-values of the respective estimates in brackets. Parameter inference is

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regression is run of the differenced variable on its lagged level, as well as its lagged differences (sometimes also with a time trend):

$$\Delta x_t = \boldsymbol{g}_0 + \boldsymbol{g}_1 x_{t-1} + \sum_j \boldsymbol{g}_{2j} x_{t-j} + v_t \; .$$

A significant negative parameter estimate for $\boldsymbol{g}_1$ 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. Phillips and Perron (1988) introduced a modified variant of this test, whereby a non-parametric correction of the standard errors is applied to capture serial correlation of the above regression.

[23] Various categories of seismic surveying activity have also been tested as proxy variables for technological progress in our drilling equations – without success. As argued by a number of authors (e.g, Forbes and Zampelli 2000, 2002; Managi et al. 2005), technological progress clearly plays an important role for the *productivity* of oil and exploration. The development of new technologies and competence has contributed to more efficient exploration efforts, also on the NCS. New technologies have enabled the companies to drill deeper and more advanced wells, increasing their reach and precision. To this end, technological progress has also caused NCS success rates to increase over the years. However, the focus of our econometric model is not on *productivity* (success), but on *activity* (effort). The absence of a time trend in our estimated drilling equations is therefore not an argument that technological progress is unimportant for oil and gas exploration on the NCS.

based on robust standard errors, to adjust for the potential bias arising from heteroskedasticity or remaining serial correlation in the residuals.[24]

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^{res}) that takes the value 0 for years before 1970, and 1 for all years after 1970. The change in this variable takes a highly significant parameter estimated in our models, and improves the quality both on the parameter estimates and the general model diagnostics.

Table 1 shows significant short-term effects on drilling efforts from all our explanatory variables, whereas longer-term effects are restricted to the oil price and cumulative oil and gas discoveries. According to R^2, our models account for 50-64 per cent of the variation in the data set.[25] Test statistics for joint parameter significance are robust, and the null hypothesis that all parameters equal zero is rejected on a 99 per cent significance level for all three models. Observe that that the error-correction coefficient is highly significant for all models, lending additional support to our hypothesis of co-integration in NCS exploration efforts. The estimated error-correction coefficients also suggest a very rapid adjustment process, as they indicate that 84 to 89 per cent of last year's deviation from the structural equilibrium is eliminated every year. Short-term oil price effects are significant only for appraisal wells, whereas a significant persistent oil price effect is detected also for wildcat wells.

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

[25] This may not seem very impressive. However, NCS activity is very volatile, both over time and across our three regions. According to rig count data from Baker Hughes over the last 25 years, average NCS rig activity is below 50 per cent of corresponding activity on the UKCS, and less than 15 per cent of the corresponding activity in the Gulf of Mexico. These larger provinces also show less relative variation in drilling and rig activity. It is therefore no big surprise that the explanatory power is lower for our models on NCS data set than for some of the previous time series studies on US and UKCS data.

Table 1. Estimated error-correction models for NCS exploration efforts

	E&A wells	Exploration wells	Appraisal wells
Estimated coefficients [a]			
Intercept	0.51^{*} (0.07)	1.18^{***} (0.00)	-2.60^{***} (0.00)
$\boldsymbol{D} \ln p_t$	0.20 (0.19)		0.57^{***} (0.01)
$\boldsymbol{D} \ln res_{t-1}$	0.88^{***} (0.00)	0.64^{***} (0.00)	1.48^{***} (0.00)
$\boldsymbol{D} D_t^{res}$	-1.90^{***} (0.00)	-1.81^{***} (0.00)	-2.04^{***} (0.07)
$\boldsymbol{D} \ln acr_{t-1}$	0.31^{*} (0.10)	0.37^{*} (0.07)	0.72^{*} (0.04)
$\ln d_{t-1}$ $(\boldsymbol{1})$	-0.84^{***} (0.00)	-0.89^{***} (0.00)	-0.86^{***} (0.00)
$\ln p_{t-1}$	0.21^{**} (0.03)	0.18^{**} (0.04)	0.35^{*} (0.07)
$\ln res_{t-2}$	0.10^{*} (0.07)		0.34^{***} (0.01)
Model diagnostics			
R^2	0.51	0.50	0.61
Joint significance	$F(7, 60)$ = 14.52	$F(5, 62)$ = 10.54	$F(7, 42)$ = 94.08
Obs. (#)	70	70	51
Derived structural coefficients (cf. Equation [9])			
$\ln p_t$	0.25^{**} (0.03)	0.20^{**} (0.03)	0.41^{**} (0.07)
$\ln res_{t-1}$	0.12^{*} (0.06)		0.40^{***} (0.00)

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
[a] p-values in brackets.

Figure 4. Estimated NCS drilling efforts
Model 1: E&A wells
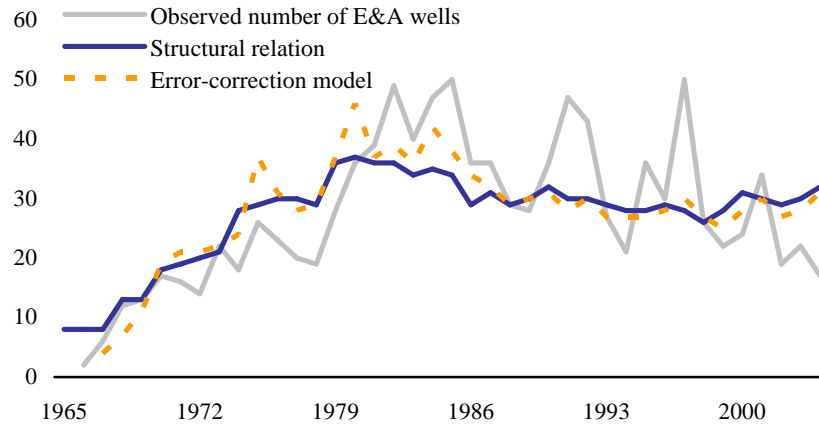
imulated drilling efforts based on coefficient estimates from Table 1.

7. Discussion of results

Figure 4 illustrates how the model captures the pattern in NCS exploration drilling efforts. The structural model for the sum of exploration and appraisal wells forms a smoothing trajectory through the more volatile pattern for the observed number of wells. The estimated error-correction model picks up some of the volatility around the structural relation, but we have to admit that some the peaks and troughs in exploration drilling remain unexplained.

Some of our explanatory variables take on robust coefficients in the econometric models. But in general, their magnitude is modest. Our structural relations imply a long-term elasticity from oil prices between 0.20 and 0.41. According to Dahl and Duggan (1998), the average of estimated oil price elasticities of US exploration activity exceeds 1. 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 oil and gas exploration vary inversely with the degree of regulation.

Figure 5. Simulation of marginal effects
E&A Wells: percentage deviation from reference scenario
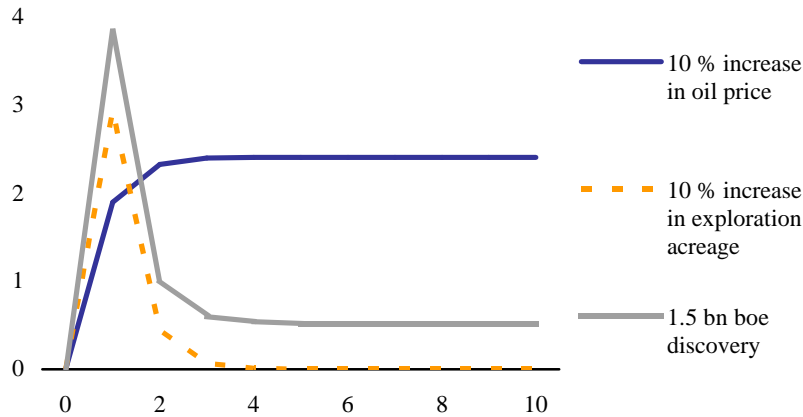
Simulated drilling efforts based on coefficient estimates from Table 1.

Figure 5 illustrate some marginal effects of shifts in the explanatory variables. Again, we apply the estimated model for the total sum of exploration wells (wildcats + appraisal wells) as a reference, and compute the effects of 3 different shifts on a 10-year horizon. The first scenario illustrates the effect of a 10 per cent permanent increase in the oil price. With an error-correction coefficient above 0.8, the adjustment process towards the structural equilibrium is rapid, and 99 per cent of the full effect is realised by the end of year 3.

The estimated structural relations do not establish a persistent effect between available exploration acreage (acr_{t-1}) and exploration drilling. This is the case for all our structural relations, and the non-persistent impact of new exploration acreage is also clearly illustrated by the second scenario of Figure 5. However, there are temporary effects from licensing rounds that provide interesting insights. A 10 per cent increase in exploration acreage will increase the drilling of exploration and appraisal wells by 3 per cent in the short-term. This suggests that there are short-term stimulative effects on exploration activity, whenever the Government offers new, unexplored acreage. But the effect dwindles rapidly, as only the most attractive prospects are drilled immediately. Hendricks and Porter (1996) offer support for this kind of result in a non-cooperative model of drilling timing, with an application for the Gulf of Mexico.

State variables for industrial maturity are usually included in empirical studies of exploration behaviour and reserve additions (Dahl and Duggan 1998). An

70

important reason for the inclusion of cumulative discoveries (res_t) and open exploration acreage (acr_t) in our analysis has been to capture the vintage dynamics of the Norwegian Continental Shelf. Figure 5 also illustrates the effect on drilling efforts from a year with total discoveries of 1.5 bn boe.[26] This representation of exploration success provides an immediate stimulus to drilling efforts of nearly 4 per cent. But most of the effect dwindles over time, leaving a long-term impact 0.5 per cent. Without new discoveries the stock of recoverable oil and gas reserves is reduced continuously through production. Accordingly, our estimated coefficients for cumulative discoveries also imply that exploration drilling is suppressed when the oil and gas province matures, ie. when new discoveries are dominated by depletion.

Finally, observe that our estimated model predicts an increase in exploration drilling since the late 1990s (Figure 4), based on observed values for the explanatory variables. This is sharply at odds with the realised development, as exploration drilling has trended down both in Norway and elsewhere in the world over the last 5 years. On the NCS, we saw a record low level of 12 exploration and appraisal wells in 2005. This stagnation in exploration spending has developed in spite of increasing oil prices, reduced production costs and substantial offers of new exploration acreage through several licensing rounds. One explanation might be a shift in industry behaviour over the last few years. After the Asian economic crisis in 1998, temporary financial distress led to a strong focus on cost discipline and short-term profitability across the oil and gas industry. Companies have also been slow to update price expectations after 1998, suggesting that the low oil price environment of the late 1990s may have had persistent effects on exploration behaviour. We believe that this situation is temporary, and that exploration is set to rise as price expectations adjust to the current market situation and the focus among oil and gas companies shift back to long-term reserve-generation and production growth.[27]

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[26] Or 240 M scm, which corresponds approximately to the annual production rates over the last years. In other words, this is the annual discovery rate required to replace reserves.
[27] See Osmundsen et al. (2006a, 2006b) for recent studies of the links between financial market pressures and investment behavior.

7. Conclusion

During the last 40 years, exploration activities on the Norwegian Continental Shelf have produced enormous oil and gas reserves, and laid the foundations for the Norwegian oil and gas industry. The Norwegian government has played an active role in the development of the offshore oil and reserves since the mid 1960s. The regulatory approach has been guided by prudent gradualism, and market forces have not been allowed to dominate the industrial arena. Careful industrial, regulatory and macroeconomic management has proved successful. During the last years, the Norwegian Model for petroleum and resource management has attracted interest in many resource-rich non-OECD countries. Norwegian authorities and Norwegian companies cooperate actively with the governments of these countries – on regulatory framework conditions, technology, and industrial development opportunities. We believe that our analysis is relevant for the type of business framework many international oil and gas companies will meet in the years ahead.

Our models are estimated for a regulated market regime, and the results reveal new and interesting insights with respect to exploration behaviour. We establish economic effects that are quite robust, but their magnitude is rather small compared to previous studies. As found by Ringlund et al. (2004), we argue that cross-country variation in exploration behaviour may well be due to variation in the degree of regulation. We establish a robust, long-term impact from the oil price, whereas the estimated short- term effects are rather weak. Our results also illustrate how new licensing rounds stimulate exploration drilling in new attractive prospects. Discoveries are also shown to provide additional feedback to exploration drilling, but this drilling response quickly culminates in anticipation of new licensing rounds. Our models are quite successful in accounting for dynamics and sluggishness in the exploration drilling behaviour, and the estimated error-correction models suggest a rapid adjustment process.

This paper has addressed one component of resource growth. In addition to exploration efforts, resource growth will depend on exploration success and average discovery size. Modern investment theory provides interesting themes for further empirical research on exploration efficiency and its relation to economic variables. Issues of uncertainty, irreversibility and asymmetry could be also relevant for the exploration process, but econometric evidence is still pending. In a wider perspective, oil and gas companies balance their drilling efforts between exploration and production drilling. A topic for further

research would also be to study how production drilling has contributed to reserve growth on the NCS, and at best, to analyse total drilling efforts in a combined framework of investment behaviour.

Appendix 1: Offshore regions on the Norwegian Continentals Shelf
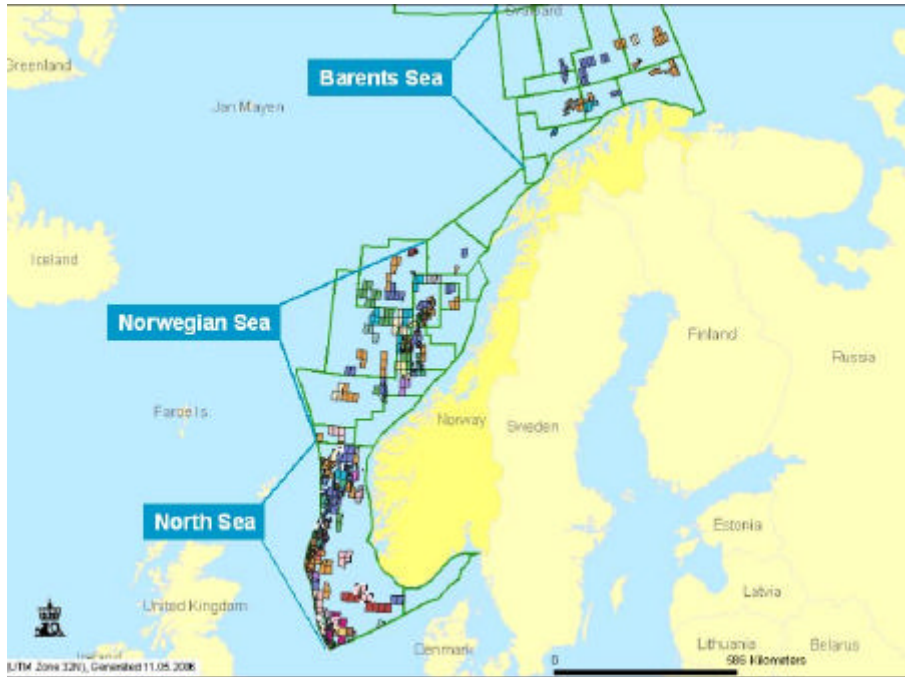
Source: Norwegian Petroleum Directorate.

Appendix 2: Tests for stationarity in ECM variables

Dickey-Fuller (DF) and Phillips-Perron (PP) test ratios computed in Stata

		Series 1	Series 2	Series 3	Series 4
		Total NCS	*North Sea*	*Norwegian Sea*	*Barents Sea*
Dependent variables					
$D \ln eaw_{kt}$	DF	-6.90***	-6.10***	-5.90***	-4.99***
	PP	-7.25***	-6.44***	-5.99***	-5.59***
$D \ln aw_{kt}$	DF	-9.63***	-9.17***	-5.01***	.. a)
	PP	-11.78***	-10.57***	-5.68***	.. a)
$D \ln ew_{kt}$	DF	-6.76***	-5.55***	-6.79***	-5.04***
	PP	-7.30***	-5.77***	-7.20***	-5.80***
Explanatory variables					
$D \ln p_t$	DF	-5.96***	-5.96***	-5.96***	-5.96***
	PP	-5.96***	-5.96***	-5.96***	-5.96***
$D \ln res_{kt}$	DF	-5.03***	-4.97***	-2.79*	-5.97***
	PP	-5.01***	-4.95***	-2.84*	-5.96***
$D \ln acr_{kt}$	DF	-5.69***	-5.36***	-4.29***	-4.93***
	PP	-5.76***	-5.48***	-4.29***	-4.93***

*) Significant at 90, **) 95 and ***) 99 per cent confidence level, respectively.
a) p-values in brackets.

Appendix 3: Full-blown ECM models for NCS exploration efforts

	E&A wells	Expl. wells	Appraisal wells
Estimated coefficients [a]			
Intercept	0.71 (0.69)	0.83 (0.73)	-1.32 (0.71)
$\boldsymbol{D} \ln p_t$	0.21 (0.21)	0.05 (0.78)	0.51 (0.04)
$\boldsymbol{D} \ln res_{t-1}$	0.98*** (0.00)	0.76*** (0.01)	1.54*** (0.01)
$\boldsymbol{D} D_t^{res}$	-2.29*** (0.00)	-2.09*** (0.00)	-2.19 (0.17)
$\boldsymbol{D} \ln acr_{t-1}$	0.35 (0.17)	0.47* (0.10)	0.73* (0.08)
$\ln d_{t-1}\ (\boldsymbol{1})$	-0.88*** (0.00)	-0.92*** (0.00)	-0.91*** (0.00)
$\ln p_{t-1}$	0.17 (0.15)	0.13 (0.43)	0.20 (0.39)
$\ln res_{t-2}$	0.26* (0.07)	0.21 (0.24)	0.54 (0.08)
D_{t-1}^{res}	-0.56 (0.20)	-0.45 (0.42)	-0.41 (0.68)
$\ln acr_{t-1}$	-0.03 (0.85)	0.00 (1.00)	-0.15 (0.63)
Trend	-0.01 (0.20)	-0.02* (0.09)	-0.01 (0.33)
Model diagnostics			
R^2	0.52	0.53	0.62
F(*)	7.39	8.13	22.32
Obs. (#)	70	70	51
Derived structural coefficients (cf. Equation [9])			
$\ln p_t$	0.20 (0.17)	0.14 (0.44)	0.22 (0.41)
$\ln res_{t-1}$	0.30** (0.05)	0.23 (0.22)	0.59* (0.06)
D_{t-1}^{res}	-0.64 (0.19)	-0.49 (0.41)	-0.45 (0.67)
$\ln acr_{t-1}$	-0.03 (0.85)	-0.00 (0.99)	-0.16 (0.62)
Trend	-0.01 (0.18)	-0.02* (0.08)	-0.01 (0.31)

*) Significant at 90, **) 95 and ***) 99 per cent confidence level, respectively.
[a] p-values in brackets.

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Efforts and efficiency in oil exploration: A vector error-correction approach

By Klaus Mohn

Abstract[1]

High oil prices and gradual resource depletion have raised global concerns for security of energy supply. Successful exploration activity is a critical factor for future oil and gas production. Based on standard assumptions of neoclassical producer behaviour and modern time series econometrics, this study reveals new insights into the process of oil and gas exploration. I find that reserve additions are enhanced by an increase in the oil price, due to responses both in effort and efficiency of exploration. Moreover, oil companies accept higher exploration risk when the oil price is high, implying lower success rates and higher expected discovery size.

JEL classification: C22, G31, Q38

Key words: Oil exploration, industrial economics, econometrics

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1. Introduction

With brisk economic growth and high oil prices, issues of energy supply have ascended on the geopolitical agenda. Global oil demand has been fuelled by strong growth, both in the OECD area and in emerging economies – like Brazil, Russia, India and China. Consequently, the sharp increase in the oil price over the last years has raised concerns among consumer interests about the security of supply (e.g., IEA, 2006). However, no oil and gas can be produced before the reserves are uncovered and proved through exploration activities. It is therefore interesting that the most important strategic challenge for the oil industry also relates to reserve replacement. Oil and gas reserves in market-oriented economies like USA, Canada, United Kingdom and Norway are faced with depletion, and exploration activities are gradually redirected towards resource-rich regions of the world (e.g. Russia, Latin America, and the OPEC countries). Unless production volumes are replaced through successful exploration efforts, the basis for future production will be undermined.

The reserve concept is one of the factors that distinguish non-renewable resource industries from other industries. Due to this defining property, oil companies engage in extremely risky exploration activities to support and grow their base of oil and gas reserves, and to sustain production activity over the longer term. Among the oil companies, the set of exploration opportunities is subject to continuous evaluation and management based on a range of criteria relating to geology, technology, economic factors, and public policies. The result of this balancing act is a dynamic exploration strategy. Moreover, the implied portfolio of exploration drilling activities yields a certain average finding rate, a particular distribution of discovery size, and ultimately, a specific rate of gross reserve additions. Consequently, the data we observe for efforts and efficiency in oil exploration are formed through simultaneous decisions in each company. This simultaneity should be appreciated also in econometric models of the exploration process.

Drilling efforts have been subject to a wide range of econometric studies since the mid 1960s, especially for the US (Dahl and Duggan, 1998). Less attention has been paid to the success and efficiency of oil and gas exploration, not to mention the interaction between efforts and efficiency. Moreover, only a few empirical exploration studies cover more than one oil price cycle. To bridge these gaps in the empirical literature on oil and gas exploration, this study examines three components of reserve growth simultaneously in an integrated novel modelling approach. A simple model for reserve-generation is derived

from standard neoclassical assumptions of producer behaviour. Fisher's (1964) decomposition of reserve growth is then applied to specify annual reserve additions as a result of drilling activity, success rates and average discovery size. Co-integration techniques (Engle and Granger, 1987; Johansen, 1995) are applied to estimate a vector error-correction model with three simultaneous equations for drilling activity, success rates and average discovery size, linking the three components of reserve-generation to relevant economic, geological and technology variables.

The under-explored data set of the econometric application covers the full history of oil and gas exploration on the Norwegian Continental Shelf (1969-2004), including the last oil price increase. The estimated model gives a breakdown of effects from explanatory variables between key components of reserve-generation, as well as a systematic separation between short-term (temporary) effects and long-term (persistent) effects in the exploration process. The proposed model framework allows a detailed analysis of factors behind exploration behaviour and reserve generation, including effects of oil price changes, historical exploration success, licensing policies, seismic surveys, depletion, and technological progress.

In terms of results, the preferred econometric models suggest that reserve-generation from exploration is influenced by variables of economics, regulation, technology, and geology. In the short-term, drilling success has a temporary feedback effect on subsequent drilling activity and reserve additions. Licensing policies has a potential to stimulate efforts and efficiency of exploration, with somewhat higher impact in the short term than in the longer term, according to the results. Moreover, accelerating seismic surveying activities have had a positive influence on exploration success, which may be seen as a reflection of the importance of technological progress in the oil exploration process. Finally, the results also suggest that an increase in the oil price has a positive effect on both efforts and efficiency in oil exploration. The estimated model provides a strong indication that the companies' appetite for exploration risk is increasing in the oil price. Specifically, an oil price increase has a negative effect on average success rates, but a positive effect on average discovery size. Still, the net effect is an increase in yield per effort. Consequently, the results for oil price effects suggest a pro-cyclical pattern not only for exploration drilling, but also for exploration risk and reserve additions.

The paper is organised as follows. Section 2 gives a brief overview of previous literature on exploration productivity. A simple model of exploration

is outlined in Section 3, before the econometric model is specified in Section 4. The data set is presented in Section 5, before econometric results are outlined and discussed in Section 6. Concluding remarks are offered in Section 7.

2. Previous research

The combination of geological and economic variables in empirical models of exploration dates back some 40 years. Fisher (1964) opened this field of research with his seminal econometric studies of US oil and gas exploration, estimating equations for the drilling rate, success rate and the discovery rate for different US Petroleum Administration Defence Districts (PADD) over the period 1946-1955.[2] Explanatory variables included oil prices, seismic crews and proxy variables for drilling costs. Based on extended versions of the same data set, refined updates of the Fisher framework were presented in a range of papers for the US oil and gas industry over the following 15 years (e.g., Erickson and Spann, 1971; Pindyck 1974, 1978; Kolb, 1979). Gradual improvements were due to improved data availability, more sophisticated modelling and additional explanatory variables.

Into the 1990s, some studies also emerge for the exploration and production of oil and natural gas on the United Kingdom Continental Shelf (UKCS; e.g., Pesaran, 1990; Favero and Pesaran , 1994). These models depart from an integrated, dynamic optimisation problem, and produced plausible econometric equations for exploration, development and production. However, their explanations of exploration efficiency are quite simple, and they also fail to establish robust estimates in support of inter-temporal maximisation. Later studies, especially for the US oil and gas industry, have therefore relaxed the assumption of inter-temporal behaviour, and several have returned to the period-by-period optimisation approach (e.g., Iledare and Pulsipher, 1999; Farzin, 2001). Implicitly, this behavioural assumption is also adopted by Ringlund et al. (2007). Still, their econometric specification of

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[2] A requirement for theory-based econometric research on the oil and gas industry is that the data set is generated in an industrial environment mainly guided by commercial principles. Further, the quality of the data will usually increase, the longer the history of the actual activity. This explains why most of the work that has been done on the application of economic theory to observed exploration behaviour is based on data from USA.

oilrig activity for a panel of non-OPEC countries is indeed dynamic. The present study follows a similar line of thought[3].

Empirical exploration models for the US oil and gas industry are surveyed by Dahl and Duggan (1998), who conclude that acceptable models have been obtained for drilling efforts, with long-term oil price elasticities above one. On the other hand, Dahl and Duggan recommend that more work should be done on drilling efficiency. The role of the oil price and technological change is especially interesting in this respect, as a role for these variables would open for policy implications beyond the stimulation of drilling efforts. Iledare (1995) include exploration efficiency (yield per drilling effort) in a two-equation system of reserve generation. However, economic variables are restricted to the drilling equation in his model, with no effects from the oil price on yield per effort. Kemp and Kasim (2006) estimate a system of equations for the exploration process based on data for five regions on the United Kingdom Continental Shelf (UKCS), and also do not include oil price variables in the equations for the discovery process. As oil companies adapt their exploration strategies according to changes in economic and financial conditions, recordings of exploration efficiency will also reflect oil price changes. To some extent, this point is acknowledged by Iledare and Pulsipher (1999), who estimate drilling effort and efficiency in onshore gas exploration in Lousiana (USA). In their estimated equation for drilling efficiency, the oil price takes a negative coefficient, and the authors suggest that the reason is a negative link between the oil price and average discovery size. However, without a split of exploration efficiency between the discovery rate and average discovery size, such an assertion remains conjectural.

Learning-by-doing and technological advances play an important role in the exploration process (e.g., Quyen, 1991; Hendricks and Porter, 1996). However, finding variables to identify these effects precisely remains an unresolved issue. A key problem is that variables that capture technological progress tend to move monotonically over time, and therefore correlate with indicators of maturation and depletion. Moreover, the explanatory content of trending explanatory variables may also be mixed. As an example, cumulative drilling may be seen both as an indicator of accumulated knowledge (Uhler, 1979; Iledare, 1995), and a measure of depletion (e. g., Pesaran, 1990). Thus, a statistically significant time trend, as well as any other trending variable may combine the information of different (opposing) effects. These

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[3] To test the validity of this assumption, a variety of interest rate variables were included in preliminary estimations. However, plausible and robust estimates could not be established for any of their coefficients.

challenges are hardly overcome by the recent studies of success rates in US oil and gas exploration by Forbes and Zampelli (2002, 2002), who suggest the use of annual time dummies to assess theimpact of technology change. A more promising attempt is offered by Managi et al. (2005), who construct an exploration-specific index of technology diffusion for their econometric studies of yield per effort in GoM exploration. A natural extension of this approach is to study the impact of specific technologies through special variables. Still, Forbes and Zampelli (2000, 2002) and Managi et al. (2005) limit their scope to exploration efficiency. 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. The modelling approach of the present study represents an indicative step in this direction.

3. A simple model of exploration behaviour

The reserve concept is a key characteristic of the production technology in the oil and gas industry. Oil companies invest in risky exploration activities to grow their reserve base, a critical requirement to sustain production over the longer term. Over the last years, markets have developed for oil and gas reserves, license shares and other petroleum assets. The implication is that exploration decisions do not necessarily require future development and production. Rather, any discovery may well be evaluated on its own merit, and a range of strategies is available for value optimisation. Oil exploration may therefore be studied as a distinct profit-generating activity among oil companies.

A simple model for oil exploration may therefore be based on the technology structure of reserve-generation. With gross reserve additions *(R)* as the output of the exploration process, the point of departure for our theoretical model is a well-behaved neo-classical production function $R = F(L, X, H, t)$, where *L* represents variable inputs, *X* represents fixed inputs and state variables, *H* is an indicator for the depletion of exploration opportunities, and *t* is an index of technological progress, usually represented by a simple time trend. Both the efficiency of this process and the accumulation of oil and gas reserves contribute significantly to the value of the firm. Consequently, oil companies maximise profits from reserve generation subject to output prices, input prices, and constraints relating to policy regulations and technology.

Under these assumptions, a restricted profit function (**P**( )) of reserve generation may be derived from a representative oil company's profit maximisation problem:

$$\Pi = \Pi(P, W, X, H, t) = \max_{R, L} \{P \cdot R - W \cdot L\}$$

$$s.t.\ F(L, X, H, t) \geq R\ ,$$

[1]

where P is the marginal value of new oil and gas reserves[4] and W represents traditional input prices. Previous literature suggests that the role of traditional inputs is dominated by other factors in the process of oil and gas exploration (e.g., Dahl and Duggan, 1998).

More sophisticated models of capital inputs normally involve explicit dynamic behaviour in terms of intertemporal profit maximisation. However, the assumption of period-by-period optimisation is justified on several grounds. First, this kind of myopic behaviour is well supported by previous studies of exploration behaviour, whereas the hypothesis of dynamic optimisation is not. In an econometric study of US oil and gas supply, Farzin (1986) obtains estimates for the discount rate among 33.4 per cent, implying a time horizon of approx. 4 years for their extraction decisions. Another example is a study of exploration and production in the United Kingdom by Pesaran (1990), where present-value maximisation is also not supported by the data. Second, the reserve definition of my study requires that recovery is highly likely at current economic and operating conditions. This definition implies a higher degree of flexibility than geological definition of reserves, and the deviation between the two concepts is determined by continuous development in variables relating to economics, policy and technology. Third, the hypothesis of discretionary profit-maximisation does not entirely exclude the idea of dynamic optimisation. As pointed out by Farzin (2001), period-by-period maximisation may rather be seen as a special case, whereby the flow of future profits is expected to grow at a rate below the discount rate.

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[4] The price of crude oil serves as a proxy in this respect. Following Iledare (1995), econometric tests have been performed for a variety of more sophisticated unit cash-flow variables, including a variety of adaptive expectations hypotheses for the oil price. These variables are typically put together in relations like: $V^e = P^e(1\text{-}c)(1\text{-}t)$, where V^e is a proxy for the expected marginal value of reserves, P^e is the expected oil price, c is a unit cost variable and t is a corresponding unit tax. However, none of the measures that incorporate various types of adaptive price expectations, unit costs and tax payments were able to outperform the simple oil price variable in the estimated models. The outlined plain formulation is therefore maintained.

A few theoretical studies of oil exploration have been occupied with human capital and learning-by-doing. Quyen (1991) stresses that the discovery of new reserves is only one of the motives of oil exploration. In addition, exploration drilling will reveal information and insights that may prove useful for future exploration activities.[5] These learning-by-doing mechanisms are linked to key personnel in the exploration process. At the same time, the information revealed through drilling efforts has a potential value for both partners and competitors in the actual exploration area. Hendricks and Porter (1996) apply a game-theoretical modelling framework to analyse how information externalities and potential free-riding affect the optimal timing of drilling decisions. As expected gains from drilling have to be balanced against expected gains from waiting for drilling information in neighbouring areas, the result is a war of attrition, giving rise to U-shaped patterns of drilling activity in each tract. Strategic interaction also provides an important role for human resources in the exploration process. Still, a clear role for labour and labour costs in models of exploration behaviour is yet to be established (Dahl and Duggan, 1998).

The simple theoretical model of this paper it therefore assumes that costs associated with capital and labour stem from a standby capacity, and that they are insensitive to fluctuations in exploration activity from one year to another.[6] The implication is that the portfolio of exploration activities is subject to discretionary evaluation and adjustment from year to year, based market developments and other changes in the opportunity set – given a fixed capacity of capital and labour. Consequently, variable inputs (L) and their prices (W) are disregarded in the further development of our model.

To approach the empirical specification, we now assume the following multiplicative form for the profit function in Equation [1]:

$$\Pi(P, X, H, t) = K^{*} P^{a^{*}} \prod_{i=1}^{n} X_{i}^{q_{i}} e^{gH + dt},$$ [2]

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[5] A popular analogy is found in the classic board game "Battleship". In the early phases of the game, with many ships on the board, expected rewards from bombing are high, with major learning effects involved whenever a new ship is hit. However, expected marginal gains, as well as the learning effects, drop towards the end of the game, when the majority of ships have been sunk.

[6] Wage and interest rate variables were included in preliminary stages of the estimation process. However, based on statistical evaluation, none of these variables could justify a position in the preferred empirical models.

where K is a constant term, and $\boldsymbol{a}^*$ and $\boldsymbol{q}_i^*$ represent elasticities of profit with respect to the oil price (P) and state and policy variables (X_i), respectively. With a negative coefficient for $\boldsymbol{g}$, the specified mechanism implies an exponential decline in the exploration opportunity set. As found by Iledare (1995), this physical rate of decline could potentially be offset by technological progress, captured in Equation [2] by the simple time trend t. Hotelling's lemma may no be applied to the restricted profit function in Equation [2] to derive the optimal supply schedule for gross reserve additions. Specifically, differentiation in Equation [2] with respect to the marginal value of new reserves (P_t) yields:

$$\frac{\partial \Pi(P,X)}{\partial P} = R^*(P,X,H,t) = KP^{\boldsymbol{a}} \prod_i X_i^{\boldsymbol{q}_i} e^{\boldsymbol{g}H + \boldsymbol{d}t}, \qquad [3]$$

where $K = K\boldsymbol{a}^*$ and $\boldsymbol{a} = \boldsymbol{a}^*\text{-}1$. An asterisk is added to R^* to distinguish desired reserve requirement from the observed level. Equation [3] may be interpreted in terms of optimal supply, and establishes a theoretically consistent relationship between reserve generation on the one hand and the oil price and various state variables on the other, derived directly from the company's profit maximisation problem.[7] Positive changes to the marginal value of reserves (P) are expected to stimulate reserve additions and exploration efforts. The marginal impact of changes to the state variables (X) will depend on the specific nature of these variables. The depletion mechanism (H) is expected to have a dampening effect on reserve-generation, partially offset by technological progress (t).

In a number of previous empirical studies of exploration behaviour, oil price effects are confined to drilling activities, whereas success rates and discovery size are determined by physical variables (e. g., Pesaran, 1990; Iledare, 1995; Kemp and Kasim, 2002, 2006). However, there is reason to believe that oil price fluctuation has a direct effect also on the productivity of the exploration process, as suggested by equations [10] and [11] (see also Iledare and Pulsipher, 1999; Forbes and Zampelli, 2000). Decision-makers in the oil companies face a set of exploration opportunities which is subject to continuous shocks, due to market developments, changes in regulations, new information, and technological innovations. Consequently, the portfolio of

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[7] The equivalent dual approach is to depart from the cost-minimisation problem of exploration activities, and derive a similar relation from the corresponding first-order conditions, whereby the marginal value of gross reserve generation is equated to its marginal cost (e. g., Farzin, 2001).

exploration activities requires continuous evaluation and management. The outcome of this balancing act is a dynamic exploration strategy. Moreover, any established combination of drilling activities will yield a certain expected finding rate, a particular distribution of discovery size, and ultimately, a specific rate of reserve additions.

For these reasons, the data we observe for efforts and efficiency in oil exploration are a result of simultaneous decisions in each company. To grasp the complexity of the exploration process, we need a model that takes explicit account of both the breakdown of reserve-generation and the simultaneity between its components. We therefore apply the useful decomposition introduced by Fisher (1964), whereby gross reserve additions (R) may be seen as the product of the rate of drilling activity (D), the success rate (S), and average discovery size (M):

$$R(P, X, H, t) = D(P, X, H, t) \cdot S(P, X, H, t) \cdot M(P, X, H, t) \quad [4]$$

Potentially, the oil price (P) and the vector of state variables (X) may influence the growth of oil and gas reserves via each of these three components, and an integrated model should provide a portrayal of each of these variables. Equation [4] implies a relationship like Equation [3] for each of the components of gross reserve generation:

$$D^*(P, X, H, t) = K^d P^{a^d} \prod_i X_i^{q_i^d} e^{g^d H + d^d t}, \quad [5]$$

$$S^*(P, X, H, t) = K^s P^{a^s} \prod_i X_i^{q_i^s} e^{g^s H + d^s t}, \quad [6]$$

$$M^*(P, X, H, t) = K^m P^{a^m} \prod_i X_i^{q_i^m} e^{g^m H + d^m t}, \quad [7]$$

where superscripts d, s, and m is introduced to separate coefficients accociated with drilling efforts (d) from the corresponding coefficients of the drilling success (s) and discovery size (m) equations, respectively. With small-caps for natural logs, gross reserve-generation can now be represented by the following sum:

$$r(p, x, H, t) = d(p, x, H, t) + s(p, x, H, t) + m(p, x, H, t) \quad [8]$$

where:

$$d^*(p, x, H, t) = k^d + \boldsymbol{a}^d p + \sum_{i=1}^{n} \boldsymbol{q}_i^d x_i + \boldsymbol{g}^d H + \boldsymbol{d}^d t, \qquad [9]$$

$$s^*(p, x, H, t) = k^s + \boldsymbol{a}^s p + \sum_{i=1}^{n} \boldsymbol{q}_i^s x_i + \boldsymbol{g}^s H + \boldsymbol{d}^s t, \qquad [10]$$

$$m^*(p, x, H, t) = k^m + \boldsymbol{a}^m p + \sum_{i=1}^{n} \boldsymbol{q}_i^m x_i + \boldsymbol{g}^m H + \boldsymbol{d}^m t. \qquad [11]$$

Consequently, the elasticity of reserve additions (R_t) with respect to the different explanatory variables may now be studied as the sum of three partial elasticities. With small caps as natural logarithms, this implies for the oil price elasticity ($\boldsymbol{e}_p$):

$$\boldsymbol{e}_p \equiv \frac{\Delta R(P, X, t)}{\Delta P} \cdot \frac{P}{R} = \frac{\Delta r}{\Delta p} = \frac{\partial d}{\partial p} + \frac{\partial s}{\partial p} + \frac{\partial m}{\partial p}. = \boldsymbol{a}^d + \boldsymbol{a}^s + \boldsymbol{a}^m \quad [12]$$

Corresponding relations apply for the vector of state variables ($\boldsymbol{e}_{x_i} = \boldsymbol{q}_i^d + \boldsymbol{q}_i^s + \boldsymbol{q}_i^m$), and for the semi-elasticities associated with depletion ($\boldsymbol{e}_H = \boldsymbol{g}^d + \boldsymbol{g}^s + \boldsymbol{g}^m$) and technological progress ($\boldsymbol{e}_t = \boldsymbol{d}^d + \boldsymbol{d}^s + \boldsymbol{d}^m$).

This integrated approach to the exploration process should be fruitful both for industry leaders and policy-makers. As an example, consider the influence on the exploration process from an increase in the oil price. An oil price increase is likely to stimulate drilling efforts. However, if the general risk inclination in the industry is affected by the oil price, an oil price increase may also induce oil and gas companies to take on higher exploration risk. This could imply a selection of more risky exploration wells, a potential reduction in discovery rates, and an increase in average discovery size. In turn, these processes could very well influence on subsequent drilling efforts. The outcome in terms of reserve generation is unclear. However, the involved effects may be addressed explicitly within the outlined model specification.

We now proceed to an econometric specification that expands the modelling approach even further, to take account of potential interaction between the three components of reserve-generation, as well as sluggishness and dynamics in the underlying data-generating process.

4. The vector error-correction model

Drilling efforts (D_t), drilling success (S_t) and average discovery size (M_t) are the endogenous variables of our model. I propose an econometric specification that meets requirements of tractable estimation, takes proper account of the dynamics of the data-generating process, and appreciates the simultaneity of efforts and efficiency in oil and gas exploration.

From the oil companies' point of view, the set of available exploration opportunities is subject to constant change in external conditions. Examples include oil price shocks, changes in regulations, new information, and technological advances. Managers respond to these changes through a continuous management of their exploration portfolio. The presence of price expectations and/or adjustment lags in the impact of the explanatory variables may also cause deviation between the actual level of reserve generation and the desired level. More specifically, the process of oil exploration may be disturbed by contractual obligations, leads and lags in the development of new technology, uncertainty about future prices, as well as regulatory constraints and other economic, psychological, and technological factors. Thus, the data-generating process may well be characterised by sluggishness and dynamics, even if the data is not the result of a dynamic optimisation procedure.

With annual time series, the variables of my model are also likely to be non-stationary. Moreover, their linear combination may also be non-stationary. In that case, direct estimation of regressions on variable levels yields inefficient coefficient estimates, threatening the validity of statistical inference. Simple estimation in the levels of the variables will also fail to describe the dynamics of the data-generating process. However, if the variables are integrated of degree 1 ($I(1)$), their difference will be stationary: $y_t \sim I(1) \implies \Delta y_t \sim I(0)$. A corollary from the literature on co-integration is that a linear combination of co-integrated non-stationary variables will produce a stationary error-term. A pioneering reference to this literature is Engle and Granger (1987), who also demonstrate that any set of co-integrated variables has a valid error-correction specification.[8] The point of departure for the econometric specification is given by the following system of dynamic equations:

$$y_t = \sum_{i=1}^{n} f_i y_{t-i} + \sum_{j=0}^{n} q_j x_{t-j} + u_t \qquad [6]$$

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[8] Hendry and Juselius (2000, 2001) provide a modern introduction to the econometrics of co-integration and error-correction models.

where $y_t = [\ d_t,\ s_t,\ m_t\ ]´$ is the vector of endogenous variables and $x_t = [\ p_t,\ e_t,\ z_t,\ H_t,\ t\ ]´$ is the vector of explanatory variables, including the oil price (p_t), the depletion indicator (H_t) and the technology index (t) for simplicity of exposition. Other explanatory variables include a variable for licensed exploration acreage (e_t) at the beginning of year t, a measure of seismic surveying activity (z_t), and a proxy for maturation/depletion (H_t). All these variables will be explained in further detail below. Lag coefficients on endogenous variables and exogenous variables are given by the f_i and q_j matrices, respectively. Finally, u_t is a *3x1* vector of white-noise residuals. If the variables of Equation [13] are co-integrated, both the dynamics and the underlying structure of its data-generating process may be estimated in a vector error-correction model (VECM) with *n* lags:

$$\Delta y_t = \sum_{i=1}^{n-1} a_i \Delta y_{t-i} + \sum_{i=0}^{n-1} b_i \Delta x_{t-j} + l\, y_{t-1} + d\, x_{t-1} + u_t \ , \qquad [14]$$

where a_i are *3x3* matrices of short-term coefficients from lagged changes in endogenous variables, and the b_i matrices contain short-term coefficients from other explanatory variables. The *3x3* matrix of error-correction coefficients is given by the *3x3* l matrix, whereas persistent effects from the explanatory variables are represented by the *3x5* d matrix. Equation [14] contains a large number of variables and coefficients, with high requirements for the data set. Our application is based on annual time series data from 1969-2004 (*n = 36*), and the modelling ambitions will have to be adjusted accordingly. With one lag and five exogenous variables the following model version is the starting point for our econometric application:[9]

$$\Delta y_t = a\Delta y_{t-1} + b\Delta x_{t-1} + l\, y_{t-1} + d\, x_{t-1} + u_t \qquad [15]$$

With variables in natural logs, the coefficients of Equation [15] can be interpreted in terms of short-term and long-term elasticities. More specifically, the b vector contains short-term elasticities of drilling efforts, discovery rates and average discovery size with respect to the explanatory variables of the model. In the long run, all change variables in Equation [14] approach zero. This property can be utilised to bring out the long-term

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[9] Contemporaneous changes in the explanatory variables were also evaluated in the process of estimation. However, based on statistical inference, a position could not be justified for any of these variables in the preferred model. For simplicity of exposition, they are therefore left out in Equation [15].

parameters (q) directly from the estimated error-correction model (Bårdsen 1989). Eliminating all changes and solving for the dependent variables, the matrix of long-run coefficients can be derived as: $q = -l^{-1}d$.

Following Equation [4], total elasticities of reserve generation are computed as the sum of partial elasticities, both for short-run (temporary) effects and for long-term (persistent) effects. Let e_j^s , e_j^l represent total elasticities of reserve generation (R_t) wrt. to explanatory variable j in the short run and long run, respectively. This yields:

$$
\begin{aligned}
e_j^s &= b_j^d + b_j^s + b_j^m \quad , \quad j = p, e, z, H, t \\
e_j^l &= q_j^d + q_j^s + q_j^m \quad , \quad j = p, e, z, H, t.
\end{aligned}
\qquad [16]
$$

Where b_j^i and q_j^i represent short-term and long-term effects on variable i from variable j. The calculation of total elasticities of reserve generation gives a systematic account for the interaction between efforts, efficiency, and other explanatory variables in the exploration process.

5. Data set and variables

Time series are retrieved from the data bases of The Norwegian Petroleum Directorate, who has collected and processed information and statistics on Norwegian oil and gas activities since the mid 1960s. Figure 1, Panel 1 illustrates total efforts in terms of exploration wells drilled per year (D_t), along with accumulated number of exploration wells (H_t), a common proxy for the depletion mechanism involved in the exploration process (e. g., Pesaran, 1990; Iledare and Pulsipher, 1999). Annual well-count is a simple and plain activity measure, has an easy interpretation, and agrees well with the selected theoretical specification. A typical feature for the NCS is that no clear ex-ante distinction is made between exploration wells for oil and exploration wells for natural gas. In the present study, the total annual sum of exploration wells therefore serves as the key indicator for exploration efforts. Exploration activity peaked during the 1980s. Over the last 20 years, exploration efforts have stagnated, and so has the number of discoveries.[10]

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[10] Observe that the annual number of discoveries (F_t) is given by the product of annual drilling activity (D_t) and the annual success rate (S_t): $F_t = D_t \cdot S_t$. In a similar fashion, exploration efficiency (G_t), or yield per effort, may be defined as the product of the annual success rate (S_t) and average discovery size (M_t): $G_t = S_t \cdot M_t$.

Figure 1. Key variables of the data set
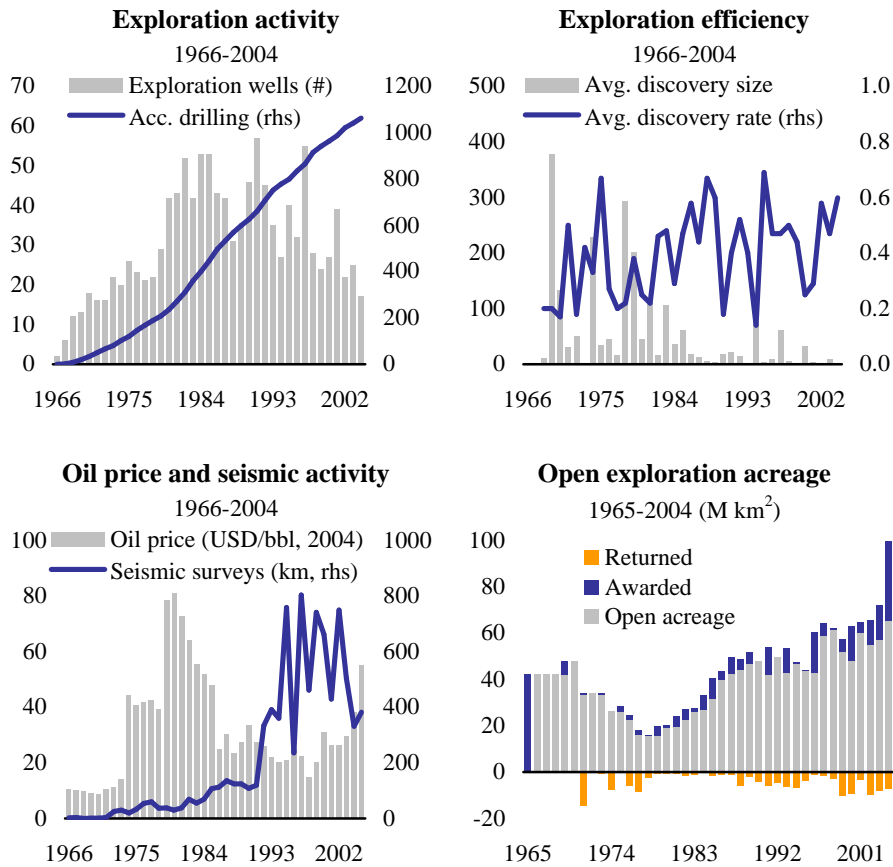
Sources: Oil price: www.EcoWin.com. All other numbers: Norwegian Petroleum Directorate.

Key components of exploration efficiency, the average success rate (S_t) and average discovery size (M_t) are illustrated in Figure 1, Panel 2. The largest discoveries were made between 1969 and 1980, and recent discoveries are miniscule compared to the typical field size of the 1970s. On the other hand, the discovery rate has not come down. This suggests that shortage of opportunity is offset by improved exploration technology and the development of specific geological competence (Forbes and Zampelli 2002, 2002; Managi et al. 2005). As oil and gas companies minimise their costs of reserve generation, the most prospective areas are normally drilled first (e. g., Iledare, 1995). The result is large average discoveries and high reserve growth in the early phases of an oil and gas province. Over time, the pool of undiscovered resources is gradually depleted by exploration activities.

Success rates may be upheld through learning-by-doing and technological progress, but average discovery size will normally fall.

The first exogenous variable is the oil price (P_t). The preferred choice for this study is Brent blend, the standard reference for North Sea crude oil. Preliminary estimations were run on both NOK and USD denominations for the oil price, and the properties of nominal versus the real price have been thoroughly tested. Based on these tests, a real USD denomination is favoured.[11]

Technological progress is captured by a linear time trend. However, the model also includes a variable for the intensity of information gathering and processing, measured by seismic surveying activity.[12] The Z_t variable represents annual seismic activity measured as square kilometres of survey coverage per year. As we see from Figure 1, Panel 3, the Z_t variable has a significant time trend, and therefore correlates with common measures of depletion, which also tend to move monotonically over time. A widely applied indicator of depletion is accumulated drilling activity (e. g., Iledare and Pulsipher 1999; Managi et al. 2005; Kemp and Kasim 2006), illustrated in top left panel of Figure 1.

The right-hand bottom panel of Figure 1 also illustrates how exploration acreage (E_t) has been regulated by the Norwegian Government. Some 42,000 km^2 were awarded in the 1st licensing round in 1965, ahead of the opening of the Norwegian Continental Shelf. Licenses that were handed back to the Government towards the mid 1970s reduced the cumulative open exploration acreage, before a series of licensing rounds added new frontier acreage in the Norwegian Sea and in the Barents Sea from 1980. Licensing policies have also been adjusted over the last few years to spur exploration activity, and large areas were awarded in mature areas and frontier areas both in 2003 and 2004. Descriptive statistics for all model variables are offered in Table 1.

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[11] Statistical inference was the key criteria for this selection. However, I also looked at the explanatory power of the 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 the preferred versions of the model.

[12] Seismic profiles of the underground are acquired by transmitting sound waves from a source above or in the substratum. The sound waves travel through the rock layers which reflect them up to sensors on the sea bed or at the surface, or down in a borehole. This enables an image of formations in the substratum to be formed. The seismic mapping of the Norwegian continental shelf started as early as 1962 (Norwegian Petroleum Directorate, 2005).

Table 1. Descriptive statistics for data sample

Variable	Obs.	Mean	St. dev.	Min.	Max.
D_t	36	27.000	12.89	0	50
S_t	36	0.3575	0.1364	0.09	0.71
M_t	36	53.632	81.385	1.74	335
P_t	36	31.201	19.179	8.8	81.2
E_t	36	38348	14874	0	65335
Z_t	36	213787	249760	48	803936
H_t	36	486.55	367.87	0	1080

Source: Norwegian Petroleum Directorate (*D, S, M, E, Z, H*; http://www.npd.no), ReutersEcowin (*P*; http://www.ecowin.com).

6. Estimation and results

The econometric analysis aims at establishing robust statistical relations for the three endogenous variables of the exploration model, explaining their development over time in terms of dynamic interaction and influence from explanatory variables.i[13] As described by Equation [14], changes in drilling efforts ($\boldsymbol{D}d_t$), discovery rates ($\boldsymbol{D}s_t$) and average discovery size ($\boldsymbol{D}m_t$) are regressed against both the changes and the lagged levels of the dependent (d_{t-1}, s_{t-1}, m_{t-1}) and independent variables (p_{t-1}, e_{t-1}, z_{t-1}, H_{t-1}, t). The error-correction approach allows a separation between short-term effects, and long-term impact from the explanatory variables. Further, the error-correction model provides explicit estimates for the interlinked adjustment pattern of the data-generating process. Due to excessive volatility in drilling rates, discovery

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[13]The size of my data set suggests that a simpler model with one or two equations might involve gains both in terms of economic explanation and not least in terms of statistical quality. Consequently, my estimations were supplemented with a corresponding single-equation ECM model for gross-reserve growth (R_t), as well as a two-equation VECM model for efforts (D_t) on the one hand and efficiency ($G_t = S_t M_t$) on the other. However, none of these alternative specifications of gross reserve growth offers an explanation that could be preferred to the presented three-equation model. Rather, these simpler specifications show weaker econometric performance, and seem to blur the behavioural detail and complexity of the exploration process.

rates, and average discovery size (cf. Figure 2), the estimated models are based on three-year moving averages for the endogenous variables. All estimation procedures are performed with the full-information maximum likelihood procedures for dynamic VAR models, as implemented in PcGive 10 (Dornik and Hendry 2001).

A requirement for our econometric model specification is that the variables are non-stationary, and integrated of the same order. We therefore stop for a moment to investigate the stationarity properties of the model variables. Augmented Dickey-Fuller tests, Dickey-Fuller generalised least squares tests, and Phillips-Perron tests are carried out for all model variables, and their results are presented in Appendix 1. Non-stationarity is rejected in only 2 out of 21 cases, and we therefore conclude that the variables of our model are indeed non-stationary. To rule out higher order integration, the same battery of tests is run on the *changes* of our model variables. Non-stationarity in the changes of the variables is rejected for 19 out of 21 cases. Consequently, we base our subsequent analysis on the presumption that the variables contain a unit root, and specify the exploration process as a model of three simultaneous error-correction equations.

The estimation procedure draws on the general-to-specific approach (Hendry 1995). The starting point of this procedure is a full version of the econometric model, including the full set of variables and lags. A sequential reduction is then pursued, whereby parameter estimates are eliminated one by one, based on statistical significance and their contribution to the general quality of the model. However, the present data set calls for modification, as a full-fledged version of Equation [14] would exhaust the degrees of freedom. Starting with the error-correction matrix ($\mathbf{1}$), the various coefficient matrices have therefore been exposed to estimation, testing, and reduction in a sequential procedure.[14] The result was a reduced version of Equation [14], with a narrow set of significant parameters and favourable econometric properties. To control for potential interaction between groups of variables, each of the previously removed variables were re-entered one by one in the final parsimonious model, to verify that they really had no significant role to play in the preferred model.

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[14] For the nested models in each of these stages, elimination of variables was based on consistently calculated confidence levels. Each of the stages in the reduction procedure was also monitored and estimation results were recorded for progress appraisal. Improvement in model quality was evaluated through the log-likelihood, as well as the Schwartz, Hanna-Quinn, and Akaike information criteria.

The result of this process is a parsimonious preferred model, represented by the following three estimated equations:

$$\Delta \hat{d}_t = \underset{(0.02)}{0.24^{**}} \Delta d_{t-1} + \underset{(0.02)}{0.28^{**}} \Delta s_{t-1} + \underset{(0.05)}{0.26^{**}} \Delta e_{t-2}$$
$$- \underset{(0.00)}{0.21^{***}} d_{t-1} - \underset{(0.04)}{0.16^{**}} s_{t-1} + \underset{(0.06)}{0.08^{*}} p_{t-1} + \underset{(0.10)}{0.03^{*}} e_{t-2} \qquad [17]$$

$$\Delta \hat{s}_t = -\underset{(0.00)}{1.19^{***}} + \underset{(0.05)}{0.33^{**}} \Delta e_{t-2} + \underset{(0.01)}{0.11^{***}} \Delta z_{t-1}$$
$$- \underset{(0.01)}{0.37^{***}} s_{t-1} + \underset{(0.16)}{0.05} m_{t-1} - \underset{(0.06)}{0.09^{*}} p_{t-1} + \underset{(0.00)}{0.08^{***}} z_{t-1} \qquad [18]$$

$$\Delta \hat{m}_t = -\underset{(0.00)}{0.73^{***}} m_{t-1} + \underset{(0.05)}{0.40^{**}} p_{t-1} + \underset{(0.01)}{0.21^{**}} e_{t-2} - \underset{(0.00)}{0.91^{***}} H_t \qquad [19]$$

*) Significant at 90, **) 95 and ***) 99 per cent confidence level, respectively.
  p-values in brackets.

The estimated system of equations passes the usual specification tests for autocorrelated residuals (LM test statistic: 0.84; p-value = 0.65), normality of residuals (LM test statistic: 9.65; p-value = 0.14), and heteroskedasticity (F test statistic: 0.38; p-value = 1.00).[15] Estimated parameters take plausible values and signs. Note that the error-correction coefficients are negative and highly significant for all the three equations. This is also an indication for co-integration (Kremers, Ericsson and Dolado 1992), and therefore supports our VECM specification.

Short-term dynamics play a modest role in the exploration process, with an exception for drilling activity (d_t). Long-run oil price effects are significant in all three equations, but not in the short run. New exploration acreage ($\mathbf{D}e_{t-1}$) largely has a temporary effect on drilling efforts (d_t) and success rates (s_t), whereas the impact on average discovery size (m_t) is persistent. Moreover, drilling efforts seem insensitive to changes in average discovery size. On the other hand, an increase in average discovery size has a weak positive effect on subsequent success rates.[16]

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[15] See Dornik and Hendry (2001) for theoretical background and specific procedures for standard specification tests and model diagnostics in PCGive 10. More detailed specification tests are presented in Appendix 2.
[16] With a p-value of 0.16, the coefficient on m_{t-1} in Equation [18] is barely significant in statistical terms. However, the variable is still retained in the preferred model to accommodate

Changes in the oil price ($\boldsymbol{D}p_{t-1}$) have no short-term effect on either of the three components of reserve generation, according to the results. On the other hand, licensing rounds ($\boldsymbol{D}e_{t-1}$) exert a significant short-term impetus to drilling efforts (0.26), to the discovery rate (0.33), and thereby also to reserve generation. Following Equation [17], the short term elasticity of reserve generation with respect to new acreage (e_e^s) can be computed to 0.68 (p-value < 0.00). This suggests an effective role for licensing policies in the short-term.[17] Finally, an increase in seismic surveying activity ($\boldsymbol{D}z_{t-1}$) has a modest, instant effect on the finding rate (s_t), but no effect on drilling activity (d_t) or average discovery size (m_t).

Observe also that the estimated drilling equation implies a significant temporary impulse from historical drilling success. As the number of discoveries (F_t) is the product of drilling efforts (D_t) and the success rate (S_t), the impact on drilling from historical exploration success can be caluculated as the sum of the two relevant short-term elasticities. For the short-term elasticity of drilling (D_t) with respect to lagged exploration success (F_{t-1}), this yields: 0.23 + 0.28 = 0.51 (p < 0.00). A temporary feedback from exploration success on subsequent drilling efforts and reserve additions is in accordance with previous results by Mohn and Osmundsen (2008).

Based on the theoretical model specification, a time trend was entered in preliminary estimations, to allow for technological progress. However, this variable could not be retained in the preferred system of estimated equations. Technological progress plays a potentially important role in the exploration process. However, the exact identification of the empirical effects remains an unresolved issue (e. g., Forbes and Zampelli, 2000, 2002; Managi et al. 2005). The reason is that variables that capture technological progress tend to move monotonically over time, and therefore correlate with indicators of maturation and depletion.

In the presented model, there is reason to believe that technological progress is captured by the variable for seismic surveying activity (Z_t). Costs of seismic surveying activity have collapsed over the 40-year history of the Norwegian Continental Shelf. Previous simple and costly methods have gradually been replaced by modern technologies for the collection and processing of

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our hypothesis of three co-integrating vectors, as indicated by preliminary tests of cointegration rank performed on the full set of time series variables.

[17] Historically, access to exploration acreage on the Norwegian Continental Shelf has been subject to strict regulations and gradual opening of new areas. See Ministry of Petroleum and Energy (2005) and Norwegian Petroleum Directorate (2005) for details.

enormous amounts of geological information. As we see from Equation [18], these activities have a positive and highly significant effect on the success rate in NCS oil and gas exploration.

On the other hand, the results do suggest a significant role for the depletion mechanism. As we see from Equations [17]-[19], the depletion indicator (H_t) is retained only for the field-size equation. As drilling activities cumulate, average discovery size tends down. This follows from an exploration behaviour whereby prospects with high reserve potential are drilled first. Moreover, this part of the results also indicates that the most important role for the depletion mechanism in NCS oil and gas exploration relates to exploration success, and not to drilling efforts. At this point, the results differ from the greater part of previous research on drilling activity (e. g., Dahl and Duggan, 1998; Mohn and Osmundsen, 2008).

One possible explanation for this result relates to differences in modelling approach. Previous studies have typically focused on single-equation models of drilling activity, whereas the present study captures effort and efficiency in a simultaneous model. Another possible explanation may be due to institutional differences between the NCS and other more market-oriented petroleum provinces. Specifically, the gradual opening and strict regulation of exploration activities on the NCS may act as a disturbing factor for the structural depletion mechanism observed in other less regulated petroleum provinces. Finally, depletion mechanisms may also be picked up by the increase over time in the success rate (s_t), which again exerts a negative influence on drilling efforts, according to the results.

Persistent effects on the three components of reserve generation from the exogenous variables are defined by the co-integrating vectors of the estimated system, and correspond directly to the long-term elasticities presented in Table 3. Partial and total effects are also illustrated in Figure 2. Following Equation [16], significance tests for the long-term parameters are computed by testing the validity of equivalent general restrictions on the estimated system. The first line of Table 3 contains a summary of estimated oil price elasticities (Appendix accounts for the derivation). The oil price exerts a persistent influence on all the three components of reserve generation in the exploration process (D_t, S_t, and M_t). As illustrated by Equation [17], the total elasticity of reserve generation with respect to the oil price is given by the sum of the three partial elasticities. The results imply that an oil price increase

of 1 per cent will produce an increase in annual reserve additions by 0.89 per cent in the long term.[18]

Table 3. Long-term elasticities of reserve-generation

	Reserve generation (R)	Exploration drilling (D)	Success rate (S)	Field size (M)
Oil price (P)	0.89[***] (0.00)	0.51[***] (0.00)	-0.17[*] (0.10)	0.55[**] (0.02)
Licensed acreage (E)	0.44[***] (0.00)	0.11 (0.16)	0.04 (0.28)	0.29[***] (0.00)
Seismic surveys (Z)	0.05 (0.62)	-0.16 (0.16)	0.22[***] (0.00)	
Depletion (H)	-1.29[***] (0.00)	0.13 (0.35)	-0.17 (0.26)	-1.25[***] (0.00)

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively. p-values in brackets.
[a] Semi-elasticity: percentage change in dependent variable from absolute change in depletion indicator.

However, Table 3 and Figure 2 also illustrate that the oil price effect varies distinctly across the three equations. Obviously, drilling efforts are invigorated by oil price increases, although the effect is quite modest.[19] On the other hand, discovery rates are suppressed when the oil price increases.

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[18] Recent trends in oil and gas exploration activity indicate that companies respond swiftly to any oil price drop, whereas the reaction to an oil price increase is more sluggish. This suggests the presence of asymmetries in oil and gas exploration behaviour, feeding into oil and gas supply (e. g., Kaufmann and Cleveland, 2001). Previous econometric applications include studies of price transmissions in commodity markets (e. g., Meyer and von Cramon-Taubadel, 2004; Grasso and Manera, 2006). Due to the limitation of the present data set, these ideas are left for future research.

[19] Surveying econometric studies of US exploration activity, Dahl and Duggan (1997) find the average corresponding elasticity to exceed one. However, our results resemble previous studies of the Norwegian Continental Shelf (Mohn and Osmundsen, 2008) and also compare well to international assessments of exploration drilling activity (Ringlund et al., 2007). Both these studies suggest that the oil price elasticity of drilling could vary inversely with the degree of regulation. With high tax protection (78 per cent marginal tax), oil companies tend to shift exploration spending into Norway when the oil price is low, and out of Norway when the oil price is high. This tendency contributes to the explanation of moderate oil price elasticities of exploration drilling on the NCS.

Finally, a positive and highly significant link is established between the oil price and average discovery size. A likely interpretation is that oil companies adjust their portfolio of exploration activities according to changes in economic and financial conditions (Reiss, 1990). In times of high oil prices, high cash-flows and high risk appetite, companies tilt their exploration activities towards risky areas (frontier exploration), with relatively low discovery rates, and with high average discovery size. When oil prices are low, cash flows are constrained, and the risk appetite is more modest, exploration strategies are typically more cautious. Exploration efforts are reduced, and focused in areas with higher discovery rates – and smaller expected field sizes (mature areas).[20]

Figure 2. Decomposed elasticities of reserve generation

Estimated partial and total elasticities by explanatory variable (per cent)
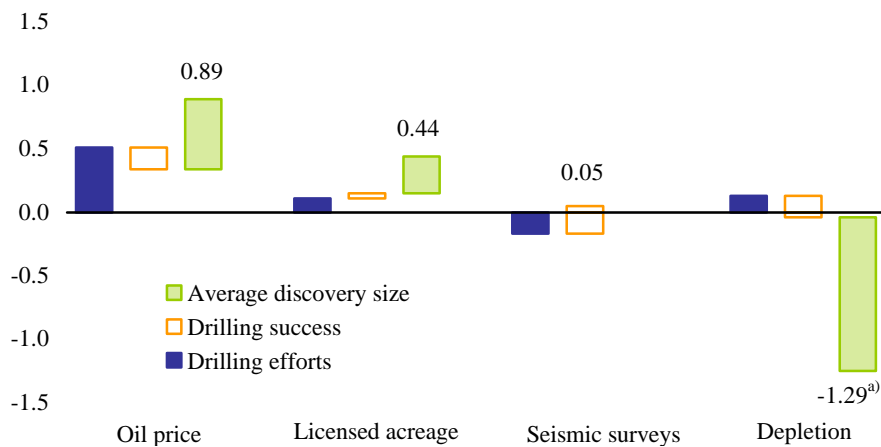
[a)] Semi-elasticity: percentage change in dependent variable from absolute change in depletion indicator.

The second line of Table 3 summarises the role of access to exploration acreage. In the long run, an increase in the amount of available exploration acreage by 1 per cent will produce an increase in annual reserve additions by

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[20] As opposed to frontier exploration areas, mature areas are typically characterized by proven exploration models, producing fields, well-developed infrastructure, transport facilities and market access. Moreover, exploration activities in these areas are usually directed at smaller satellite fields which can be tied back to already producing facilities of larger reservoirs (in decline), without the large investments involved by stand-alone field developments in new oil and gas regions (Norwegian Petroleum Directorate, 2005).

0.44 per cent, according to the results. This effect has two significant sources. First, a modest increase in drilling activity is sustained even in the long-term when new acreage is offered, although the long-term impact is far smaller than the short-term effect. Second, new licensing rounds have a positive effect on average discovery size. With drilling efforts focusing on the most prospective available blocks at any time, it is natural that new licensing rounds will result in higher average discovery size.

7. Conclusion

An accurate understanding of the economics of oil and gas exploration is crucial to provide a complete representation of oil and gas supply. Based on standard assumptions of neoclassical producer behaviour and modern time series econometrics, this study reveals new insights into the process of oil and gas exploration. The estimated model produces plausible and robust estimates for short-term and long-term effects from the oil price, licensing rounds and seismic surveying activity, and provides a full breakdown of the potential sources of growth in oil reserves.

The proposed econometric model provides a framework for specific analysis of exploration behaviour, allowing detailed studies of oil price changes, exploration success, licensing policies, technological progress, and resource depletion. The application on NCS data suggests that material contributions to total resource growth work via exploration efficiency, and that studies of exploration efforts fall short of explaining the full process of reserve generation. The results establish a relation between exploration efficiency, oil price, licensing policies and seismic surveying activity. These insights from a highly regulated oil and gas province are useful both for companies and policy-makers, as oil and gas investment now find their way into new regions, with a higher degree of regulation and government intervention than Western oil and gas companies have been used to.

My results clearly suggest that variables relating to economics, regulation, and technology play an important role for reserve generation through exploration, in addition to the physical process of geological depletion. Specifically, short-term fluctuations in drilling and reserve-generation are influenced by historical exploration success. Moreover, licensing policy also has a potential to affect both drilling activity and success rates in the short-term, but without continuous addition of new acreage, the long-term effects are muffled. The estimated effects for seismic surveying activity on the development of the

success rate also suggest a significant role for technological progress in the model.

According to the preferred econometric model, reserve-generation is enhanced by an increase in the oil price, with a long-term elasticity of 0.89. Both effort and efficiency in oil exploration is stimulated by an oil price increase, according to the results. When the oil price increases, oil companies take on more exploration risk. Consequently, discovery rates will fall whereas the average discovery size will increase. The net effect is an increase in yield per effort. The implication is a pro-cyclical pattern for both exploration risk and reserve-generation.

There are also interesting policy implications to be made. First, our modelling approach clearly illustrates that policy measure need not and should not be limited to the regulation of drilling activity. With reserve additions as the ultimate target, the potential gains from measures to stimulate the success rate or average field size may well exceed the importance of drilling activity. Second, our results suggest that annual reserve additions are procyclical, due to the strong positive link between the oil price and average discovery size. If the government interest is to stabilise reserve growth over time, this result provides a case for countercyclical exploration policies.

A caveat of the present study relates to data sufficiency. The presented application is done on a rather small data set from the Norwegian Continental Shelf. The estimated models provide interesting new insights on the process of oil and gas exploration, but the empirical foundation of the results calls for additional assurance. An appraisal of the usefulness of the proposed modelling framework should therefore await the application of the model to other non-OPEC oil and gas provinces.

A interesting route for further sophistication is to test the symmetry of the various sources of oil and gas resource growth. As an example, we suspect that an oil price drop has a different effect on exploration activity than an equivalent increase, at least in the short term. Corresponding asymmetries may also be relevant for accumulated discoveries and exploration acreage. To develop their base of oil and gas reserves, oil and gas companies balance their drilling efforts between exploration and production drilling. A topic for further research would also be to study how the balance between production and exploration drilling is affected by economic, geological and policy variables – at best in a combined framework of investment behaviour.

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Appendix 1. Stationarity tests for model variables

Augmented Dickey-Fuller tests (ADF), Dickey-Fuller GLS tests (DF GLS), and Phillips-Perron tests (PP).

Levels of variables[*]

	d_t	s_t	m_t	p_t	e_t	z_t	h_t
ADF	-0.16	0.82	-1.06	0.36	0.45	0.83	3.38
DF GLS	-1.01	-3.32[*]	-3.67[*]	-1.59	-1.42	-2.17	-0.56
PP	0.39	-1.29	-1.08	0.36	0.40	0.74	1.20

Changes in variables[*]

	Dd_t	Ds_t	Dm_t	Dp_t	De_t	Dz_t	Dh_t
ADF	-3.1[***]	-4.1[***]	-5.1[***]	-4.3[***]	-3.7[***]	-6.3[***]	-4.7[***]
DF GLS	-3.1[**]	-2.9	-5.2[***]	-4.3[***]	-4.1[***]	-8.3[***]	-1.41
PP	-3.4[***]	-8.0[***]	-6.2[***]	-6.0[***]	-5.8[***]	-9.3[***]	-11.7[***]

Note: 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 (ADF), a regression is run of the differenced variable on its lagged level, as well as its lagged differences (sometimes also with a time trend):

$$\Delta x_t = f_0 + f_1 x_{t-1} + \sum_{j=2}^{n} f_j \Delta x_{t-j} + v_t$$

The unit root test involves a null hypothesis that $f_1 = 0$, against $f_1 < 0$. Non-rejection of the null is an indication that the variable expressed in levels (x_t) is non-stationary. Elliot, Rothenberg and Stock (1996) propose a modified version of the Dickey-Fuller test, based on detrending via generalised least squares (DF GLS), for improved power and precision. The Dickey-Fuller test accounts for serial correlation by use of additional lags of the first-difference variable. Phillips and Perron (1988) introduced a modified variant of this test (PP), whereby a non-parametric correction of the standard errors is applied to capture serial correlation of the above regression.

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
[a] All variables in natural logs; drilling effort (d_t), success rate (s_t), average field size (m_t), real oil price (p_t), licensed exploration acreage (e_t), seismic surveying activity (z_t), depletion indicator (h_t).

Appendix 2. Specification tests and model diagnostics

		Drilling activity d_t	*Success rate* s_t	*Discovery size size* m_t	*Full model* *VECM*
LM (1,2)	*F(*,*)*	2.64* (0.09)	2.92* (0.08)	1.64 (0.22)	0.85 (0.63)
ARCH (1,2)	*F(*,*)*	0.56 (0.58)	1.51 (0.24)	0.35 (0.71)	..
Normality (LM)	*c²(*)*	6.19* (0.05)	0.37 (0.83)	5.64* (0.06)	9.94 (0.13)
Heteroskedasticity	*F(*,*)*	0.39 (0.96)	1.21 (0.47)	0.19 (1.00)	0.38 (1.00)

Note: *LM (1,2)* represents the Lagrange Multiplier test for autocorrelated residuals (Dornik and Hendry 2001), whereby estimated residuals are regressed on original variables and lagged residuals. The null is no autocorrelation. There are weak indications of autocorrelation in the drilling and success rate equations, but not for the systems version (*VECM*) of the test. The second line is the autoregressive conditional heteroskedasticity (*ARCH*) test (Engle, 1982). The present form tests the joint significance of lagged squared residuals in the regression of squared residuals and lagged squared residuals. Again, the null is that the model is well-behaved. The *ARCH* test can not reject the null that the model is ok for any of the equations of the system. The third line is the Lagrange multiplier test for normality of the residuals. This follows the procedure by Doornik and Hansen (1994), and tests whether the skewness and kurtosis of the residuals correspond to those of a normal distribution. Under the null, the residuals comply with the normal distribution. Again, we have indications of non-normality in the drilling and field-size equations. However, normality of the residuals is not rejected for the systems version of the test. The fourth line presents the test for heteroskedasticity proposed by White (1980). An auxiliary regression is involved, whereby the squared residuals are regressed on the original variables and their squares. By rejection, this test implies that the variance of the error process depends on the regressors and their squares. Non-rejection implies that the model is all right. No indications of heteroskedasticity are revealed by this test.

[*)] Significant at 90, [**)] 95 and [***)] 99 per cent confidence level, respectively
[a)] p-values in brackets.

Appendix 3. Long-term elasticities of reserve generation

Letting all changes in Equations [17]-[19] approach zero, and solving for the dependent variables yields the following system of long-term equations:

$$\hat{d}_t = \underset{(0.09)}{-0.76}^* s_t + \underset{(0.01)}{0.38}^{**} p_t + \underset{(0.01)}{0.14}^{**} e_t \qquad [A4.1]$$

$$\hat{s}_t = \underset{(0.26)}{0.14} m_t - \underset{(0.08)}{0.24}^* p_t + \underset{(0.00)}{0.22}^{***} z_t \qquad [A4.2]$$

$$\hat{m}_t = \underset{(0.02)}{0.55}^{**} p_t + \underset{(0.00)}{0.29}^{***} e_t - \underset{(0.00)}{1.25}^{***} H_t \qquad [A4.3]$$

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
  p-values in brackets.

The long-term impact on reserve generation from a change in the oil price is the sum of the impact on each of the three long-term equations (cf Equation [12]). The straightforward solution would be to pick out the oil price coefficients directly from the long-term equations and calculate their sum. However, this approach will neglect the simultaneity of the three equations, and more sophistication is therefore required. As an example, the oil price effect on drilling activities (d_t) will depend not only on the estimated direct oil price effect (0.38), but also on repercussions via the success rate (s_t) and average discovery size (m_t). Accordingly, the overall oil price effect on drilling is calculated as:

$$\frac{\Delta d}{\Delta p} = \frac{\partial d}{\partial p} + \frac{\partial d}{\partial s}\frac{\partial s}{\partial p} + \frac{\partial d}{\partial s}\frac{\partial s}{\partial m}\frac{\partial m}{\partial p} \qquad [A4.4]$$

Applied to the estimated system of long-term equations, this yields:

$$\frac{\Delta d}{\Delta p} = 0.38 - 0.76 \cdot (-0.24) - 0.76 \cdot 0.14 \cdot 0.55 \qquad [A4.5]$$

The result is an estimated long-term oil price elasticity of drilling at 0.48. A restriction that this combined coefficient equals zero is clearly rejected ($p < 0.00$). Consequently, the estimated long-term oil price elasticity of drilling is significant at a 99 per cent confidence level. For the success rate

equation ($\hat{s}_t$), this procedure gives an estimated long-term oil price elasticity at -0.15 (p = 0.13), and 0.69 (p < 0.00) for the field size equation ($\hat{m}_t$). In summary, we now have:

$$\frac{\Delta r}{\Delta p} = \frac{\Delta d}{\Delta p} + \frac{\Delta s}{\Delta p} + \frac{\Delta m}{\Delta p} \;=\; \underset{(0.00)}{0.51^{***}} - \underset{(0.10)}{0.17^{*}} + \underset{(0.02)}{0.55^{***}} = \underset{(0.00)}{0.89^{***}} \quad [A4.6]$$

This is the procedure applied to derive the long-term elasticities of Table 3.

Part 2

Micro-econometric studies of oil and gas investment

Chapter 4

Investment and uncertainty in the international oil and gas industry

By Klaus Mohn and Bård Misund

Abstract[1]

Standard theory of irreversible investments and real options suggests a negative relation between investment and uncertainty. Richer models with compound option structures open for a positive relationship. This paper presents a micro-econometric study of corporate investment and uncertainty in a period of market turbulence and restructuring in the international oil and gas industry. Based on data for 170 companies over the period 1992-2005, we estimate four different specifications of the q model of investment, with robust results for the uncertainty variables. The estimated models suggest that financial market volatility creates a bottleneck for oil and gas investment and production, whereas oil price volatility has a stimulating effect.

JEL classification: C32, G31, L72

K*ey words*: Capital formation, uncertainty, dynamic panel data models.

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1. Introduction

Economic theory is yet to produce a clear-cut conclusion on the sign of the investment-uncertainty relationship. Standard theory of irreversible investment and real waiting options suggest that the relationship is negative (Dixit and Pindyck, 1994). However, recent contributions (e.g., Smit and Trigeorgis, 2004) point out that investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. For the oil and gas industry, increased oil price volatility will increase the value of both these types of real options. Thus, the theory of compound options may give rise to a positive relationship between investment and uncertainty (Kulatilaka and Perotti, 1998; Sarkar, 2000). Empirical studies are therefore required to settle the question.

Our study combines investment theory with modern econometric procedures to test the impact of industry uncertainty and market turbulence on total investment expenditures in the oil and gas industry. Applying modern panel data estimators on a data set covering 170 companies over the period 1992-2005, our approach draws on recent empirical research of the relation between investment and uncertainty.[2] A Q model of investment is derived and augmented with measures for overall risk and industry-specific risk. The inclusion of stock market and oil price volatility in our econometric model produces highly significant parameters, suggesting that Q does not offer the exhaustive prediction of investment implied by theory. Still, our results are unanimous on the sign of the investment uncertainty relationship. General financial market uncertainty seems to be negatively related to investment among the companies in our sample, well in line with theoretical results from the irreversibility literature. On the other hand, industry-specific uncertainty may be under the influence of compound options, as an increase in oil market volatility has a highly significant and positive effect on capital formation in the oil and gas industry.

A growing mistrust developed between oil companies and the capital markets over the 1990s, as the management of the companies had offered inferior investment returns for several years (Antill and Arnott, 2002). Triggered by the temporary oil price collapse in 1998, pressures for operational and financial performance in the short term were coupled with demands for increased dividends to shareholders. A combined result of these developments

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[2] Carruth, Dickerson and Henley (2000) offer a comprehensive survey of the empirical literature on investment and uncertainty. See Bond et al. (2005) for a recent overview of studies based on company data.

was a wave of mergers and acquisitions that erased former prominent independent names such as Elf, Fina, Mobil, Amoco, Arco, YPF, Texaco, Phillips, Lasmo, and Unocal. The international oil and gas industry entered a new stage towards the end of the 1990s, with heavy focus on production growth, cost-cutting, operational efficiency and short-term profitability. Huge cash-flows were building when the oil price started increasing at the turn of the century, and a large share was returned to shareholders, through comprehensive share buyback programmes and extraordinary dividends.

Figure 1. Oil price and financial market volatility
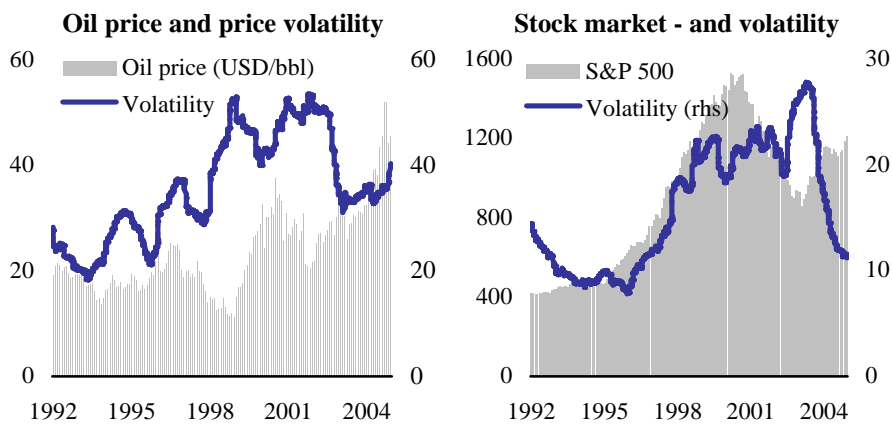
Volatility: Annualised standard deviation of daily price/index change (250 days rolling data window). See Section 5 for details.
Source for oil price and stock market data: Reuters Ecowin (http://www.ecowin.com).

A reflection of these events and trends is that international oil and gas companies were faced with increasing uncertainty over the 1990s. This mirror image can be traced in relevant commodity and financial markets. As illustrated in Figure 1, a period of oil price stability was succeeded by increasing volatility from the mid 1990s, culminating with the oil price slump caused by the Asian economic crisis in 1998. The scope of this study is to explore how these developments influenced the formation of capital in the oil and gas industry. More precisely, our econometric assessment may be seen as a test of how the industrial upheaval of the late 1990s may have affected investment, production and oil supply from the international oil and gas companies in the aftermath of the Asian economic crisis.

The paper is organised as follows. Section 2 gives a brief review of previous research on investment and uncertainty, focusing especially on empirical

120

studies. Our econometric specification is outlined in Section 3. A brief tour of the data set is the subject of Section 4. Estimation procedures and results are presented and discussed in Section 5, before some concluding remarks are offered in Section 6.

2. Previous research

The sign of the investment uncertainty relationship has received interest from theorists and empirical researchers for many years. Early theoretical contributions (e.g., Oi 1961; Hartman 1972; Abel 1983) stress the implications of convexity of the profit function. This property stems from standard neoclassical theory of producer behaviour, and implies that price variation may be exploited for profit maximisation. In this framework, an increase in uncertainty will raise the marginal valuation of investment, giving a positive link between capital-accumulation and 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. Irreversibility provides firms with a real option to defer investment. Any increase in the uncertainty around future profitability will enhance the value of this waiting option, implying a negative investment response to increased uncertainty. However, this conclusion is relaxed in recent contributions to the literature on strategic investment and real options. As pointed out by Smit and Trigeorgis (2004), the decision to invest implies not only the sacrifice of a waiting option, but also a potential reward from the implicit acquisition future development options.[3] Higher uncertainty will increase the value of both these types of real options (Kulatilaka and Perotti 1998; Sarkar 2000).[4] At the same time, the value of waiting options is also eroded by imperfect competition and strategic investment (Grenadier 2002; Akdogu and MacKay 2007). Empirical studies are therefore required to determine the sign of the investment-uncertainty relationship.

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[3] See Schwartz and Trigeorgis (2004) for an updated compilation of the relevant literature on real options and investment under uncertainty.

[4] This is also in line with recent contributions to the theoretical investment literature, where asymmetries relating to irreversibility do not hold independent of decision horizon. In a model with (long) investment lags, Bar-Ilan and Strange (1996) conclude that uncertainty may have an invigorating effect on capital formation.

According to a survey by Carruth, Dickerson and Henley (2000), empirical studies confirm a quite robust negative link between investment and uncertainty, with more clear-cut results for studies of micro data than for aggregate data. Modern panel data techniques have also stimulated a variety of empirical studies, and most of these are also supportive of a negative impact of uncertainty on investment. See Bond et al. (2005) for a recent overview.

A range of options is available for uncertainty indicators, and no consensus is yet obtained for the appropriate way to proxy uncertainty in empirical models. Fuss and Vermeulen (2004) applies business sentiment surveys to address price and demand uncertainty, as perceived by company managers in Belgium. Guiso and Parigi (1999) retrieve their measures for demand uncertainty from an investment survey among Italian business leaders. Bond et al. (2005) derive proxies for uncertainty from the observed spread in analysts' earnings forecasts. An alternative method is to incorporate risk measures embedded in the term structure of relevant prices, like interest rates or option prices (e.g., Ferderer 1993).

Volatility forecasting models are common in early empirical studies of investment and uncertainty, whereby expectations were approached through predictions from *ARCH* or *GARCH* models estimated on high-frequency data (e.g., Price, 1996). The strength of this approach lies in the explicit address of expected volatility. However, this strategy also introduces model uncertainty in two stages.[5] Furthermore, *ARCH* and *GARCH* models estimated on high-frequency data will usually imply a low persistence of shocks for our purpose. The majority of recent work therefore relies more directly on observed uncertainty measures, and so will our modelling approach. However, our approach does not rest on a single scalar measure of uncertainty, like share price volatility. Rather, we define uncertainty variables to enable an independent address of two distinct sources of uncertainty, in the capital market on one hand, and the oil market on the other.

A few econometric studies have also addressed the development of oil and gas fields 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. Hurn and Wright (1994) find no statistical

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[5] Volatility predictions become sensitive to model choice and exhibit substantial variation across alternatives. The validity of the model specification becomes momentous to the validity of the predictions. See also Engle (1982) for instructive reflections on this point.

significance of oil price variability in their investment equations for oil and gas fields in the same region. We are not aware of previous micro-econometric studies of company data that address investment and uncertainty specifically for the oil and gas industry.

3. Econometric model specification

Tobin (1969) gave rise to one of the currently most popular models of modern empirical investment research, relating investment to the ratio (q) of market value of capital to its replacement value. This model is simple and has an intuitive appeal. Moreover, theory implies that Tobin's q represents a sufficient statistic for investment, a property that has been tested in a range of empirical applications. Popular applications include studies of capital market imperfections (Hubbard 1998) and uncertainty (Carruth, Dickerson, and Henley, 2000) in investment behaviour.

With standard neoclassical behavioural assumptions, Bond and Van Reenen (2007) show that the following linear relationship is implied by the q model of investment:[6]

$$\left(\frac{I}{K}\right)_{it} = a + \frac{1}{b}Q_{it} + e_{it} , \qquad [1]$$

K_t represent the stock of fixed capital, and I_t is gross investment, $Q_{it} = q_{it} - 1$, and e_{it} is an additive shock to adjustment cost function, normally treated as a residual in the econometric specification. We include fixed effects (h_i) and time-specific error-components (z_t) in this error-term according to the following structure: $e_{it} = h_i + z_t + e_{it}$. Equation [1] is also augmented with a vector of uncertainty indicators (s_t). The first is the volatility of overall stock market returns, measured as the annualised standard deviation of daily returns on the S&P500 index. We will refer to this measure as general market risk – or *extrinsic* risk. To capture industry-specific or *intrinsic* risk, we include a corresponding volatility measure for the crude oil price. Both variables will be defined and discussed in the data section below.

With company data over 14 years, it is hard to believe that the idiosyncratic, time-varying error-component (e_{it}) is serially uncorrelated. We therefore

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[6] See Appendix 1 for the full derivation of the Q model of investment.

include lags of both endogenous and exogenous variables, yielding for the econometric equation:

$$\left(\frac{I}{K}\right)_{it} = b_0 + b_1\left(\frac{I}{K}\right)_{it-1} + b_2 Q_{it} + b_3 Q_{it-1} + b_4 s_t + b_5 s_{t-1} + e_{it}, \quad [2]$$

Based on this specification, we may now test whether the investment impact of an increase in uncertainty is temporary ($b_4 \neq 0$; $b_4 + b_5 = 0$) or persistent ($b_4 + b_5 \neq 0$). Obviously, the same test procedure is available for the Q_{it} variable.

Rather than a general investigation of the *Q* model, the key objective of this study is to test the impact of uncertainty on oil and gas investment. We will therefore test the robustness of the relationship between investment and uncertainty with a variety of control variables. Standard econometric procedure is to approach *Q* via the market-to-book ratio. However, this approach involves pitfalls of measurement error, jeopardising not only the coefficient estimate for Q_{it} but also the validity of the econometric model (e.g., Erickson and Whited 2000). If the ratio of market value to fundamental value has a constant expectation, Bond and Cummins (2001) demonstrate that *q* may be identified in a semi-log specification (see Appendix 2 for a formal exposition). Our first alternative to Equation [2] is therefore to replace Q_{it} and Q_{it-1} with $\ln Q_{it}$ and $\ln Q_{it-1}$, respectively. With efficient markets, the sharp rise in the oil price over the last 10 years should be reflected in company valuations, book values, and consequently also in our Q_{it} variable. However, this might not be the case in the presence of financial market bubbles and noisy share prices. In alternative specifications, we therefore augment both the above versions of the model with a cash-flow variable. As we will see, the role of our uncertainty variables is quite robust across these specifications.

As shown by Nickell (1981), the lagged endogenous variable does not have the desired exogeneity properties in dynamic panel data models. A variety of instrumental variable techniques have been developed to handle this endogeneity bias. Anderson and Hsiao (1981) propose a *2SLS* estimator for a transformation in first differences, with instruments that are correlated with the transformed lagged dependent variable and orthogonal to the differenced error term. Lagged levels of the lagged dependent variables are valid instruments to obtain consistent estimates of the dynamic model, according to this approach. In a corresponding first-difference *GMM* framework, Arellano and Bond (1991) show that deeper lags of the dependent variables are also

valid as instruments. A problem with the original Arellano Bond framework is that lagged levels of the dependent variable make poor instruments for first differences of persistent time series, and especially for variables that are close to a random walk.[7] In meeting this challenge, Arellano and Bover (1995) demonstrate that additional moment conditions may be provided by the inclusion of the original level equations in the system of equations to be estimated, with significant efficiency gains. This estimator is referred to as the system *GMM* estimator, and is further refined by Blundell and Bond (1998), and Blundell, Bond and Windmeijer (2000). We take advantage of these developments in the estimation of Equation [2].

4. Data

Our data sample is an unbalanced panel of oil and gas companies (1992-2005) drawn from the JS Herold oil and gas financial database.[8] We utilise the following data items denoted in USD; market capitalisation, total assets, long-term debt, and capital expenditure. In line with previous literature we use the sum of market capitalisation of equity and long term debt in year *t* divided by total assets in year *t-1* as our proxy for Tobin's *q*. The model variable Q_{it} is then defined as: $Q_{it} = q_{it} - 1$. Investment (I_{it}) is measured by total capital expenditure and the capital stock (K_{it}) is represented by total assets.[9]

The JS Herold database consists of financial and operating data from annual financial statements of 542 publicly traded energy companies worldwide. From this universe we select firms mainly engaged in exploration and production (E&P or upstream) activities. This leaves us with 169 oil and gas companies, resulting in *169x13* = 2197 potential firm years. Out of these, 827

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[7] Persistent time series are defined by the role of history for their development, with positive correlation between current and lagged values. As an example, consider the simple *AR(1)* process: $y_t = a y_{t-1} + v_t$. Subtracting y_{t-1} from both sides now yields: $y_t - y_{t-1} = (a-1)y_{t-1} + v_t$. Consequently, as the autoregressive coefficient *a* approaches 1, *D*yt (= $y_t - y_{t-1}$) will approach a random walk (v_t). In general, a random walk process (*I(0)*) for the difference implies that the level of the same variable is integrated of degree 1 (*I(1)*).

[8] Founded in 1948, John S. Herold Inc. is an independent research firm that specialises in the analysis of companies, transactions, and trends in the global energy industry. JS Herold serves a global client base with analyses and key financial and operational data on the valuation, performance, and strategy of more than 400 oil and gas companies (http://www.herold.com/).

[9] Our investment variable is the sum of exploration and development spending. In preliminary estimations, separate equations for these to investment types were estimated in a less sophisticated specification, with robust results for the uncertainty variables. However, our data source does not permit the specification of a *Q* model for each of these investment types.

observations are missing. On the original sample, we apply a number of additional sample selection criteria. First, we exclude non-positive values of total assets, investment and *Q*. Second, we leave out observations where firms are likely to have undergone substantial changes due to mergers, acquisitions or divestments. Using the annual growth rate in total assets as a signal of restructuring, we remove observations where companies show annual growth in excess of 33 per cent. This particular screening procedure reduces the number of observations by 554. This is quite a substantial reduction, and is a result of certain characteristics among oil and gas companies.

Table 1. Descriptive statistics for data sample

	Obs.	*Mean*	*St. dev.*	*Min.*	*Max.*
$(I/K)_{it}$	778	0.183	0.116	0.000	1.108
$(CF/K)_{it}$	778	0.072	0.305	0.000	3.385
Q_{it}	778	0.817	1.080	0.000	9.212
s_t^m	14	15.411	5.971	7.887	26.081
s_t^p	14	36.16	10.378	20.149	52.573

Source: JS Herold (http://www.herold.com).

As illustrated in the introduction, our data set covers a period of massive restructuring in the oil and gas industry (Weston, Johnson, and Siu, 1999). Furthermore, many of the companies use a particular accounting method called the successful efforts method (FASB, 1982). Under this method only cost incurred from the exploration of successful oil wells are capitalised and included on the firms' balance sheets. Hence, the drilling of a successful oil or gas well may result in a substantial change in the balance sheets, especially for smaller firms. On a data set of US manufacturing firms, Baum et al. (2006) trim by the 5th and 95th percentiles. A similar approach to our data set would result in the inclusion of firms with asset growth in excess of 150 per cent. We deem our somewhat conservative approach more appropriate for our purpose.

After this screening procedure, the data set is down to 778 firm years, or 35 per cent of the original total. A reduction of 827 (38 per cent) is due to missing data, 554 (25 per cent) is due to exclusion of firm-years with extreme asset growth, and 38 (2 per cent) is due to other screening procedures. Lags and differences shave off another 335 observations, taking the number down

to 443 for the estimation of the dynamic model. Descriptive statistics for the variables used in the analysis are presented in Table 1. The average investment rate for our sample is about 18 per cent. This is somewhat higher than for other comparable studies, due to material capacity growth and increasing development costs in the oil and gas industry.

To address general financial market risk as well as industry-specific risk, we calculate two different measures of aggregate uncertainty. The first is the volatility of the S&P 500 index of the US stock market. The underlying index value is adjusted for divident payments, to portray total investment returns. The second is a corresponding volatility measure for the oil price. We illustrate the methodology for the oil price. Based on daily price (p_{kt}) data for the brent blend quality for each of the last 14 years, we calculate annualised standard errors of daily returns ($r_{kt}=\boldsymbol{D}p_{kt}$, $k = 1, 2 .. N$, $t = 1992\text{-}2005$):

$$ \boldsymbol{s}_t^p = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(r_{kt}-E(r_{kt})\right)^2}, \qquad [3] $$

where N is the annual number of trading days ($\sim$ 250) and the average daily change in each year is used as a proxy for $E(r_{kt})$. Corresponding volatility measures are calculated for S&P 500 index, to produce two annual volatility variables for our model. Daily calculations of these volatility measures with a rolling window of 250 trading days are illustrated in Figure 1 in the introduction. This methodology is according to financial market practice, and in line with previous studies (e.g., Paddock, Siegel, and Smith, 1988; Hurn and Wright, 1994).

Oil price volatility has increased from an annualised level of 20-30 per cent during the early 1990s to 40-50 per cent during 1998-2002, when the oil industry was substantial restructuring and a severe oil price drop occurred during the Asian economic crisis (Weston, Johnson, and Siu, 1999). Since then, oil price volatility has fallen to levels just below 40 per cent, which is slightly higher than average levels from the 1990s.[10] From moderate levels around 10 per cent, the volatility of US stock market returns increased

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[10] A standard result from the literature is that the oil price responds positively to increases in volatility, due to increased demand for storage (Pindyck, 2001; Geman, 2005). At historically high prices, the recent drop in oil price volatility may therefore seem like an oxymoron. One possible interpretation is that the oil market has gone through a structural shift. In that case, the established new long-term price level may have broken the historical connection between price level and price volatility.

gradually towards 20 per cent at the end of the 1990s. This volatility increase coincided with the "New Economy" optimism, which created a pricing bubble in large parts of the equity market at the turn of the century (Shiller, 2000). After a temporary peak at approx. 25 per cent in 2003, stock market volatility has fallen sharply over the last couple of years, to levels more typical for the 1990s.

5. Estimation and results

We acknowledge the potential endogeneity challenges in our modelling framework. First, an endogeneity bias for the lagged endogenous variable of dynamic panel data models is firmly established in the literature (e.g., Arellano 2003), as discussed above. Second, there may well be endogeneity challenges involved for the Q variable as well. For the last 10 years or so, Osmundsen et al. (2006) argue that oil and gas companies have been rewarded by the equity market for strict capital discipline. Pressures from financial markets have probably put a lid on investments to support the short-term key performance indicators in the oil and gas industry, especially return on average capital employed (*RoACE*). As market valuation is the numerator of our Q, this variable might therefore also not have all the desired exogeneity properties. Consequently, both the lagged endogenous variable and the Q ratio are treated as potentially endogenous variables in our estimation framework.

The standard textbook solution to endogeneity is to apply additional exogenous variables (which by assumption are uncorrelated with the error term) to instrument the suspected endogenous predictor. Unfortunately, independent instrumental variables are usually hard to find for the typical microeconometric study of company data, and our analysis is no exception. However, Arellano and Bond (1991) show that a range of instruments is available in the lagged differences and levels of endogenous and predetermined variables. We therefore rely on the *GMM* approach suggested by Arellano and Bond, and refined by a range of subsequent contributions. See Arellano (2003) for an updated overview.

As pointed out by Bond (2002), instruments in first differences are likely to be weak when the individual time series have near unit root properties. The original Arellano Bond estimator therefore requires autoregressive parameters to be significantly less than one in simple autoregressive specifications. Before we proceed to the estimation of the dynamic Q model, we therefore check the dynamic properties of our series. A simple *AR(1)* specification is

regressed for each of the variables in our model, using the *OLS levels* and the *fixed effects* (*FE*) estimators. Coefficient estimates and p-values for the lagged dependent variable are reported in Table 3.

Table 2. AR(1) estimates for model variables

Depvar/ Estimator	$(I/K)_{it}$	$(CF/K)_{it}$	Q_{it}	s_t^m	s_t^p
OLS	0.477^{***} (0.000)	0.928^{***} (0.000)	0.759^{***} (0.000)	0.684^{***} (0.010)	0.302 (0.261)
FE	0.078^{***} (0.022)	0.958^{***} (0.000)	0.424^{***} (0.000)		

[*]) Significant at 90, [**]) 95 and [***]) 99 per cent confidence level, respectively.
[a]) p-values in brackets.

The persistence is highly significant for all variables, but the results do not suggest the presence of a unit root for any of them. We therefore apply the system version of the *GMM* estimator (Arellano and Bover, 1995), including the original level equations in the estimated system of equations. Applying an instrument matrix with deeper lags of both first-differences and levels of the predetermined variables, this procedure provides improved efficiency to the original Arellano Bond framework.

The original Arellano Bond procedure involves a two-step *GMM* estimator, whereby a consistent estimate for the weight matrix from a first step is applied to obtain the asymptotically efficient estimator in the second step.[11] The two-step estimator involves efficiency gains in the presence of heteroskedasticity. On the other hand, it has a downward bias, especially in small samples. However, Windmeijer (2005) proposes a finite-sample correction of the two-step covariance matrix, showing substantial accuracy gains in Monte Carlo simulations. Our results are based on the small sample adjustment recommended by Windmeijer.[12] Table 3 presents estimates for four different model specifications, the simple Q model with and without the cash-flow variable, and the semi-log Q model with and without the cash-flow variable.[13]

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[11] All the presented estimations are performed with robust estimators for the covariance matrix.
[12] See Bond (2002) for a discussion of strengths and weaknesses of one-step versus two-step GMM estimators.
[13] The models are estimated in Stata 9.0, using the xtabond2 estimator developed by Roodman (2006).

Table 3: Estimation results, dynamic investment model

	Model 1	Model2	Model 3	Model 4
Estimated parameters				
$(I/K)_{it-1}$	0.514*** (0.000)	0.432*** (0.000)	0.474*** (0.000)	0.346*** (0.008)
Q_{it}	-0.005 (0.523)		-0.016* (0.059)	
Q_{it-1}	0.006 (0.645)		-0.010 (0.275)	
$\ln Q_{it}$		0.003 (0.555)		-0.006 (0.288)
$\ln Q_{it-1}$		-0.002 (0.759)		0.009 (0.304)
$(CF/K)_{it}$			0.410 (0.085)	0.245 (0.179)
$(CF/K)_{it-1}$			-0.433 (0.089)	-0.263 (0.176)
s_t^m	-0.047*** (0.002)	-0.037** (0.026)	-0.048*** (0.003)	-0.045** (0.004)
s_{t-1}^m	0.034*** (0.002)	0.027** (0.034)	0.033*** (0.008)	0.031* (0.054)
s_t^p	-0.010*** (0.002)	-0.009** (0.019)	-0.011** (0.012)	-0.012** (0.034)
s_{t-1}^p	0.030*** (0.002)	0.022** (0.048)	0.030** (0.003)	0.028* (0.054)
Model diagnostics				
Wald c^2	179.96*** (0.000)	101.22*** (0.000)	201.97*** (0.000)	71.88*** (0.000)
Hansen J	67.12 (0.246)	35.05 (0.138)	47.05 (0.429)	30.34 (0.299)
AB AC(1)	-3.72*** (0.000)	-3.26*** (0.001)	-1.88* (0.060)	-2.23** (0.026)
AB AC(2)	-1.51 (0.131)	0.13 (0.895)	-1.43 (0.152)	1.24 (0.215)
Firms	115	99	67	56
Obs (#)	443	335	220	150

Note: All estimates obtained from the System GMM estimator, as implemented in Stata 9.0 by Roodman (2006). The lagged investment rate $(I/K)_{it-1}$ is treated as endogenous, and instrumented according to *GMM* procedures. The instrument matrix includes lagged differences and levels of all explanatory variables in each model. To avoid the problems relating to too many instruments (Roodman, 2007), a maximum lag length for instrument variables is set to 3.

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
[a] p-values in brackets.

Explanatory variables include lagged levels of the endogenous variable, as well as current and lagged levels of all explanatory variables. The Wald c^2 statistic is a test for joint significance of all model parameters. The Hansen *J* test is a test for the validity of the over-identifying restrictions implied by the instrument matrix.

Arellano and Bond (1991) recommend the Sargan statistic to test the exogeneity properties of the instruments as a group, with a null of invalidity. However, the Sargan statistic is sensitive to heteroskedasticity and autocorrelation, and tends to over-reject in the presence of either. We therefore follow Roodman's (2006) advise and report the Hansen *J* statistic,[14] which is robust. *AB AC(n)* is the Arellano-Bond test for n^{th}-order autocorrelation in the differenced residuals, with a null of no autocorrelation. Non-rejection of 1st order autocorrelation is as expected, and not critical for the validity of the differenced equations. 2nd order autocorrelation in the residuals of the differenced model would be more troublesome, as it would imply a breach of the assumption of well-behaved residuals in the level representation of our model, as specified by Equation (2).

All four specifications pass the battery of specification tests, and show satisfactory general performance. Tests for joint parameter significance are highly significant and the inclusion of time dummies is strongly justified. According to the Hansen *J* statistic, the validity of our over-identifying restrictions can not be rejected for any of the four models. The Arellano Bond test statistics suggests 1st order autocorrelation in the residuals of our differenced equations, but 2nd order autocorrelation does not seem to be a problem.

Observe that the *Q* ratio does not contribute significantly to the explanation of investment rates, according to our results. Estimated parameters for the Q_{it} and lnQ_{it} variables are highly unstable and statistically insignificant, with one exception – where the estimated coefficient takes the wrong sign. Consequently, our results suggest that the *Q* ratio is a poor indicator for investment in the international oil and gas industry. Results for the cash-flow variable suggest a temporary effect from cash-flow on investment rates, but no persistence. The estimated sum of the two cash-flow variables is statistically insignificant for both Model 2 and Model 4.

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[14] The Hansen *J* statistic is the minimised value of the two-step *GMM* criterion function (Hansen, 1982).

On the other hand, both volatility measures take stable and highly significant parameter estimates across all the four model specifications. The immediate investment response to an increase in stock market volatility is negative. However, this negative effect is dampened over time, due to the positive coefficient of lagged stock market volatility. In contrast to the results for the *Q* ratio, the sum of the two coefficients for stock market volatility is negative and highly significant.

Based on Model 1, various effects of volatility changes are calculated and presented in Table 4. From Column 1, we see that the cumulated effect of an increase in stock market volatility can be calculated to –0.013, with a p-value of 0.001. The implication is that an increase in our annualised volatility measure of 1 percentage point will reduce average the average investment rate by 1.3 percentage points. Thus, we establish a highly significant negative effect between oil and gas investments and extrinsic risk. Abel and Eberly (1999) argue that real investment options are appreciated by rational agents, and that the effects of uncertainty are embedded in the *Q* ratio. However, our result indicates that company valuation does not fully reflect the influence of aggregate uncertainty. This result could be evidence that company managers are more sensitive to *extrinsic* risk than analysts and investors.[15]

Table 4. Estimated investment-uncertainty effects
Model 1

	s_t^m	s_t^p	$s_t^m + s_t^p$
Contemporaneous effect	-0.047[***] (0.002)	-0.010[***] (0.002)	-0.057[***] (0.002)
Lagged effect	0.034[***] (0.002)	0.030[***] (0.002)	0.064[***] (0.002)
Long-term effect	-0.013[***] (0.001)	0.020[***] (0.003)	0.007[***] (0.027)

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
[a] p-values in brackets.

As illustrated in the second column of Table 4, results are quite different for oil price volatility, our *intrinsic* (industry-specific) risk indicator. In the short-term, an increase in oil price volatility of 1 percentage point will reduce the

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[15] This is not in conformity with the standard result (Cadsby and Maynes, 1998), whereby managers are seen as more risk-averse than shareholders, causing investment behaviour characterised by inertia and myopic loss aversion. Rather, our result suggests some form of over-confidence among managers in the oil and gas industry, along the lines of Malmendier and Tate (2005). This also corresponds well with

average investment rate by 1 percentage point. Moreover, the lagged effect of oil price volatility takes a positive sign, and is higher in magnitude than the current effect. The sum of the two effects is 0.020, with a p-value of 0.003. This implies that the longer-term effect of an increase in oil price volatility by one percentage point is an increase in the average investment rate by 2 percentage points.

A simultaneous increase in both uncertainty indicators by one percentage point, will produce an immediate reduction in investment. This is in accordance with the real options approach to investment, where negative effects on investment from uncertainty are especially important in the short run (Bloom 2000; Carlsson 2007). However, note also that a persistent increase of 1 percentage point in both our volatility indicators produces a lasting positive impulse to investment rates (p = 0.027). Our overall results are therefore not supportive of the standard result of theories of irreversible investment, which normally suggest a negative relationship between investment and uncertainty.

Our key findings are also at odds with the bulk of the empirical literature, which are dominated by reports of a negative investment-uncertainty relationship (Carruth, Dickerson, and Henley, 2000; Bulan, 2005; Bloom et al., 2007). Traditionally, the oil and gas industry has a prominent place in the investment literature on irreversible investments, and irreversibility is usually connected to a negative relationship between investment and uncertainty. Favero, Pesaran and Sharma (1992) and Mohn and Osmundsen (2007) are examples of previous econometric studies that have detected a negative influence from oil price variability on investment in the oil and gas industry, although in a quite different context.[16]

Oil price shocks are usually temporary, and oil companies may therefore consider any increase in oil price volatility as a transitory phenomenon. In that case, peaking oil price volatility will usually be followed by a period of stimulating relief, resulting in a positive lagged effect of oil price volatility

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[16] Favero, Pesaran and Sharma (1992) apply field data from 53 oil fields on the United Kingdom Continental Shelf, and estimate the effect of uncertainty on the appraisal lag (i.e. the time span between discovery and development). Mohn and Osmundsen (2007) specify and estimate an econometric model of exploration and appraisal drilling on aggregate drilling data from the Norwegian Continental Shelf (NCS) over the period 1965 to 2004. The present study applies investment data from companies with a live portfolio of projects and assets with a variety of regional, technological and maturity characteristics. The approach of this paper is probably the best approximation of investment decisions and management behaviour among international oil and gas companies.

133

changes. In other words, irreversibility issues may dominate if the increase in volatility is viewed as temporary. On the other, the impact of profit convexity and/or compound options dominates for any permanent increase in uncertainty. We find it interesting that the modern approach to strategic investments and compound options is supportive of this kind of result (e.g., Smit and Trigeorgis, 2004).

7. Conclusion

Over the last 15 years, international oil and gas companies have gone through a period of industry upheaval, restructuring and escalating market turbulence. Since the beginning of the 1990s, business principles have gradually gained additional ground, and today competition among international oil companies is more aggressive than ever (Weston, Johnson, and Siu, 1999). Easily accessible oil and gas reserves in market-oriented economies like USA, Canada and United Kingdom are faced with depletion. Oil and gas investments are now gradually redirected in a rat race for increasingly scarce oil and gas resources. Our results should therefore be interpreted in the context of strategic investments (Smit and Trigeorgis, 2004).

Modern literature of strategic investment embeds issues like real options, game theory and imperfect competition, and may therefore be seen as an extension of the irreversible investment theory. As pointed out by Kulatilaka and Perotti (1998), fixed investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. For the oil and gas industry, an increase in the oil price volatility will increase the value of both these types of real options. Thus, the theory of compound options may give rise to a positive relationship between investment and uncertainty.

We specify and estimate a dynamic Q model of investment, augmented with various uncertainty indicators as well as a cash-flow variable. The model is estimated on a panel of company data over the period 1992-2005, applying modern *GMM* techniques for dynamic panel data models. The model performs satisfactory, in terms of parameter significance, specification tests, and general model diagnostics. The estimated Q model do not offer a satisfactory empirical explanation for oil and gas investments, as suggested by theory. Thus, our results suggest that the Q ratio is a poor indicator for investment in the international oil and gas industry.

Still, we establish a robust link between investment and two sources of uncertainty. General financial market risk is negatively related to investment among the companies in our sample. On the other hand, oil price volatility takes a highly significant and positive parameter value. A possible interpretation of this result is the revitalisation Oi's (1961) argument for "the desirability of price instability . . .". This study therefore suggests a revitalisation of return convexity issues in studies of investments, based on modern theories of compound options.

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Appendix 1. Derivation of the Q model

We follow Bond and van Reenen (2007), and consider the profit function of a representative firm, given by:

$$\Pi_t(K_t, I_t, e_t) = p_t F(K_t) - p_t^I [I_t + G(I_t, K_t, e_t)] \qquad [A1.1]$$

$F(K_t)$ is a well-behaved neoclassical production function, K_t represent the stock of fixed capital, and I_t is gross investment. The firm puts its product at the market at the price p_t. $G(I_t, K_t, e_t)$ is an adjustment cost function, p_t^I is the price of investment goods, and e_t is a stochastic shock to the adjustment process. Under standard neo-classical behavioural assumptions, the firm's dynamic optimisation problem is stated as:

$$V_t = \max E_t \left[\sum_{i=0}^{\infty} b^i \, \Pi(K_{t+i}, I_{t+i}, e_{t+i}) \right] \qquad [A1.2]$$

where V_t is firm value, $b = \frac{1}{1+r}$ is a constant discount factor, and $E_t[.]$ denotes the expected value conditional on information available in period t. Firm value as defined by Equation [2] is maximised subject the usual constraint on capital accumulation:

$$K_t = (1-d)K_{t-1} + I_t \qquad [A1.3]$$

where d is an exogenous and fixed rate of depreciation for capital. First-order conditions are given by:

$$\left(\frac{\partial \Pi_t}{\partial I_t} \right) = -\mathbf{1}_t \qquad [A1.4]$$

$$\left(\frac{\partial \Pi_t}{\partial K_t} \right) = \mathbf{1}_t - b(1-d)E_t \mathbf{1}_{t+1} \qquad [A1.5]$$

where the Lagrange multiplier $\mathbf{1}_t = \frac{1}{1-d} \left(\frac{\partial V_t}{\partial K_{t-1}} \right)$ represents the shadow value associated with capital accumulation. Equation [A1.4] sets this shadow value equal to the marginal cost of acquiring an additional unit of capital in period t. The first-order condition [A1.5] describes the relation between shadow values

in period t and future shadow values. Linear homogeneity of the profit function implies:

$$\Pi_t = K_t \frac{\partial \Pi_t}{\partial K_t} + I_t \frac{\partial \Pi_t}{\partial I_t} \qquad [A1.6]$$

The first-order conditions of Equations [A1.4]-[A1.5] are now combined with [A1.3] to yield:

$$\boldsymbol{l}_t(1-\boldsymbol{d})K_{t-1} = \Pi_t + \boldsymbol{b}E_t\big[\boldsymbol{l}_{t+1}(1-\boldsymbol{d})K_t\big] \qquad [A1.7]$$

Solving this equation forward we obtain for the value of the firm:

$$\boldsymbol{l}_t(1-\boldsymbol{d})K_{t-1} = E_t\left[\sum_{i=0}^{\infty} \boldsymbol{b}^i \Pi_{t+i}\right] = V_t. \qquad [A1.8]$$

We now define marginal q_t as the ratio of the shadow value of capital to purchase cost $q_t \equiv \frac{l_t}{p_t^I}$. Hayashi (1982) demonstrates that under linear homogeneity of the profit function marginal q equals average q. A useful implication of the Hayashi conditions is that the unobservable shadow value of capital can be related to an observable average q ratio, namely the ratio of total asset value to its replacement cost:

$$q_t = \frac{\boldsymbol{l}_t}{p_t^I} = \frac{V_t}{p_t^I(1-\boldsymbol{d})K_{t-1}} \qquad [A1.9]$$

Equation [9] presents marginal q_t as the ratio of V_t to the replacement cost value of the capital stock from the previous period. The numerator (V_t) represents the sum of discounted cash-flows from the existing capital stock, and captures changes in current and expected product prices, production plans, unit costs and discount rates. The denominator represents the cost of replacement for the capital stock. Thus, Tobin's q theory of investment suggests that companies with superior investment returns (high q) attract more capital and spend more on capital investment than underperforming firms.

We follow the mainstream approach to adjustment costs, (e.g., Bond et al., 2005), and assume a quadratic adjustment cost function:

$$G(I_t, K_t, e_t) = \frac{b}{2}\left[\left(\frac{I_t}{K_t}\right) - a - e_t\right]^2 K_t, \qquad \text{[A1.10]}$$

where b is a coefficient to represent the importance of adjustments costs. Equation [A1.10] states that the unit cost of capital adjustment is a convex function of the investment rate, that adjustment costs kick in as soon as some investment threshold (a) is passed, and that the investment process is disturbed by stochastic shocks (e_t). With this specification, the first-order condition in Equation [4] can be modified into a simple relation between investments and the q ratio in company i:

$$\left(\frac{I}{K}\right)_{it} = a + \frac{1}{b}Q_{it} + e_{it}, \qquad \text{[A1.11]}$$

where $Q_{it} = q_{it}-1$, and a and b are parameters of the adjustment cost function.

Appendix 2. A specific form of measurement error

A potential wedge between market value (V_t) and fundamental company value (V_t^F) represents the core of the problem of measurement error. With m_t as the measurement error, the key idea may be summarised as:

$$V_t = V_t^F + m_t \qquad\qquad [\text{A2.1}]$$

Noisy share prices and stock market bubbles increases the hazard of relying uncritically on market values for the estimation of the Q model. Bond and Cummins (2002) propose a modified specification to identify the investment model in the presence of measurement error. Their point of departure is a specific multiplicative form of measurement error, whereby:

$$
\begin{aligned}
V_t &= V_t^F e^{m_t} \\
m_t &= m_{t-1} + x_t \\
E_{t-1}(x_t) &= 0
\end{aligned}
\qquad\qquad [\text{A2.2}]
$$

The scaling factor follows an AR(1) process with an autoregressive parameter equal to one. Taking logarithms now yields:

$$\ln V_t = \ln V_t^F + m_t \qquad\qquad [\text{A2.3}]$$

As the applied *GMM* estimators are based on differences, [A2.1] further implies:

$$\Delta \ln V_t = \Delta \ln V_t^F{}_t \qquad\qquad [\text{A2.4}]$$

To simplify, if the measurement error is represented by a scaling factor with a constant expectation, the percentage change in market value will equal the percentage change in the fundamental value. Consequently, a semi-log specification of the Q model will allow identification of Q even in the presence of measurement error.

Chapter 5

Shifting sentiments in firm investment: an application to the oil industry

By Klaus Mohn and Bård Misund

Abstract[1]

Recent developments in the oil and gas industry suggest that investment behaviour is not necessarily changeless over time. We propose a micro-econometric procedure to investigate the stability of investment behaviour. Applying system GMM methods on a panel data set for 253 oil and gas companies over 14 years, we estimate accelerator models of investment with error-correction. Robust econometric evidence indicates a structural break in oil and gas investment in 1998. The process of capital formation over the last years is more flexible than before, with significant and material changes in the role of explanatory factors like cash flow and uncertainty.

JEL classification: C32, G31, L72

K*ey words*: Capital formation, dynamic panel data models, structural break

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1. Introduction

The process of company investment expenditure and capital formation is influenced by a range of internal and external variables, covering aspects of economics, policies, institutions and technology. Changes and shocks in prices, liquidity and uncertainty may carry over to management mentality. Moreover, substantial shifts in the economic environment of the firm may also induce changes in the underlying models of investment behaviour. We propose a micro-econometric framework to assess how the process of capital formation at the firm-level might be affected by a period of far-reaching industrial upheaval and restructuring.

This is the first study to apply company data in a micro-econometric assessment of investment behaviour in the oil and gas industry. Based on accounting information for 253 companies over the period 1992-2005, we specify the process of capital formation as an accelerator model with error-correction (Bean, 1981), whereby investment is explained as a continuous adjustment process towards a long-term equilibrium relation between capital and output. The error-correction process is disturbed by temporary shocks, and by variation in a set of financial and operational control variables. The dynamic panel data model is estimated with *GMM* techniques introduced by Arrellano and Bond (1991). Based on the industrial restructuring of the late 1990s, we apply a flexible dummy-variable technique to test for the presence of a structural break in oil and gas company investment.

Our results provide robust evidence for two historical regimes of investment behaviour in the international oil and gas industry over the last 15 years; one from 1992 to 1997, and one from 1998-2005. Interesting insights are revealed by the shift in various coefficients of our model. Specifically, the late rise in oil price and cash-flows has had a far smaller impact on investment rates than what was typical before 1998, suggesting that financial market pressures in the aftermath of the Asian economic crisis have caused tightened capital discipline in recent years (Osmundsen et al., 2006). Moreover, the early 1990s were characterised by a negative relationship between investment and uncertainty, whereas the recent increase in oil price volatility has spurred investment over the last few years. This result is at odds with the vast majority of previous studies of investment and uncertainty (Dixit and Pindyck, 1994; Carruth et al., 2000), but well in line with recent development of theories of compound options and strategic investment (Abel et al., 1996; Smit and Trigeorgis, 2004). As far as we can see, this kind of robust empirical support

147

for a positive investment/uncertainty relationship is unprecedented in econometric studies.

Figure 1. Investment indicators in the international oil and gas industry
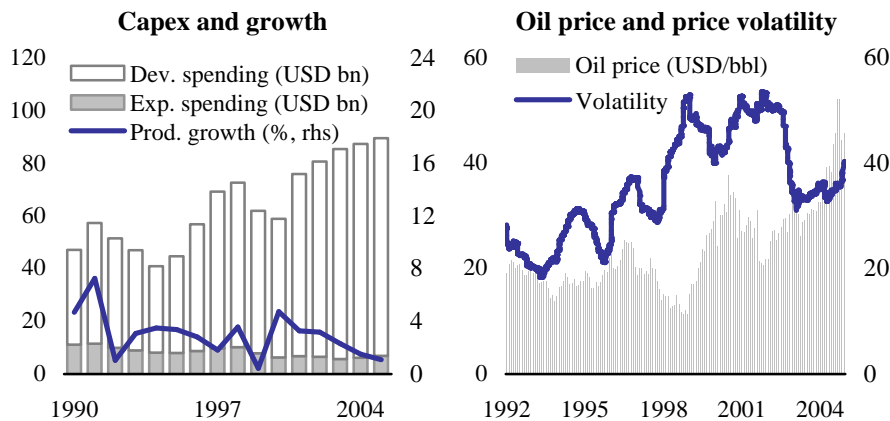
Oil price volatility: Annualised standard deviation of daily price change (250 days rolling data window).
Sources: Investment indicators: Deutsche Bank (2005), oil price and stock market data: Reuters Ecowin (http://www.ecowin.com).

From around 1985 and towards the end of the 1990s, the international oil and gas companies were exposed to extensive changes in their market, business and political environment. Oil and gas production temporarily lost its former national, political and strategic superstructure, and financial principles gained ground. Processes commonly referred to as globalisation advanced rapidly, with far-reaching implications in terms of economic and financial integration, intensified restructuring and improvement efforts, accelerating technology diffusion, enhanced competition and increased uncertainty. International oil and gas companies were hesitant in responding to these changes, and were outpaced by the emerging industries of telecom, media and technology (TMT).

Towards the end of the 1990s, oil companies' failure to deliver satisfactory investment returns triggered a massive pressure for restructuring, strategic change and improved financial performance (Weston et al., 1999). A combined result of these developments was a wave of mergers and acquisitions that erased former prominent independent names such as Elf, Fina, Mobil, Amoco, Arco, YPF, Texaco, Phillips, Lasmo – and recently also Unocal. The international oil and gas industry entered a new stage towards the end of the 1990s, with heavy focus on production growth, cost-cutting,

operational efficiency and short-term profitability. Scorecards of key performance indicators were presented to the financial market, as an implicit incentive scheme between investors and senior management in the companies. Osmundsen et al. (2007) discuss potential implications for capital formation and oil supply, but an empirical analysis of investment behaviour through the period is yet to be published.

Due to strengthened capital discipline (Dobbs et al., 2006), oil and gas exploration and production activities has failed to respond to increasing oil prices over the last years. Figure 1 illustrates that production growth among Western major oil and gas companies has remained low in the aftermath of the Asian Economic Crisis in 1998. The figure also shows that the share of exploration spending in total E&P investments has been cut back substantially since 1990. However, an increasing share of oil industry investments has been directed at short and medium term development projects rather than long-term reserve replacement.

These developments clearly suggest that the mechanisms of investment behaviour are not necessarily stable over time. Financial friction may both be raised and resolved by exogenous disturbances. Similarly, demand and price shocks, changes in industry structure and competition, financial market pressures and policy changes may change company managers' attitudes to risk and uncertainty. The role of these variables in investment behaviour should therefore be addressed in terms of regime-shifting behaviour. The paper is organised as follows. Section 2 provides a selective overview of recent contributions to the micro-econometric investment literature, with a special focus on financial friction, real options and uncertainty, dynamic panel data models, and oil and gas applications. The econometric model is derived in Section 3, whereas the data set is introduced and discussed in Section 4. Estimation and results are presented in Section 5, before some concluding remarks are offered in Section 6.

2. Previous research

Based on early theoretical contributions from pioneers like Haavelmo (1960), Jorgenson (1963) and Tobin (1969), empirical interest in investment behaviour has a long tradition in economic research. Chirinko (1993) offers a survey of modelling strategies and results up to the early 1990s, exploring a range of applications of neo-classical models, models with explicit dynamics and various reduced-form models. An essential conclusion from Chirinko's

(1993) study is that user cost variables tend to be less important for capital formation at the firm level than revenue and cash-flow variables, casting doubt on the empirical performance of the standard neo-classical investment model. The development of dynamic panel data techniques has resulted in a number of micro-econometric investment studies, developed for general representations of investment behaviour,[2] but also for topical studies like capital market imperfections (Hubbard, 1998) and irreversibility/uncertainty issues (Carruth et al., 2000).

In more recent years, important questions have been raised regarding the role of cash-flow variables in structural models of investment. Critics argue that the common interpretation of cash-flow effects as evidence of capital market imperfections (Hubbard, 1998) is seriously flawed, due to measurement error in market valuation variables (Erickson and Whited, 2000), model specification, and identification problems (Kaplan and Zingales, 1997; Gomes, 2001). Consequently, the attraction has increased for non-structural models (Bean, 1981; Mairesse et al., 1999; Bond et al., 2003), with less theoretical restrictions and without the standard source of measurement error from traditional q models. In a reconciling modelling approach, Moyen (2004) asserts that financially constrained firms actually require another investment model than non-constrained firms. Our econometric approach extends this line of thought, investigating the possible regime-shifting behaviour in the oil and gas industry between periods with more and less financial restriction.

Standard theories of irreversible investment and real waiting options imply a negative investment-uncertainty relationship (Dixit and Pindyck, 1994), contesting the traditional neoclassical "desirability of price instability" argument (Oi, 1961; Hartman, 1972; Abel, 1983). However, a reconciling study by Abel et al. (1996) illustrates how both these perspectives can be accommodated in modern theories of investment. Adding future put options of contraction to the traditional call options of deferral, ambiguous results are produced for the sign of the investment/uncertainty relationship. Recent applications in management and finance (e.g., Kulatilaka and Perotti, 1998; Smit and Trigeorgis, 2004) also stress that investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. Increased uncertainty will increase the value of both waiting and development options. Moreover, the value of waiting options is also eroded by imperfect competition and strategic investment

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[2] See Bond and Van Reenen (2007) for a general overview.

(Grenadier, 2002; Akdogu and MacKay, 2007). Empirical studies are therefore required to settle the investment-uncertainty relationship.[3]

In terms of econometric specification, there is a separation in the empirical investment literature between structural models and reduced-form models. Structural models are derived directly from the firm's dynamic optimisation problem, with explicit mechanisms for adjustment costs and intertemporal behaviour. On the other hand, reduced-form models are usually derived from general auto-regressive distributed-lag (*ADL*) models, relating current and lagged investment to current and lagged values of various explanatory variables. As these models are not linked explicitly to an underlying theory of investment behaviour, coefficients from these models do not have a straightforward interpretation. However, several researchers (e. g., Oliner et al., 1995); Mairesse et al., 1999) note that reduced-form models tend to perform better for forecasting purposes than structural models. Consequently, *ADL* models remain the preferred choice among forecasters. Chirinko et al. (1999) conclude that "the applied econometrician must choose between distributed lag models that are empirically dependable but conceptually fragile and structural models that have a stronger theoretical foundation but an unsteady empirical superstructure".

The development of panel data methods has facilitated a change of perspective from macroeconomic to microeconomic behaviour. Panel data sets enable the researcher to account not only for the dynamics of the investment process, but also for cross-sectional variation between companies. A key challenge with dynamic panel data models concerns the simultaneity issues that arise in models with fixed effects and lagged dependent variables. Starting with Anderson and Hsiao (1981), a variety of instrumental variable techniques has been suggested to resolve this issue. A widely employed approach is the generalised method of moments (*GMM*) procedure originally suggested by Arrellano and Bond (1991), refined in a range of subsequent contributions, and applied in the majority of modern micro-econometric investment studies. See Bond (2002) and Arrellano (2003) for updated reviews.

The typical panel data set for company data contains information for a relatively large number of companies (large *N*) over a limited number of time periods (small *T*). This restricts the potential for a robust portrayal of dynamic behaviour over longer time periods. Small *T* panels also reduce our ability to

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[3] According to Carruth et al. (2000), econometric studies are supportive of a quite robust negative link between investment and uncertainty.

uncover trends and shifts in parameters over time, and to study structural breaks in the data set with stringent methods. With 253 companies over 14 years, our data set is generated over a full financial and oil market cycle, covering periods of consolidation, restructuring, stability, vulnerability, suppression – and "irrational exuberance" (Shiller, 2000).

Previous studies of oil and gas investment have been occupied with various types of aggregate data (e.g., Pesaran, 1990) or field-specific data (e.g., Hurn and Wright, 1988; Favero et al., 1992; Favero and Pesaran, 1994), with a more or less explicit concern for the exhaustibility issues of oil and gas resources. The capital stock in each of our data units represents a portfolio of reserves and fixed assets at various stages of development, and with various regional, technological and product characteristics. Consequently, our investment figures capture total investment in each company in a range of different projects. With such a genuine company perspective on oil and gas investments, the non-renewable properties of oil and gas investment become less apparent than in field-specific data and regional time series data.

3. An accelerator model with error-correction

The dynamics of capital formation is complex, and even more so when we consider investment at the company level as an aggregate of many types of capital. The vast empirical literature on structural investment models has not been convincing in terms of results. Bond and van Reenen (2007) survey empirical investment models derived from economic theory, and discuss a variety of the challenges and shortcomings related to models derived directly from the producer's dynamic optimisation problem. Our data set does also not offer the richness in variables required for a full-blown structural modelling approach. As the accelerator model is also not plagued by the problems of measurement error in the traditional q models, we therefore base our study on a reduced-form approach.

A common alternative is to rely on a dynamic econometric specification for the data-generating process that is not explicitly derived from structural relations for optimal adjustment behaviour. An example of such an approach is the accelerator model with error-correction, introduced into the investment literature by Bean (1981). More recent applications include Driver and Moreton (1991), Darby et al. (1999) and Mairesse et al. (1999).

A common starting point for these studies is a long-term relation between the desired capital stock (K_{it}^*), output (Y_{it}) and the user cost of capital (J_{it}):

$$K_{it}^* = A_i Y_{it} J_{it}^{-s} \ . \tag{1}$$

This formulation is consistent with profit maximisation under CES production technology. According to common practice in the literature, we assume a long-term capital-output elasticity at unity. The special case of Cobb Douglas production technology would imply **$s = 1$**. On the other hand, a fixed captital-output ratio implies that **$s = 0$**. Imperfect competition with firm-specific mark-up can be reflected by the constant term A_i. Alternatively, the constant term may reflect a company-specific distribution parameter in the production function. Letting small-caps indicate natural logarithms, Equation [1] implies for the long-term equilibrium relation:

$$k_{it}^* = a_i + y_{it} - \boldsymbol{s} j_{it} \ . \tag{2}$$

The property of a unity long-term elasticity between desired capital and output can now be exploited by letting the production level serve as a proxy for the desired capital stock. Our next step is to envelope Equation [2] in a general dynamic model, accounting for the sluggishness of adjustment of the actual capital stock. As noted by Bond et al. (2003), an implicit assumption of this approach is that the desired level of capital without adjustment costs is proportional to the desired capital level in the presence of adjustment costs. Further, we assume that any variation in the user cost of capital can be captured by the combination of firm-specific effects and time-specific dummy variables.[4] Bearing this in mind, our point of departure is a standard 2nd order autoregressive distributed lag (ADL) for the capital stock (k_{it}):

$$k_{it} = \boldsymbol{a}_1 k_{it-1} + \boldsymbol{a}_2 k_{it-2} + \boldsymbol{b}_0 y_{it} + \boldsymbol{b}_1 y_{it-1} + \boldsymbol{b}_2 y_{it-2} + u_{it} \ , \tag{3}$$

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[4] The treatment of the user cost is in line with previous applications of accelerator models with error-correction for investment studies. Our specification allows for differences in user costs between companies, but the implicit assumption is that changes over time in the user costs are common to all companies. At this point it should also be noted that a key result from the empirical investment literature is that price and volume variables are far more important for capital formation than variables affecting user costs (Chirinko, 1993). Casual observation also suggests that capital costs play a subordinate role in the investment process of oil and gas companies. Management and financial market attention is rather focused oil price expectations, reserve and production potentials (in addition to various risk indicators).

where u_{it} is an error term. Our assumption of a long-run unit elasticity of capital with respect to output requires that $(b_0 + b_1 + b_2)/(1 - a_1 - a_2) = 1$. We may therefore take differences and rearrange Equation [3] to obtain a standard error-correction model of the type:

$$\Delta k_{it} = (a_1 - 1)\Delta k_{it-1} + b_0 \Delta y_{it} + (b_0 + b_1)\Delta y_{it-1}$$
$$+ (a_1 + a_2 - 1)[k_{it-2} - y_{it-2}] + u_{it} , \qquad [4]$$

where the bracketed term $(k_{it-2} - y_{it-2})$ represents the error-correction term (e_{it-2}). Error-correcting behaviour now implies that its coefficient is negative. This means that any deviation between the actual and the desired capital stock will be corrected through investment. To arrive at a specification in the investment rate (I_{it}/K_{it-1}), we follow the mainstream literature and approximate the change in the desired capital stock as $Dk_{it} = (I_{it}/K_{it-1}) - d_i$, where d_i is a company-specific depreciation rate. For simplicity of exposition, we also define the investment rate (i_{it}) as: $i_{it} \equiv I_{it}/K_{it-1}$. Further, we include x_{it} as a set of control variables, to allow for the influence of cash flow measures, uncertainty proxies and operational indicators that may have an influence on investment. Finally, we include fixed effects (h_i) and time-specific error-components (z_t) in the error-term according to the following structure: $u_{it} = h_i + z_t + e_{it}$, yielding for the equation to be estimated:

$$i_{it} = r i_{it-1} + g_0 \Delta y_{it} + g_1 \Delta y_{it-1} + l e_{it-2} + p x_{it} + h_i + z_t + e_{it} , \qquad [5]$$

where r is an autoregressive coefficient on the lagged dependent variable, l is the error-correction coefficient, indicating the speed of adjustment towards the long-term equilibrium. The deviation from the long-term equilibrium is represented by $e_{it-2} = k_{it-2} - y_{it-2}$.

The scope of our study is to investigate if investment behaviour among international oil and gas companies has changed over the last 14 years. To explore for structural breaks in the data-generating process, we need techniques that allow for parameter instability across historical sub-samples. Moreover, our model should be sufficiently flexible to account for a structural break that applies only to a subset of the variables involved. As an example, the autoregressive structure of the model (i_{t-1}) may well be stable, whereas behavioural change is observable for uncertainty variables (x_{it}), and possibly also for the speed of adjustment, as measured by the estimated response to changes in the equilibrium error (e_{it-2}). To open for this kind of instability, we employ a flexible dummy-variable technique on the parameters of the models.

154

We illustrate the technique for the $\boldsymbol{p}$ vector of the control variables (x_{it}). Letting t^* represent the year of the structural break, dummy variables are defined as follows:

$$d_t = \begin{cases} 0 & if \quad t < t^* \\ 1 & if \quad t \geq t^* \end{cases} \qquad [6]$$

Equation [6] introduces the shift variable to be applied for the subsequent years after the structural break. Now, the $\boldsymbol{p}x_{it}$ term of Equation [5] is replaced by a composite term:

$$\boldsymbol{p}x_{it} = \boldsymbol{p}_0 x_{it} + \boldsymbol{p}_1 d_t x_{it} \ , \qquad [7]$$

A null of stability implies $\boldsymbol{p}_1 d_t = 0$, and the total impact of a change in the x_{it} variable is represented by the parameter $\boldsymbol{p}_0$ for the full sample period. On the other hand, if $\boldsymbol{p}_1$ is statistically significant, the null is rejected, and we have evidence of a structural break for the variable in question. For this case, the sensitivity of investment rates with respect to changes in x_{it} is still given by $\boldsymbol{p}_0$ for the first period ($t < t^*$). However, an additional shift parameter ($\boldsymbol{p}_1$) is introduced at the point of the structural break ($t = t^*$), and the full effect is therefore $\boldsymbol{p}_0 + \boldsymbol{p}_1$ for the subsequent years of the sample. Statistical tests may now be applied to test for these structural breaks for each of the variables, and simultaneously for any (sub-) set of variables of our model.[5]

In addition to dynamic part of the model (i_{it}, i_{it-1}, $\boldsymbol{D}y_{it}$, $\boldsymbol{D}y_{it-1}$) and the error-correction term (e_{it}) of Equation [5], our estimated models also include four financial and operational indicators in the vector of control variables (x_{it}). The first is a cash-flow measure ($c_{it}=CF_{it}/K_{it-1}$), to test for the impact of financial factors in the investment process (Schiantarelli, 1996; Hubbard, 1998). In addition, the cash-flow variable will capture the effect of oil price variation, including changes in adaptive oil price expectations.[6] The next variable is

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[5] Based on the result from preliminary estimation, the shift is restricted to the error-correction term (e_{it}) and the vector of control variables (x_{it}). Econometric tests are not supportive of a structural shift for the dynamic part of the model (i_{it-1}, $\boldsymbol{D}y_{it}$, $\boldsymbol{D}y_{it-1}$).

[6] A range of control variables has been tested, including various oil price variables, result variables and cash-flow variables. The best econometric results were obtained in a model with the described cash-flow indicator as the financial variable. Joint significance of model parameters of this version outperformed alternative specifications, and the sign and magnitude of the estimated coefficients allowed the most reasonable interpretation. We therefore assume

included to capture industry-specific risk, as proxied by oil price volatility (s_{it}). As with the cash-flow variable, the econometric performance of this volatility variable is improved when divided by lagged capital stock ($v_{it} = s_{it}/K_{it-1}$), and this scaling procedure is therefore adopted in the estimated model. We also include a measure for individual company exposure to oil vs natural gas. Our o_{it} variable represents the share of oil in total oil and gas reserves, and the variable is lagged one period in the estimated models, to capture the lag structure in the development of oil and gas reserves. Finally, the reserve replacement rate (r_{it}) is included to test for the specific influence on investment from reserve replacement efforts.[7]

4 Data

Our data sample is an unbalanced panel of oil and gas companies (1991-2005) drawn from John S. Herold Company's (JS Herold) oil and gas financial database.[8] The JS Herold database consists of financial and operating data from annual financial statements of more than 500 publicly traded energy companies worldwide. From this universe we select firms mainly engaged in exploration and production (E&P or upstream) activities. This leaves us with 253 companies and a sample of 3290 potential firm-years.

On this initial sample we apply a screening procedure. First, we exclude all firms with less than 100 employees in the first year of observation. Second, we require at least six years of data from each firm, and firms not meeting this requirement are excluded. Third, firms that have undergone major restructuring, such as mergers and acquisitions or de-mergers, need to be excluded as the usual models of investment may not characterise these discrete adjustments well. We therefore remove observations where the

that all relevant financial information, including oil price variation, is captured by the cash-flow variable retained in the preferred model version.

[7] The key differentiating factor of the production technology among oil and gas companies is the reserve concept. The stock of oil and gas reserves represents a crucial input in this production process. But oil and gas reserves are not readily available in well-functioning input markets, like the case is for most other traditional inputs. Rather, oil and gas companies have to invest in very risky exploration activities, to support and grow the base of oil and gas reserves. Thus, our reserve replacement variable is included to capture the impact on total investment from companies' efforts to sustain production activity over the longer term.

[8] Founded in 1948, John S. Herold Inc. is an independent research firm that specialises in the analysis of companies, transactions, and trends in the global energy industry (http://www.herold.com/).

change in sales from any one year to the next exceeded a factor of three.[9] Missing observations, lagged variables, and the screening procedure reduce the number of firm years to 1765, a total reduction of 46%.

Table 1. Descriptive statistics for data sample

	Obs.	*Mean*	*St. dev.*	*Min.*	*Max.*
i_{it}	1765	0.288	0.600	-0.913	12.801
y_{it}	1765	0.140	0.355	-0.837	5.300
k_{it}	1765	7.004	2.297	1.082	12.179
c_{it}	1765	0.211	0.323	-5.170	3.593
v_{it}	1765	0.372	1.079	0.000	17.549
r_{it}	1765	1.426	1.552	-14.490	19.171
o_{it}	1765	0.438	0.271	0.000	1.000

Data source: JS Herold (http://www.herold.com).

Following Miller (1990), the majority of investment studies combines stock and flow information using the perpetual inventory method to construct capital stocks ($p_t^I K_t$):

$$p_t^I K_{it} = (1-\boldsymbol{d}) p_{t-1}^I K_{it-1} \frac{p_t^I}{p_{t-1}^I} + p_t^I I_{it} \qquad [8]$$

K_{it} is the capital stock at current replacement cost, p_t^I is the price of investment goods,[10] I_{it} represent real investment, and $\boldsymbol{d}$ is the constant rate of depreciation, assumed at 8 per cent.[11] In line with previous research, we use the net book value of tangible fixed capital assets in the first observation in the sample period (adjusted for previous years' inflation) as our initial value. Our proxy for the price of investment goods (p_t^I) is the implicit price deflator

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[9] A factor of 3 is only slightly higher than the maximum year-to-year change in oil price in our sample. A lower factor may therefore exclude observations not affected by a major restructuring, where annual sales growth is simply induced by oil price changes.

[10] Our proxy for the price of investment goods is the implicit price deflator for non-residential gross private domestic investment (structures, equipment and software) from the US national accounts.

[11] Bond et al. (2003) also assume a constant rate of depreciation of 8 per cent for manufacturing companies. For comparability, we assume the same rate of depreciation.

for non-residential gross private domestic investment (structures, equipment and software) from the US national accounts. Subsequent estimates of capital stocks were calculated according to Equation [8].

Our investment variable (I_{it}) is based on financial statement data on capital expenditure and additions to property, plant and equipment (PP&E), acquisitions and proceeds from sales of PP&E (disposals). We apply a measure of investment including M&A (acquisitions and disposals) as this provides the best econometric results. The investment rate is calculated as investment divided by lagged capital stock. As Table 1 shows the mean investment rate is 0.288, which is higher than comparable studies of investment behaviour. In a study of European manufacturing companies, Bond et al. (2003) document investment rates of 0.110 to 0.125. With comparable rates of depreciation, this suggests a slightly higher rate of capital accumulation in our sample than in previous studies of manufacturing industries. This assertion is also supported by the fact that our sample reveals a higher average change in production (0.140) and cash flow rates (0.211) than comparable studies.

Our estimated models also include four financial and operational indicators in the vector of control variables (x_{it}). Cash-flow (CF_{it}) is computed by adding back depreciation (as reported in the financial statements) to net income (as reported). In order to improve econometric performance, we scaled this cash flow with lagged capital, resulting in the c_{it} variable of our econometric analysis. While the mean c_{it} in our sample is 0.211, the investment rate i_{it} is 0.288 (Table 1). This indicates that the average oil and gas firm in our sample have been investing more money than it has been able to generate internally.

The product mix (o_{it}; oil exposure) is calculated as the ratio of oil reserves to total oil and gas reserves, as reported in the oil companies' supplementary oil and gas disclosures. While oil is reported in million barrels (mmbbl), gas is reported in billion cubic feet (bcf). In order to calculate oil and gas reserves in barrels of oil equivalent (boe), a conversion factor of 6 is used (i.e. 6 bcf = 1 mmbbl). Our sample reveals that the mean oil share of total reserves is approximately 44 per cent.

The reserve replacement ratio (r_{it}) is calculated as the ratio of annual reserve additions to annual extraction. A reserve replacement ratio of 1.0 implies full replacement of the annual production volume (through exploration and/or acquisitions). A mean r_{it} of 1.426 in our sample indicates that the average firm

has generated more reserves than they have decimated through production over the period (Table 1).

Carruth et al. (2000) survey the variety of approaches to the measurement of uncertainty in empirical investment studies. To approach the most important source of uncertainty for international oil and gas companies, our point of departure is the historical volatility of the oil price.[12] Based on daily price (p_{kt}) data for the brent blend quality for each of the last 15 years, we calculate annualised standard errors of daily returns ($r_{kt} = \boldsymbol{D}p_{kt}$, $k = 1, 2 . . N$, $t = 1992\text{-}2005$):

$$\boldsymbol{s}_t = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left(r_{kt} - E(r_{kt})\right)^2}, \qquad [9]$$

where N is the annual number of trading days (~ 260) and the average daily change in each year is used as a proxy for $E(r_{kt})$. This methodology is according to financial market practice, and in line with previous related studies (e.g., Paddock et al., 1988; Hurn and Wright, 1994). A running daily calculation of this volatility measure is illustrated in Figure 1 in the Introduction (p. 3). Oil price volatility has increased from an annualised level of 20-30 per cent during the early 1990s to 40-50 per cent during 1998-2002, when the oil industry endured substantial restructuring and a severe oil price drop during the Asian economic crisis (Weston et al., 1999). Since then, oil price volatility has fallen to levels just below 40 per cent, which is slightly higher than average levels from the 1990s.

5. Estimation and results

Our econometric model is a dynamic panel data model for investment behaviour, to be estimated with micro data for international oil and gas companies over the period 1992-2005. The introduction of the lagged dependent variable on the right hand side of the econometric equation introduces a potential endogeneity bias. The standard approach to potentially

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[12] A range of options is available for uncertainty indicators, and no consensus is yet obtained for the appropriate way to proxy uncertainty in empirical models of investment. Forward-looking volatility forecasting models (Engle, 1982) are common in early empirical studies of investment and uncertainty. However, this strategy also introduces model uncertainty in two stages. Furthermore, ARCH and GARCH models estimated on high-frequency data will usually imply a low persistence of shocks for our purpose. The majority of recent work therefore relies more directly on observed uncertainty measures (Carruth et al., 2000).

endogenous explanatory variables is to augment the estimation procedure with additional exogenous instrumental variables. Bond (2002) show that a range of instruments is available in the lagged differences and levels of endogenous and predetermined variables. As additional instrument variables we also include total revenue, as well as annual dummy variables. We apply the general method of moments (*GMM*) approach initially suggested by Arellano and Bond (1991), and refined by a range of subsequent contributions. See Arellano (2003) for an updated review.

Our point of departure for the econometric estimation is the model specified in Equation [5]. Specifically, we regress the investment rate (i_{it}) against lagged investment (i_{it-1}), current and lagged production growth ($\boldsymbol{D}y_{it}$, $\boldsymbol{D}y_{it-1}$) and an error-correction term ($e_{it-2} = k_{it-2} - y_{it-2}$) that captures the hypothesised equilibrium-correcting adjustment in the data-generating process. In addition to the dynamic part of the model (i_{it}, i_{it-1}, $\boldsymbol{D}y_{it}$, $\boldsymbol{D}y_{it-1}$) and the error-correction term (e_{it}), we include four variables to control for the influence of cash-flow variations (c_{it}), oil price uncertainty (v_{it}), reserve-replacement efforts (r_{it}) and product mix (o_{it}).

As pointed out by Bond (2002), the instruments available for the equations in first differences are likely to be weak when the individual time series are highly persistent, i.e. they have near unit root properties. The reason is that differenced unit root variables will approach random walks, offering limited information as instrumental variables.[13] The original Arellano Bond estimator therefore requires autoregressive parameters to be significantly less than one in simple autoregressive specifications. Our specification of an error-correction model also requires that the variables of the estimated equation are stationary. We therefore estimate a simple *AR(1)* specification for the variables in our estimated equation to test the dynamic properties of our model variables.

Table 2 reports *OLS*, *fixed-effects* and *GMM* results for the estimated auto-correlation coefficient from the *AR(1)* regression for all our model variables. The hypothesis of an exact unit root is rejected for all variables. These results are consistent with our dynamic modelling approach. Observe also that the

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[13] Persistent time series are defined by the role of history for their development, with positive correlation between current and lagged values. As an example, consider the simple *AR(1)* process: $y_t = \boldsymbol{a}y_{t-1} + v_t$. Subtracting y_{t-1} from both sides now yields: $y_t - y_{t-1} = (\boldsymbol{a} - 1)y_{t-1} + v_t$. Consequently, as the autoregressive coefficient $\boldsymbol{a}$ approaches 1, $\boldsymbol{D}yt$ ($= y_t - y_{t-1}$) will approach a random walk (v_t). In general, a random walk process ($I(0)$) for the difference implies that the level of the same variable is integrated of degree 1 ($I(1)$).

derived error correction term e_{it} ($= k_{it} - y_{it}$) is clearly less persistant than both of its two constituents k_{it} and y_{it}. As suggested by the error-correction literature (e.g., Engle and Granger, 1987; Hendry and Juselius, 2000), the combination of highly persistent variables in a cointegrating vector produces a variable with improved stationarity properties for econometric estimation. We take these results as support for our specification of investment as an accelerator model with error-correction.

**Table 2. AR(1) estimates for model variables**

Depvar	OLS	Fixed Effects	System GMM
i_{it}	0.063*** (0.000)	-0.037 (0.477)	-0.253** (0.012)
y_{it}	0.972*** (0.000)	0.767*** (0.000)	0.960*** (0.000)
k_{it}	0.965*** (0.000)	0.840*** (0.000)	0.956*** (0.000)
e_{it} ($= k_{it} - y_{it}$)	0.873*** (0.000)	0.724*** (0.000)	0.748*** (0.000)
c_{it}	0.347*** (0.000)	0.013** (0.011)	0.005 (0.935)
v_{it}	0.723*** (0.000)	0.598*** (0.000)	0.574*** (0.000)
r_{it}	0.039* (0.086)	-0.024 (0.648)	-0.141*** (0.001)
o_{it}	0.914*** (0.000)	0.469*** (0.000)	0.784*** (0.000)

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

Our next step is to test for the structural break we are hypothesising. At this point, our approach draws on a flexible dummy-variable approach equivalent to the framework introduced by Chow (1960), and refined in a series of subsequent contributions (e.g., Holtz-Eakin et al., 1988; Andrews and Lu, 2001). Equation [5] is estimated with all control variables and all shift parameters (cf. Equations [6]-[7]). We then test the joint significance of all shift parameters, with a null of no structural break. Rejection implies statistical support for the presence of a structural break. Further, our testing procedure implies that the point of the structural break (t^*) is endogenised, as the described stability test is repeated for all the possible break points (years) granted by our data set. We test for structural breaks in our model for all the

years between 1995 and 2004, one by one.[14] Results from these tests provide valuable guidance in our selection of year for the structural break (t^*), which we suspect took place sometime in the late 1990s. Relevant χ^2 test statistics from this procedure are illustrated in Figure 2, along with their respective p values.

Figure 2. Detection of structural break
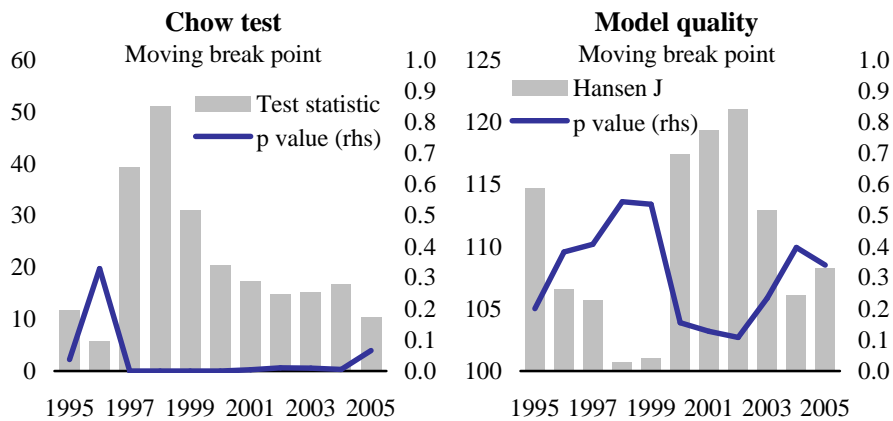
GMM estimation of Equation [5] with shift parameters for error correction term (e_{it}) and the four control variables ($x_{it} = [\ c_{it},\ v_{it},\ r_{it},\ o_{it}\ ]$).

Figure 2 illustrates that the likelihood of a structural break is at its maximum in 1997/1998. We also report the Hansen's *J* statistic, from a test for the exogeneity properties of our instrument matrix. Rejection of the null implies that the validity of our over-identifying restrictions is threatened, which would be an indication of model misspecification. The power of this test is at its minimum in 1998, implying that the validity of our over-identifying restrictions is at its highest for the model with a structural break in 1997/1998. We take this as further support for the hypothesis of a structural break in investment behaviour. The assumption of a structural break in oil and gas investment in 1997/1998 is therefore adopted in the following econometric analysis.

We now proceed to the estimation of our accelerator model with error-correction, as stated by Equation [5]. Table 3 presents the result for three

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[14] The presence of lagged variables in the model, and the application of deeply lagged instruments, reduces the quality of this test procedure for breaking points further back than 1995.

different model versions. Model 1 is the model in its simplest for, without any control variables (x_{it}). Model 2 includes four financial and operational control variables as described above. The shift dummies of Equation [6] are applied in Model 3, to allow for variable-specific structural breaks in investment behaviour in the error-correction term (e_{it}) as well as the control variables (x_{it}), whereas stability over the period is assumed for the dynamic part of the model (i_{t-1}, $\boldsymbol{D}y_t$, $\boldsymbol{D}y_{t-1}$).[15]

Table 3 also presents a selection of model diagnostics, which indicate satisfactory performance for all the three model versions. The Wald $\boldsymbol{c}^2$ statistic is a test for joint signficiance of all model parameters. Arellano and Bond (1991) recommend the Sargan statistic to test the exogeneity properties of the instruments as a group, with a null of validity. However, the Sargan statistic is sensitive to heteroskedasticity and autocorrelation, and tends to over-reject in the presence of either. We therefore follow follow Roodman's (2006) advise and report the more robust Hansen J statistic as an indicator for the validity of the over-identifying restrictions.[16] $AB\ AC(n)$ is the Arellano-Bond test for n^{th}-order autocorrelation in the differenced residuals, with a null of no autocorrelation. Non-rejection of 1st order autocorrelation is as expected, and not critical for the validity of the differenced equations. 2nd order autocorrelation in the residuals of the differenced model would be more troublesome, as it would imply a breach of the assumption of well-behaved residuals in the level representation of our model.

The lagged investment rate (i_{it}) takes a small, negative and statistically significant coefficient, indicating that periods of high investment are normally followed by a downward correction, and vice versa. According to our results, production growth ($\boldsymbol{D}y_{it}$, $\boldsymbol{D}y_{it-1}$) is an especially important driver for investments among oil and gas companies, with sizeable, positive, and highly significant parameter estimates. On average, an increase in oil and gas production growth by one percentage point yields an increase in the investment rate of 0.67 percentage points (p value < 0.01) in our preferred model.

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[15] This assertion is supported by statistical inference from preliminary estimations, where the structural shift was allowed also for the dynamic part of the model. These full-fledged models produced more insignificant parameter estimates, and their overall quality diagnostics proved them inferior to the presented estimated models.

[16] The Hansen J statistic is the minimised value of the two-step *GMM* criterion function (Hansen, 1982).

Table 3. Estimated accelerator models with error-correction

System GMM estimates obtained with Stata 9.0

	Model 1	*Model 2*	*Model 3*
Estimated coefficients [a]			
Intercept	2.116*** (0.000)	2.382*** (0.001)	1.175*** (0.004)
i_{it-1}	-0.077* (0.081)	-0.083** (0.027)	-0.127* (0.016)
$D y_{it}$	0.613*** (0.000)	0.504*** (0.000)	0.443*** (0.000)
$D y_{it-1}$	0.258*** (0.001)	0.204*** (0.005)	0.162** (0.033)
e_{it-2}	-0.184*** (0.000)	-0.201*** (0.001)	-0.059 (0.170)
$d_t \cdot e_{it-2}$			-0.055*** (0.001)
c_{it-1}		0.200*** (0.001)	0.979*** (0.000)
$d_t \cdot c_{it-1}$			-0.787** (0.027)
v_{it}		-0.241 (0.314)	-0.554*** (0.000)
$d_t \cdot v_{it}$			1.128*** (0.000)
o_{it}		-0.247*** (0.005)	-1.162*** (0.000)
$d_t \cdot o_{it}$			1.392*** (0.000)
r_{it}		0.028*** (0.005)	0.069*** (0.006)
$d_t \cdot r_{it}$			-0.058* (0.072)
Model diagnostics			
Wald c^2	119.94*** (0.000)	220.77*** (0.000)	292.88*** (0.000)
Hansen J	176.84 (0.133)	158.50 (0.364)	100.70 (0.546)
AB AC (2)	-0.01 (0.996)	0.03 (0.972)	-0.37 (0.709)
Firms (#)	232	232	232
Obs (#)	1737	1737	1737

Dependent variable: Investment rate (i_{it}). Explanatory variables: lagged investment rate (i_{it-1}), production growth ($D y_{it}$, $D y_{it-1}$) error-correction term ($e_{it-2} = y_{it-2} - k_{it-2}$), cash-flow variable ($c_{it}$), oil price volatility (v_{it}), reserve replacement efforts (r_{it}) and relative oil exposure (o_{it}). See Section 3 and 4 for definition and description of model variables.
*) Significant at 90, **) 95 and ***) 99 per cent confidence level, respectively
[a] p-values in brackets.

Our choice of model specification is supported by the plausible and significant estimate for the error-correction coefficient (Kremers et al., 1992), except in Model 3. The parameter estimate of the error-correction term (e_{it}) suggests that 12-20 per cent of any equilibrium error is adjusted every year. This may seem sluggish, but compares well with previous empirical studies for manufacturing industries (e.g., Mairesse et al., 1999; Bond et al., 2003). The structural break parameter suggests that the pace of adjustment was slower in the early 1990s than over the last years of the sample. This agrees well with industrial developments over the last 10 years or so; intensified restructuring and improvement efforts, accelerating technology diffusion, enhanced competition and increased uncertainty (Weston et al., 1999). Consequently, industrial upheaval contributed to a more flexible investment process, with higher rates of adjustment than in previous years.

We also obtain material precise parameter estimates for the cash-flow variable (c_{it}). A common interpretation used to be that these coefficients represent signals of capital market imperfection and financial friction (Hubbard, 1998). However, we recommend caution in the interpretation of these coefficients. Even without the common source of measurement error from the structural models (Erickson and Whited, 2000), critics have argued that significant cash-flow coefficients might be due to model misspecification (e.g., Kaplan and Zingales, 1997; Gomes, 2001). Moreover, the fact that our reduced-form model is not explicitly linked to an underlying theory of investment behaviour also implies that the cash-flow coefficient does not have a straightforward interpretation. Still, our results provide econometric evidence that access to internal funds plays a role in the data-generating process of firm investment. Prior to the structural break in 1998, when the oil price was low, earnings were modest and profitability was moderate, our results suggest that availability of internal funds played a material and statistically significant role in capital formation. The estimated coefficient of 0.98 implies that variations in the cashflow rate produced similar changes in the investment rate during this period.

This also corresponds well to casual observation across the industry in the aftermath of the Asian economic crisis and the subsequent oil price drop in 1997-1998. However, sentiments changed in 1998, and the response in oil and gas investment to the subsequent oil price increase was muted. The shift parameter for our cashflow variable cuts the original coefficient by 0.79, suggesting that the connection between investment and internal funds has become weaker over the last 10 years. A likely interpretation is that financial market pressures for capital discipline in the aftermath of the Asian economic

crisis put a lid on oil and gas investments from the late 1990s (Osmundsen et al. 2006, 2007).

The economic results may seem even more thought-provoking for our uncertainty indicator (v_{it}). Table 3 suggests that the role of uncertainty in the investment process has changed markedly over the 15 years of our data sample. During the first period, an increase in uncertainty gives a statistically significant dampening effect on oil and gas investment, as implied by standard theory of irreversible investment and real waiting options (Dixit and Pindyck, 1994; Carruth et al., 2000). However, recent theoretical contributions (Kulatilaka and Perotti, 1998; Smit and Trigeorgis, 2004) point out that investment implies not only the sacrifice of a waiting option, but also a potential reward from the acquisition of future development options. For the oil and gas industry, an increase in oil price volatility will increase the value of both these types of real options. Aguerrevere (2003) also notes that long construction lags, which are typical for the oil and gas industry, tend to undermine the net effect of uncertainty on investment. The reason is that the time-to-build factor increases the value and relevance of future development and growth options in the investment decision. Thus, the theory of compound options may give rise to a positive relationship between investment and uncertainty. With a positive and highly significant coefficient for the period after 1998,[17] an increase in uncertainty seems to have had a stimulating effect on capital formation over the last few years. This result should be interpreted in the context of imperfect competition, resource scarcity and strategic investments, which have become increasingly important in the international oil and gas industry (see also Weston et al., 1999).[18]

The estimated models also provide evidence that gas-prone companies are characterised by a higher rate of capital accumulation than companies dominated by oil reserves. This effect is captured by our o_{it} variable, which represents the share of oil in the total reserve base. We see this as an indication of the huge investment requirements on the companies who shifted production from oil to natural gas over the 1990s. However, the difference in

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[17] Based on the far-right column of Table 3 (Model 3), the sum of the two estimated volatility coefficients is $-0.554 + 1.128 = 0.574$, with $p < 0.01$.

[18] Boyle and Guthrie (2003) also suggest that financial frictions may increase the risk of future funding shortfalls. This will reduce the general value of waiting, and may therefore increase investment beyond the optimal level. Moreover, an additional source of a positive investment/uncertainty relationship is introduced. Based on this idea, an interaction term between cashflow and uncertainty has also been tested in our model. However, this combined variable did not produce significant parameter estimates, and could therefore not be included in the preferred model.

investment rates between oil-prone and gas-prone companies seems to be a phenomenon of the 1990s. More specifically, our results indicate that average investment rates of oil-prone companies have caught up with gas-prone companies since the turn of the century.

Finally, our results suggest that reserve replacement efforts drew capital resources beyond the requirements of production growth over the first period of our sample. On the other hand, the effect is largely outweighed by the shift parameter for this variable, implying that no specific investment impulse can be attributed distinctly to reserve replacement in the period after 1998. The background for this development is related to the fact that accessible oil and gas reserves have become increasingly scarce. International oil and gas companies struggle to replace their production, at increasing access cost for new reserves. Even though reserve replacement rates have turned down, the involved capital requirements are probably upheld. This constitutes a likely explanation for the negligible impact on oil and gas investment from reserve replacement efforts over the last few years.

6. Conclusion

The process of capital formation in the oil and gas industry is an important part of the supply side dynamics in the oil market. Understanding how oil and gas companies think in terms of investment is therefore essential to develop and maintain the required insights for meaningful analyses of oil price formation. Over the last 15 years, international oil and gas companies have gone through a period of industry upheaval, restructuring and escalating market turbulence. Since the beginning of the 1990s, business principles have gradually gained ground, and today competition among international oil companies is more aggressive than ever. Easily accessible oil and gas reserves in market-oriented economies like USA, Canada and United Kingdom are faced with depletion. Oil and gas investments are now gradually redirected in a rat race for increasingly scarce oil and gas resources. On this background it should come as no surprise that investment behaviour among international oil and gas companies has changed gears.

We provide firm econometric evidence that the investment process among international oil and gas companies changed significantly towards the end of the 1990s. The investment process over the last years is more flexible than before, with significant changes in the role of explanatory factors like

uncertainty, reserve replacement efforts and product mix. We find robust statistical support for cash-flow effects, with recent investment rates less sensitive to changes in oil price and cash flow than in the early 1990s. More surprisingly, we find that the investment uncertainty relationship changed sign in the late 1990s. Whereas an increase in oil price volatility would reduce investments in the early years of our sample, investment over the last few years has gained stimulus from increasing oil price uncertainty. We see this as empirical support for recent contributions on investment and compound options. Finally, our results suggest that operational factors like product mix and reserve replacement efforts have lost some of their historical influence on the investment process.

Industrial leaders and their companies respond continuously to changing political and market environments. Their mindset and models may be stable for periods. However, from time to time their way of thinking is also challenged by external forces. And sometimes these pressures even bring about deeper changes. Our study demonstrates that such a change took place in the oil and gas industry in the 1ate 1990s, in response to the industrial upheaval and massive pressure from financial markets. A fruitful direction for future research would be to relate these changes to company characteristics, possibly within a structural model framework.

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Part 3

Oil company investment and market interaction

Chapter 6

Valuation of international oil companies

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Abstract[1]

According to economic theory, exploration and development of new oil and gas fields should respond positively to increasing petroleum prices. But since the late 1990s, stock market analysts have focused strongly on short-term accounting return measures, like RoACE, for benchmarking and valuation of international oil and gas companies. Consequently, exaggerated capital discipline among oil and gas companies may have reduced their willingness to invest for future reserves and production growth. Based on panel data for 14 international oil and gas companies for the period 1990-2003, we seek to establish econometric relations between market valuation on one hand, and simple financial and operational indicators on the other. Our findings do not support the general perception of RoACE as an important valuation metric in the oil and gas industry. We find that the variation in company valuations is mainly explained by the oil price, oil and gas production, and to some extent reserve replacement.

JEL classification: C22, G31, Q38

Key words: Oil exploration, Reserve generation; Industrial economics: Econometrics

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1. Introduction

During the last few years, global energy demand has been fuelled by healthy economic growth, both in the OECD area and in emerging economies – like China. On the other hand, production among international oil and gas companies has been stagnant, and OPECs market share and influence has increased correspondingly. Tight market conditions, political unrest in important supplying regions and increasing concerns for security of supply have caused a sharp increase in oil prices. Commentators and analysts have linked the current high oil prices to a lack of investments in the oil sector:

"*I am disappointed about the shortfall of investments on the supply side. Large, international oil companies seem to prefer looking for oil at the NYMEX trading floor, instead of exploring for resources around the world. They have a social responsibility, but prefer to buy back their own shares*,"

Dr. Fatih Birol, Chief Economist, International Energy Agency (IEA).

Casual observation and aggregate data support the view that oil and gas exploration and production has failed to respond to increasing oil prices over the last years. Figure 1 illustrates that production growth among Western major oil and gas companies has remained low. The figure also shows that the share of exploration spending in total E&P investments has been cut back substantially since 1990. Recent research has indicated a stronger relationship between cash-flow variables and investments (e.g. Caballero, 1999; Stein, 2003; Bertrand and Mullainathan, 2005). However, and increasing share of oil industry investments have been directed at short and medium term development projects rather than long-term reserve development (see also Dobbs et al., 2006).

The industrial dynamics of oil and gas can shed light on the changes in company behaviour over the last years. From around 1985 and towards the end of the 1990s, the international oil and gas industry was subject to extensive changes in their market, business and political environment. Globalization advanced rapidly, and had far-reaching implications for politics, economics, technology, competence, communication and financial markets. Oil and gas production gradually lost much of its former national, political and strategic superstructure, and financial principles gained ground throughout nations, industries and companies. The investment universe of the international oil and gas industry expanded, as more and more countries opened their petroleum sector for foreign direct investments. Deregulation and market liberalization progressed, and former national oil companies were

177

privatised all around the world. Finally, the oil and gas industry's failure to deliver satisfactory returns triggered a massive pressure for restructuring, strategic change and improved financial performance throughout the industry.

Figure 1. Investment and production growth among Western oil majors
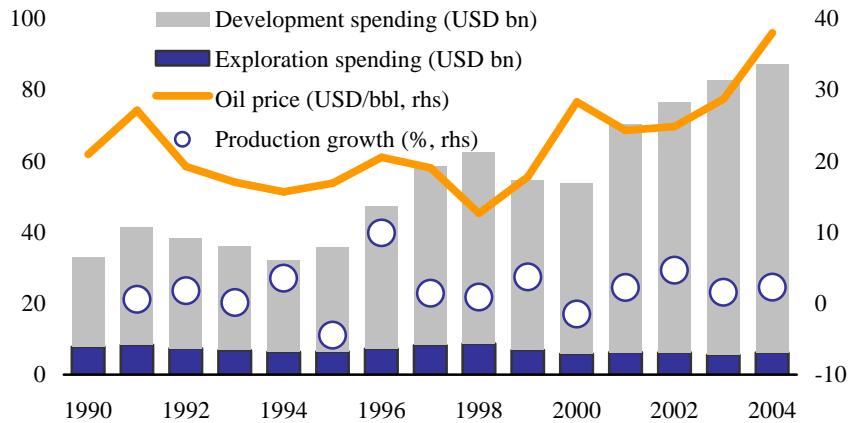
Data source: Deutsche Bank: Major Oils 2004.

A combined result of these developments was a wave of mergers and acquisitions that erased former prominent independent names such as Elf, Fina, Mobil, Amoco, Arco, YPF, Texaco, Phillips, Lasmo – and recently also Unocal (see Weston et al., 1999).

The international oil and gas industry entered a new stage towards the end of the 1990s, with heavy focus on production growth, cost-cutting, operational efficiency and short-term profitability. Scorecards of key performance indicators were presented to the financial market, as an implicit incentive scheme between investors and senior management in the companies. Communicated targets for short-term accounting returns (return on average capital employed) and production (cagr – compound annual growth rate) are listed for a selection of companies in Table 1.

The single most important performance indicator among international oil and gas companies has probably been RoACE.[2] This crude measure of capital return is a vital input to valuation analyses among stock market analysts. The measure has also been widely adopted by the international oil and gas

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[2] RoACE is defined as net income adjusted for minority interests and net financial items (after tax), as a percentage ratio of average capital employed.

companies, as illustrated in Table 1. As late as in March 2004, an investor presentation from Exxon argues the case for RoACE as a good indicator of financial performance.[3]

Table 1. Operational and financial targets communicated in 2003
Target year in brackets

Targets	RoACE	Production (cagr)
ExxonMobil	"Slight increase"	3 % (2007)
RD/Shell	13-15% ("longer term")	3 % (2007)
BP	"Slight increase"	3-5 % (2005)
ChevronTexaco	16-17 %	..
Total	15.5 % (2005)	5 % (2007)
ConocoPhillips	12-14% (2006)	3% (2006)
Eni	13 % (2006)	6% (2006)
BG Group	13% (2006)	12% (2006)
Hydro	8.5 % (2006)[*]	8 % (2007)
Statoil	12.5 % (2007)	6 % (2007)

Source: Company presentations.
[*] Communicated in 2004.

But RoACE has its flaws (e.g. Antill and Arnott, 2002). Inherent in the unit of production depreciation method in the oil sector, RoACE will fall in the first years of a project cycle. Later in the project cycle, when investments fall and the capital asset depreciates, RoACE will rise. Accordingly, RoACE is boosted in periods of divestment. As the lead times for exploration projects are long, the focus on short-term return on capital may have caused a shift in management attention to cost-cutting and value-maximization of existing reserves (efforts to increase oil recovery). The strong focus on RoACE and capital discipline by analysts and investment banks may thus have put a cap on oil companies' investment budgets. This behaviour may not reflect a reasonable trade-off between short-term profitability and long run production growth (development of new reserves).

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[3] ExxonMobil Analyst meeting, presentation given to the financial community on 10 March 2004, available at http://ir.exxonmobil.com/.

The intention of our paper is to study the interaction between the international oil and gas industry and the financial markets. We focus on international and integrated oil and gas companies, whereas previous studies have largely concentrated on US companies whose primary business involves exploration, development and production of oil and gas (e.g. Quirin et al., 2000; Berry et al., 2001; Bryant, 2003). Studies of the value relevance of accounting information from US E&P companies typically only consider 2-4 years of data. Our data set from 1990-2003 allows us to investigate market and company behaviour over 14 years, covering a full oil price cycle. This enables us to take advantage of the additional information in the time-series dimension. Additionally, our data set includes the recent period of substantial industrial restructuring. To our knowledge, no other study has examined the relationship between financial indicators and the financial markets for international oil and gas companies during this period. The most recent study covers the years 1994-1996 (Bryant, 2003), prior to the RoACE era of the latter part of the 1990's.

Our results have interesting implications for the understanding of empirical valuation mechanisms, and also shed additional light on supply-side dynamics in the oil market over the last few years.

The paper is organised as follows. Section 2 outlines the use of financial and operational indicators for valuation purposes among stock market analysts. Section 3 summarises relevant previous research on valuation and financial indicators. Section 4 presents a simple econometric model to test for the validity of the analysts' approach to stock market valuation, based on panel data for 14 major oil and gas companies over the period 1990-2003. Econometric results are presented and discussed in section 5, before section 6 concludes the study and points out possible directions for future research.

2. Key performance indicators and stock market valuation

Being a successful stock market analyst can be very rewarding, but is indeed also demanding. One single person often has to keep track of a wide range of companies, and provide superior advice and consistent investment recommendations to exacting investors with no concerns but to maximise their returns and to outperform their benchmarks. No wonder, therefore, that both analysts and investors have to relate to some simplified indicators that can help them in developing relative valuations and investment rankings.

Ideally, valuation should be undertaken by means of net present value analyses (cf. Antill and Arnott, 2000; Smith, 2004). The value of a company is then determined by the cash flow, growth and risk characteristics. However, stock market analysts often lack the necessary resources for continuous updates of detailed valuations, and therefore often resort to relative valuation (Damodaran, 2002). Relative valuation requires less assumptions, it is quick, and easy to communicate.

A widespread approach among oil and gas analysts has been to plot key performance indicators (KPIs) among the companies against their respective market-based valuation multiples (e.g. EV/DACF). These KPIs are also subject to active communication and continuous follow-up from the majority of Western oil and gas companies. An example is illustrated in Figure 2.

Figure 2. RoACE and EV/DACF 2003
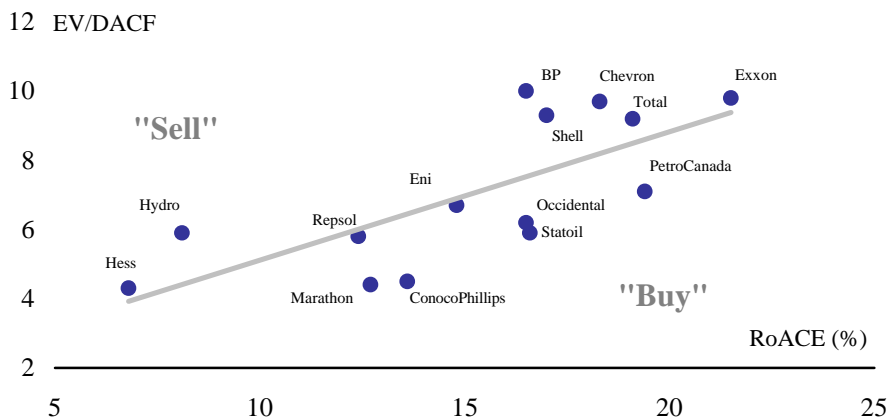
Data source: Deutsche Bank (2004), authors' regression line (cf Table 2).

RoACE is defined as net income adjusted for minority interests and net financial items (after tax), as a percentage ratio of average capital employed. Capital employed is the sum of shareholders' funds and net interest-bearing debt. EV, or Enterprise Value, is the sum of the company's debt and equity, at market values.[4] DACF, or Debt-Adjusted Cash Flow, reflects cash flow from operations plus after-tax debt-service payments.

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[4] For total debt, book value is used as a proxy for market value. This is less of a problem than for equity, as the difference between market values and book values is quite moderate for corporate debt.

Simple correlations are illustrated and calculated by analysts, at best with a regression line for a cross-section of observations. Note that the fit is not very convincing (R^2 below 0.5). Nevertheless, this method is applied to produce buying and selling signals for the companies' stocks. The tractability of Figure 2 is that the estimated regression line will divide the "cheap" companies from "expensive" companies, paving the way for indicative investment recommendations.

In their *Global Integrated Oil Analyser*, UBS Warburg (2003) state: "Our key valuation multiple is EV/DACF". . . . Each of the stocks which we rate a 'Buy' is trading below the average level relative to its returns. EV/DACF versus RoACE provides the key *objective* input into the process of setting our target prices." Similar statements about valuation, multiples and return on capital are made in Deutsche Bank's publication *Major Oils*, and related publications from other investment banks.

Other common key performance indicators include oil and gas production (growth), unit production costs, unit finding and development cost, and various measures of reserve replacement. Such a set of indicators can be perceived as a simplified implicit incentive scheme presented to the companies by the financial market. In responding to these incentives, the companies strike a balance between short-term goals of return on capital and long-term goals of production growth and reserve replacement.

3. Previous research

The interest for the relationship between financial performance and valuation of oil companies is not new.[5] A typical result from previous studies is that accounting information, such as earnings and book equity, is insufficient in the equity valuation process for oil and gas exploration companies. Although some studies have concluded that accounting information, such as net income and the book value of equity are value-relevant in cross-sectional studies, the dominating view has been that historical cost accounting is inappropriate for accurately conveying the oil and gas companies' financial performance to the financial markets. The following quote from the US Financial Accounting Standards Board underscores this point:

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[5] For general analyses of valuation multiples, see Damodaran (2002), and Liu et al. (2001).

"*An important quality of information that is useful in making rational investment, credit, and similar decisions is its predictive value—specifically, its usefulness in assessing the amounts, timing, and uncertainty of prospective net cash inflows to the enterprise. Historical cost based financial statements for oil and gas producing enterprises have limited predictive value. Their usefulness is further reduced because a uniform accounting method is not required to be used for costs incurred in oil and gas producing activities.*"

(FASB, 1982).

Thus, there is a potential hazard in relying solely on accounting measures, such as RoACE, in equity valuation.

McCormack and Vytheeswaran (1998) point out particular problems in valuation of oil and gas companies, since the accounting information in the upstream sector "does a distressingly poor job of conveying the true economic results". There are measurement errors in petroleum reserves. The response to new information is asymmetric; bad news is quickly reflected in the reserve figures whereas good news takes more time to be accounted. Moreover, reserves may be exposed to measurement errors since they are noted in current oil price (and not the mid cycle price), and since they do not include the value of any implicit real options. Finally, McCormack and Vytheeswaran claim a bias in the reported figures, as the large and profitable oil companies are more conservative in their reserve estimates than most of the others. This may explain the importance that many analysts have put on company reputation, a factor that has been partially jeopardised by the recent reserve write-down in Royal Dutch/Shell.

As for depreciation, the successful-efforts method produces initial depreciations that are too high. The unit-of-production method also has the effect of depreciating assets too quickly. A possible implication is that an extra cost is added to new activity, whereas inertia is rewarded. Other measurement challenges specific to the oil business are cyclical investment patterns and long lead times; these features can exacerbate the measurement errors. Similar effects may occur from the fact that discoveries are discontinuous and stochastic.

McCormack and Vytheeswaran (1998) perform econometric tests on financial relations for the largest oil and gas companies. Total shareholder return is tested against EBITA (earnings before interest, taxes and amortization), RONA (return on net assets), after-tax earnings, ROE (return on equity), and free cash flow. Estimated relations between valuation and financial indicators

183

were very weak or non-existent. More robust relations were established when Economic Value Added (EVA) and reserves were introduced in the model.[6]

Antill and Arnott (2002) address the strategic dilemma between return on capital and production growth in the petroleum industry. They claim that the 2002 RoACE-figures of some 15 % were due to the fact that the companies possess legacy assets that have low book values but still generate a considerable cash flow. If market values of the capital employed were applied, Antill and Arnott estimate that RoACE would fall to approximately 8-9 %, which is more consistent with the cost of raising capital. One problem with RoACE, they add, is that capital employed will always reflect a mixture of legacy and new assets. The implication is that RoACE does not adequately reflect incremental profitability,[7] and therefore falls short of being a good measure for current performance. Antill and Arnott (2002) argue that the oil companies should accept investment projects with lower internal rate of return (IRR), as the growth potential would add value to the companies.

Chua and Woodward (1994) perform econometric valuation tests for the American oil industry, 1980-1990. They test P/E-figures for integrated oil companies against dividend payout, net profit margin, asset turnover, financial leverage, interest rate, and Beta. However, they fail to uncover robust relations in the data set. The estimated interactions are weak, and some of them even have "wrong" signs. Chua and Woodward do not find support for the P/E-model. They therefore go on to test the stock price against cash flow from operation (following year and preceding year), dividend payout, net profit margin, total asset turnover, financial leverage, interest rate, Beta, and proven reserves. Future cash flow and proven reserves are statistically significant explanatory factors, thus offering support for a fundamental approach to valuation. An increase in proven reserves of 10% produced an average increase in the stock price of 3.7%.

Quirin et al. (2000), in their analysis of US oil and gas exploration companies 1993-1996, find that certain ratios such as the reserves replacement ratio, reserves growth, production growth and the finding costs-to-depreciation ratio are perceived by analysts as being instrumental during the equity valuation process of oil and gas companies. Their results indicate that these ratios provide incremental information over accounting

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[6] EVA is a trade mark of Stern Stewart & Co.
[7] Using measures as RoACE thus favors companies having a large fraction of legacy assets in their portfolio.

information, including earnings and book value of equity. Recently, Cormier et al. (2003) found that cash flows and changes in reserves provide incremental information over reported earnings for a data set of Canadian petroleum companies.

4. Data and model specification

Our data set consists of stock price and accounting information for 14 international oil and gas companies over the period 1990-2003, as reported by Deutsche Bank (2004).[8] The upper bound for the number of observations is 14x14 = 196. However, ovservations are missing for some of the companies in some of the years. For example, data is not available for Statoil before the company was listed in 2001. Hence, the number of observations is 142.

Key performance indicators in our data set include oil and gas production, reserve replacement ratios, unit production costs and unit finding and development costs. Oil and gas production (OGP_{it}) is defined as total production of liquids and natural gas, as reported in financial statements (SEC 10K reports).[9] The reserve replacement ratio (RRR_{it}) is calculated by dividing the sum of changes in proved reserves (discoveries plus revisions plus purchases minus sales as reported according to SFAS No. 69) by production.[10] This ratio is an indicator of the companies' ability to replenish annual production volumes and grow its reserves. Unit production costs (UPC_{it}) is defined as production costs (as reported according to SFAS No. 69) divided by production. Production costs include the costs to operate and maintain producing wells and related equipment and facilities. Finding and development cost (FDC_{it}) is defined as sum of costs incurred for exploration and development activities (as reported according to SFAS No. 69) divided by the changes in proved reserves from discoveries and revisions (total proved reserve additions). FDC_{it} represents the cost of finding a barrel of oil equivalent (proved reserves), and preparing it for production. RoACE (R_{it}), enterprise value (EV_{it}) and debt-adjusted cash flow ($DACF_{it}$) are defined and discussed in section 2. Our oil price variable (P_t) is the annual average of daily quotes of dated brent (source: US Department of Energy (EIA)).

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[8] The selection of companies include Amerada Hess, BP, ConocoPhillips, ChevronTexaco, Eni, Exxon, Marathon Oil, Hydro, Occidental Petroleum, Petro-Canada, Royal Dutch/Shell, Repsol YPF, Statoil, and Total.
[9] Filed with the U.S. Securities and Exchange Commission (SEC).
[10] Statement of Financial Accounting Standards No.69. "Disclosures about Oil and Gas producing activities".

If a company's stock is performing well, it is vital to know whether it is merely due to a favourable oil market sentiment, or if superior stock market performance can be attributed to real improvements in the company's underlying operations. In a cross sectional setting, variations in market multiples may be due to variations in upstream exposure among the oil and gas companies. Some oil and gas companies publish RoACE-figures that are normalised for oil and gas price volatility. However, normalization procedures and mid-cycle market assumptions will vary across companies.

Figure 3. Oil Price and RoACE for Western Major Oil Companies
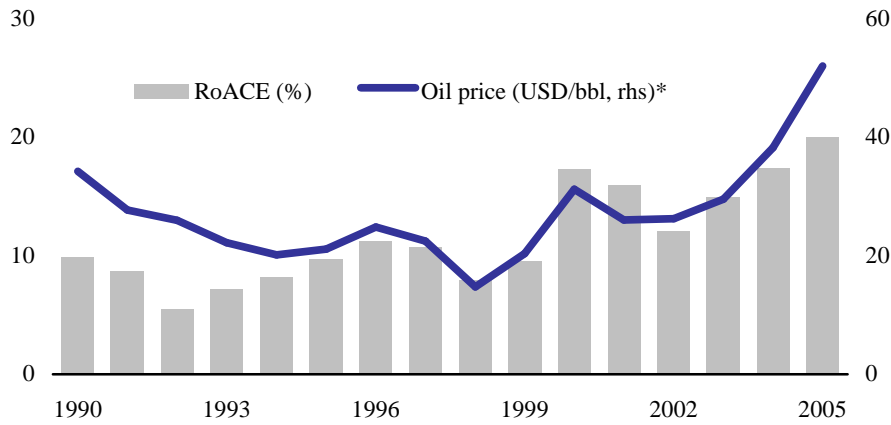
Data source: Deutsche Bank (2004).

Figure 3 indicates that average non-normalised RoACE does not add much information beyond the oil price. Thus, the benefits of normalised return figures should be obvious. Normalised RoACE figures are not available in our data set. The oil price is therefore included in the model to control for the cyclical price influence in output markets, as underlying performance is the target of our analysis. Our basic econometric model is:

$$m_{it} = A_i + \boldsymbol{a}P_t + \sum_{i=1}^{n} \boldsymbol{b}_i KPI_{it} + \boldsymbol{g}R_{it} + u_t \qquad [1]$$

m_{it} is the ratio between EV and DACF,[11] A_i is the set of company-specific dummies (or fixed effects), P_t is the crude oil price (dated brent), KPI_{it} is a

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[11] EV is enterprise value and DACF is debt-adjusted cash flow. Cf. section 2 for definitions and discussion.

vector of key performance indicators (e.g. production, unit production cost, finding and development cost, reserve replacement ratio etc.) and R_{it} represents RoACE.[12] a, b_i and g are the parameters to be estimated, and u_t is an error term with the usual white noise characteristics. In some regressions, a subset of the parameters will be restricted to zero.

Table 2. Cross-section regressions of EV/DACF against RoACE

Year	RoACE coefficient	p-value	R^2	Obs.
1990	-0.166	0.399	0.18	6
1991	-0.697[***)]	0.003	0.85	7
1992	-0.439[***)]	0.009	0.78	7
1993	-0.462	0.118	0.41	7
1994	-0.749	0.107	0.43	7
1995	-0.387[*)]	0.081	0.42	8
1996	-0.240	0.214	0.24	8
1997	0.096	0.378	0.08	8
1998	0.308	0.193	0.16	12
1999	0.841[**)]	0.011	0.46	12
2000	0.136	0.471	0.05	13
2001	0.136	0.559	0.03	13
2002	0.088	0.705	0.01	14
2003	0.359[***)]	0.002	0.56	14

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

5. Estimation and results

We start by estimating simple cross-section regressions of the market multiple against RoACE for each of the years in the panel. This provides evidence with respect to the reliability of simple plots and regressions like the ones in Figure 2 above, and which are commonly used by stock market analysts. Results from the initial cross-sectional regressions are presented in Table 2.

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[12] Various specifications have also been tested with expected oil price as the explanatory variable. We applied market expectations as observed in the futures market in preliminary regressions, as well as a range of weighted averages of historical prices (adaptive expectations hypothesis). In econometric terms, all these variables were outperformed by the observed oil price.

The number of observations vary from 6 (1990) to 14 (2003). The estimated RoACE coefficients measure the absolute response in EV/DACF to a change in RoACE of 1 percentage point. In general, these crude models perform rather poorly. The estimated coefficients are unstable, unfocused, and their t-values vary significantly over time. The statistical fit of these cross-sectional models is also not very impressive. R^2 varies from 0.01 to 0.56, with an average for the 13 equations at 0.34. The valuation relevance of simple cross-sectional regressions of EV/DACF on RoACE is therefore not justified.

Figure 3. Estimated RoACE coefficient from cross-section regressions
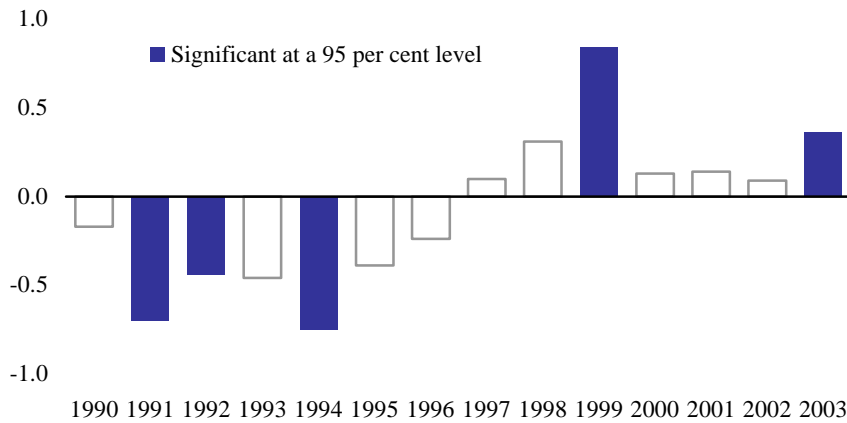
Still, there are a couple of insights that are worth mentioning. First, the estimated RoACE coefficient is negative (and significant) for a number of years early in the data period. For these years, the evidence suggests that the valuation impact from RoACE performance has actually been negative. Second, there is a positive trend in the estimated coefficients, as illustrated in Figure 3 (solid background on the bars indicates statistical significance at the 95 per cent level). Although the estimated valuation impact of RoACE performance is negative for the first half of the 1990s, the negative effect dwindles over time, and is replaced by positive coefficients for the last part of the period. However, the positive valuation impact from RoACE is statistically significant for only two of the years, namely 1999 and 2003.

To exploit the full power of our data set, we now estimate the simple formulation above for the full panel data set. The oil price is also introduced as an additional explanatory variable, in an attempt to correct for the influence on RoACE from fluctuating market conditions over the time

188

dimension of our data set. Estimated results from this specification are presented as Model 1 in Table 3.

Table 3. Estimated Panel Data Models for EV/DACF

	Model 1	Model 2	Model 3	Model 4
	OLS Pooled data	*OLS Company effects*	*OLS Company effects*	*2SLS Company effects*
Estimated coefficients [a]				
Oil price	-0.167[***] (0.006)	-0.111[*] (0.093)	-0.270[***] (0.000)	-0.332[***] (0.000)
RoACE	0.065 (0.263)	-0.004 (0.953)	0.056 (0.286)	0.042 (0.758)
Oil and gas production	..	..	0.004[***] (0.000)	0.004[***] (0.000)
Reserve replacement	..	..	0.065 (0.664)	0.039 (0.811)
Model diagnostics				
R^2	0.05	0.89	0.94	0.50
Joint significance	$F_{(2, 139)}$ = 3.95 p = 0.021	$F_{(16, 126)}$ = 64.60 p = 0.000	$F_{(18, 122)}$ = 99.55 p = 0.000	$F_{(16, 113)}$ = 7.13 p=0.000
Obs. (#)	142	142	140	130

[*] Significant at 90, [**] 95 and [***] 99 per cent confidence level, respectively.
[a] p-values in brackets.

In Model 1, the RoACE coefficient takes the "correct" sign, but is statistically insignificant. On the other hand, a highly significant negative relationship is revealed between EV/DACF and the oil price. The oil price coefficient is also highly significant. A negative effect on the valuation multiple from oil prices may seem contra-intuitive. However, a positive (negative) oil price shock will tend to inflate (deflate) current DACF. For the multiple to stay constant, enterprise value (EV) will have to adjust accordingly. Mean-reverting oil price expectations will imply that an oil price shock is temporary. The effect on earnings will not be persistent, and the valuation response will be muted. On impact, EV/DACF will therefore move contrary to the oil price.

Model 2 introduces company-specific dummy variables by allowing the constant term to vary by company, in addition to RoACE and the oil price. With this specification, the estimated oil price coefficient is somewhat lower than for model 1, and statistically significant only at the 10% level.

The estimated RoACE coefficient is now marginally negative, but the p-value is higher than in Model 1, and the statistical significance of this parameter is therefore also lower. However, the introduction of the company-specific effects adds substantial quality to the overall statistical explanation of EV/DACF. The estimated company-specific effects for Model 2 are illustrated in Figure 4. With t-values ranging from 4.26 to 9.15, the estimated coefficients are highly significant. An $F(14, 126)$ test for the joint significance of the company-specific effects gives a test statistic of 8.16, with a p-value of 0.0000. As expected, the company-specific constant terms of our model closely resemble the ranking of average EV/DACF for the companies over the period 1990-2004.

Figure 4. Estimated dummy variable coefficients of Modell 2
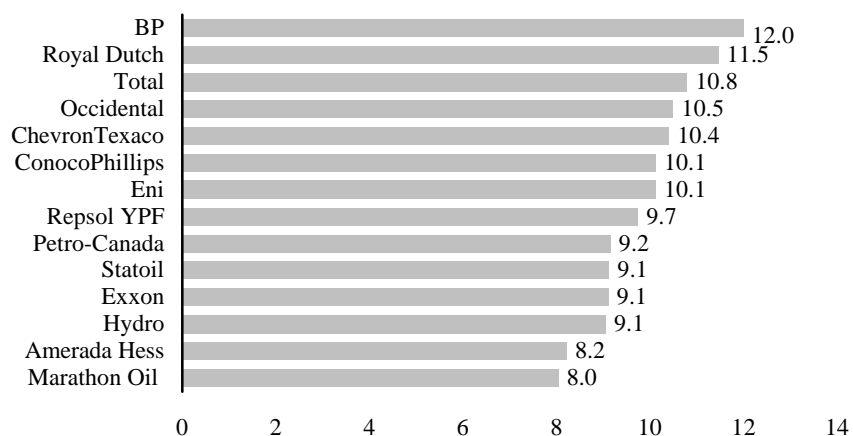
With an R^2 figure of 0.89, the explanatory power of Model 2 is good, and vastly improved from Model 1. The test statistic for joint significance of the model parameters also increases sharply, compared to the model without company dummies. This indicates that fixed company characteristics, like reputation, represent an important part of the explanation of the variation in EV/DACF across companies.

Model 3 introduces oil and gas production and the reserve replacement ratio as additional key performance indicators. The effect of RoACE on company valuation remains small and insignificant. The negative effect from current oil prices now increases, and the statistical robustness prevails. The estimated valuation impact from oil and gas production takes the correct sign, and is highly significant. Finally, the estimated coefficient for the reserve replacement rate is small, and its standard deviation is high. R^2 now approaches 0.95, and the test-statistic for joint significance of the parameters is also even higher than in Model 2.

Models 1, 2 and 3 implicitly assume that normal exogeneity requirements are met for the explanatory variables. However, key performance indicators may depend on management's decisions. The potential problem is that those decisions are not exogenous. They are made by management, under the influence of financial markets. The simultaneity issue is therefore critical, and cannot be ignored.

The problem of endogeneity has been discussed and addressed in a wide range of areas of the literature on accounting and capital markets, but a consensus on how to address the problem is not yet reached. Nikolaev and van Lent (2005) argue that there is no clean-cut statistic or diagnostic instrument available to test for endogeneity. The general advice from the econometrics literature is to apply introspection (Wooldridge, 2002) and reasonableness (Greene, 2000; Kennedy, 2003) as a way to determine whether there is an endogeneity problem.

The standard textbook solution to endogeneity is to apply additional exogenous variables (which by assumption are uncorrelated with the error term) to instrument the suspected endogenous predictor. Unfortunately, adequate instrumental variables are usually hard to find for the typical accounting study, and our analysis is no exception.

There are several measures that researchers should report in order to help the reader assess the reasonableness of an IV application (Larcker and Rusticus (2005)). First, it is crucial that the choice of instrumental variables is justified. Second, the full results of the first-stage regression must be reported, including the partial F-statistic and partial R^2. Third, analyses similar to the 'unconstrained' second-stage should be reported.

We apply two additional instrumental variables to correct for the potential endogeneity bias in our model, which is most likely associated with the

RoACE variable (R_{it}). The first is production cost per boe (UPC_{it}). The second is finding and development cost per boe (FDC_{it}). For a company's portfolio of projects, average unit costs will reflect not only the company's performance in the fields they operate themselves, but also the performance of other operators through participation in partner-operated fields. The widespread cooperation and partnerships in the international oil and gas industry is therefore likely to ensure the exogeneity of these variables. Both the instrumental variables are also lagged by one period, to reduce the risk of feedback effects from market valuations.

The first step of our 2SLS estimation produces the following equation for RoACE (p-values in brackets):

[2]

$$\hat{R}_{it} = A_i + 0.533 \cdot P_t + 0.000 \cdot OGP_{it} + 0.164 \cdot RRR_{it} - 1.478 \cdot UPC_{it-1} - 0.173 \cdot FDC_{it-1}$$

$$(-0.000) \quad (0.763) \quad (0.503) \quad (0.000) \quad (0.018)$$

$$OBS = 130 \qquad R^2 = 0.58 \qquad F(17,112) = 9.24$$

*) p-values in brackets.

where A_i represent the set of company dummies. Equation [2] accounts fairly well for RoACE variation among the companies in our data set. The company dummies seem to crowd out the effect of oil and gas production, as the OGP_{it} coefficient is small and insignificant. The RoACE impact of an increase in unit production costs (UPC_{it}) is clearly negative, and so is the effect of an increase in finding and development costs (FDC_{it}). The estimated effect of an increase in the reserve replacement ratio (RRR_{it}) is also positive. In statistical terms, this effect is less distinct than the others. The overall fit is satisfactory, and the test statistic for the joint significance of all parameters is robust.

The second stage applies predicted values for RoACE from equation [2] instead of the observed values in our data set. The resulting 2SLS estimates for EV/DACF are compared with OLS estimates in models 2 and 3 in Table 1. What we observe is that all coefficients are fairly stable across the two specifications.

Models 3 and 4 suggest that EV/DACF is strongly influenced by oil price fluctuations and variations in production levels (revenue variables). Reserve replacement affects estimated company valuation, but the coefficient is not significant in statistical terms. Finally, the estimated valuation impact from

192

RoACE takes the expected sign, but the effect is small and statistically insignificant in both the models.

8. Concluding remarks

Over the last decade, we have experienced an unusual combination of high oil prices and low exploration efforts. One possible explanation is the use of short-term accounting returns (RoACE) as a key valuation metric among stock market analysts. We test the quality of this valuation indicator, and our analysis provides new and interesting insights on the links between financial markets and company behaviour.

To assess valuation drivers, a simple econometric model is specified and estimated on market and accounting data for 14 major oil and gas companies from 1990 to 2003. The company-specific valuation multiple EV/DACF is regressed against a number of financial indicators, as well as the oil price. Our models take into account the potential endogeneity challenge in our data for market valuation and company performance.

A robust result is that valuation multiples respond negatively to an increase in the oil price, implying that oil and gas companies are priced at mid-cycle oil prices. Our results also suggest that there is a robust and material influence on market valuations from oil and gas production. As the fluctuation over time is moderate for oil and gas production, this variable may serve as a proxy for company size. This suggests that company size and reputation still plays an important role in the valuation process. In our results, reserve replacement contributes positively to stock market valuation, but the effect is quite modest, and the significance is marginal.

On the other hand, the general perception of RoACE as an important value-driver is not supported by our estimated model, which is based on market valuations and accounting data for 14 major international oil and gas companies over a 14-year period. More precisely, our results indicate that the valuation impact of this simple profitability measure is negligible. We have offered some possible explanations to this result. First, the effect of short-term return on capital can be crowded out by interdependent explanatory factors (multi-collinearity). Second, RoACE figures used in external analyses (and in our regressions) are not normalised to mid-cycle market conditions. Consistent data for normalised RoACE are unfortunately not available. Third, the RoACE figures suffer from the traditional shortcomings of historical cost-

accounting in measuring true profitability (measurement errors). Researchers have repeatedly argued that this is particularly important for the oil and gas industry (e.g., Antill and Arnott, 2002).

Our study elucidates some the weaknesses of RoACE for company valuation purposes. Our primary focus is on inter-company comparisons and relative stock market valuation. Within the individual companies, a consistently normalised RoACE may still be a useful key indicator in their internal efforts to improve operational and financial performance over time.

This paper represents an early attempt to substantiate the links between market valuation and financial and operational indicators in the international oil and gas industry. The results are interesting, but preliminary. Our belief is that profitability and returns on invested capital is linked to company valuations. However, our RoACE variable does not establish this link. Future research should explore alternative measures of underlying financial performance, to overcome the weaknesses of RoACE.

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196

Chapter 7

Financial market pressure, tacit collusion and oil price formation

By Finn Roar Aune, Klaus Mohn, Petter Osmundsen,
and Knut Einar Rosendahl

Abstract[1]

We explore a hypothesis that a change in investment behaviour among international oil companies (IOC) towards the end of the 1990s had long-lived effects on OPEC strategies, and on oil price formation. Coordinated investment constraints were imposed on the IOCs through financial market pressures for improved short-term profitability in the wake of the Asian economic crisis. A partial equilibrium model for the global oil market is applied to compare the effects of these tacitly collusive capital constraints on oil supply with an alternative characterised by industrial stability. Our results suggest that even temporary economic and financial shocks may have a long-term impact on oil price formation.

JEL classification: C32, G31, L72

K*ey words*: Capital formation, dynamic panel data models, structural break

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1. Introduction

Ever since the oil price shocks of the early 1970s, the Organization of the Petroleum Exporting Countries (OPEC) has been followed with massive interest from the public, reflecting the vital significance of the oil price to industry, households and financial markets. The special structure of the oil market has also attracted scholarly interest, with numerous studies of OPEC's role and strategy in various models of producer behaviour under imperfect competition (e.g., Smith, 2005; Fattouh, 2007). Less attention has been given to the role of producer behaviour in non-OPEC countries. Nevertheless, investment behaviour in the international oil and gas industry is an important part of supply-side dynamics in the oil market, and therefore also an important factor behind the formation of oil prices.

Our key hypothesis is that a strategic redirection of the international oil industry towards the end of the 1990s has had long-lived effects on OPEC strategies – and on oil price formation. Starting in 1998, increased focus on shareholder returns, capital discipline and return on capital employed (RoACE)[2] caused a slowdown in investment rates and production growth among international oil companies (Antill and Arnott, 2002; Osmundsen et al., 2006). Strong growth in oil demand and consolidation in the competitive fringe allowed OPEC to raise their price ambitions significantly at the turn of the century (Haskel and Scaramozzino, 1997; Kohl, 2002). The objective of this study is to quantify the oil price impact of these developments. Using a detailed simulation model for the global oil market, we examine the effects of the change in investment pattern on oil supply and oil prices, as compared with a situation characterised by industrial stability and unchanged price ambitions within OPEC.

Oil demand is quite inelastic to oil price changes, and tightly linked to GDP growth.[3] As noted by Lynch (2002), the dissection of crude oil supply is less straightforward, with geology, geopolitics, and imperfect competition as

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[2] RoACE is defined as net income adjusted for minority interests and net financial items (after tax) as a percentage ratio of average capital employed, where capital employed is the sum of shareholders' funds and net interest-bearing debt.

[3] The macroeconomic role of the oil price has intrigued macroeconomic researchers for decades (Barsky and Killian, 2004). Empirical studies suggest that oil price changes above some threshold level will have contractionary effects on global economic activity (e.g., Jiménez-Rodriguez and Sánchez, 2004; Jones, Leiby and Paik, 2004; IMF, 2005). Distributional effects are also involved, as the rewards of an increase in the oil price are reaped by oil-exporting nations, whereas the costs tend to be carried by less wealthy oil-dependent countries (e.g, Gately and Huntington, 2002; World Bank, 2005).

important complicating factors. At the same time, the degree of concentration among the most important oil producers is significant, leaving a potential scope for pricing power (Fattouh, 2007). Total oil supply is comprised by production from two groups of players. One is the group of OPEC countries, with national oil companies situated in the most resource-rich regions of the world (Noguera and Pecchenino, 2007). The other is often referred to as non-OPEC, strongly influenced by the group of international oil companies (IOCs). Most of these companies have their origin in the western hemisphere, they have private shareholders, and their shares are traded on stock exchanges in London and New York.

Osmundsen et al. (2007) argue that changes in the interaction between listed oil companies and their shareholders have suppressed investment behaviour and production growth among these companies from 1998 and onwards. We present a more comprehensive assessment of the oil market impact of changes in IOC investment behaviour. Our modelling approach allows an empirical assessment of supply side dynamics following the change in investment policies in the oil industry after the Asian economic crisis. The model simulations clearly suggest that enhanced capital discipline caused a temporary slowdown in investment and production growth among international oil companies. Consequently, global exploration activities, investment expenditures and oil production growth were suppressed, allowing OPEC to raise their price ambitions. Specifically, we find that the curb on IOC investments around the turn of the century caused an increase in the oil price of nearly 10 per cent in the long run. Both OPEC and non-OPEC producers gain from this development, whereas the cost is carried by oil-importers and consumers.

The paper is organised as follows. Section 2 provides a review of previous research of OPEC behaviour and oil industry dynamics, as well as a discussion of the rationale for our hypotheses about supply side behaviour. In Section 3, we introduce the FRISBEE model, and discuss two different scenarios for the oil market – to isolate the effects on exploration activities, investments, oil production growth and price formation. Concluding remarks and directions for future research are presented in Section 4.

2. Financial market pressures and OPEC behaviour

The last serious oil demand shock was experienced in 1998-1999, when the Asian economic crisis reduced anticipated demand growth rates by some 2

percentage points (EIA, 2006). One result was a change in investment behaviour among the IOCs. At the same time, the Asian economic crisis had the effect of pulling the OPEC countries together. OPEC regained market power and oil price ambitions were raised. We explore the behavioural changes of OPEC and the IOCs in greater detail below.

2.1 Tacit collusion in IOC investment

In the late 1990s, both the oil market and the financial market turned against the oil and gas industry. First, the "New Economy" euphoria made investors shift their investments from oil and gas to IT stocks. Oil and gas companies were generally perceived as old-fashioned and inefficient, with limited exposure to the exuberance of the IT sector. Second, the Asian economic crisis caused a sharp slowdown in global oil demand. In 1998 the oil price touched record lows of 10 USD/bbl., increasing the uncertainty and anxiety also with respect to oil price expectations. The result was not only a severe pressure on current oil company cash flows, but also an increasing scepticism with respect to future earnings. In consequence, oil and gas companies failed to deliver competitive returns to their shareholders.

One response to these developments was a wave of mergers to build scale, reap synergies, and improve efficiency. This process erased a range of former prominent independent names,[4] and attracted interest both from researchers (e.g., Weston et al., 1999; Fauli-Oller, 2000) and regulators (Scheffman and Coleman, 2002; Froeb et al., 2005). Another response from the international oil industry was a strategic redirection from development of reserves and production in the longer term to operational efficiency and capital discipline in the short to medium term. Companies were benchmarked and rated according to a specific set of financial and operational performance indicators (Antill and Arnott, 2002; Osmundsen et al., 2007). The most important of these indicators was RoACE.

An example of common benchmarking and valuation practices is illustrated in the left-hand panel of Figure 1, where a financial market valuation multiple[5] is plotted against RoACE for major oil and gas companies. A regression is often added to illude "normal valuation", and deviations from this relationship offer signals to buy or sell the stock. This practice of

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[4] Examples include Elf, Fina, Mobil, Amoco, Arco, YPF, Texaco, Phillips, Lasmo, Unocal – and recently also Hydro.

[5] EV, or Enterprise Value, is the sum of the company's debt and equity, at market values. DACF, or Debt-Adjusted Cash Flow, reflects cash flow from operations plus after-tax debt-service payments.

benchmarking and valuation made reported RoACE increase more than the oil price increase would suggest (see also Dobbs et al., 2006).

Figure 1. IOC valuation and financial indicators
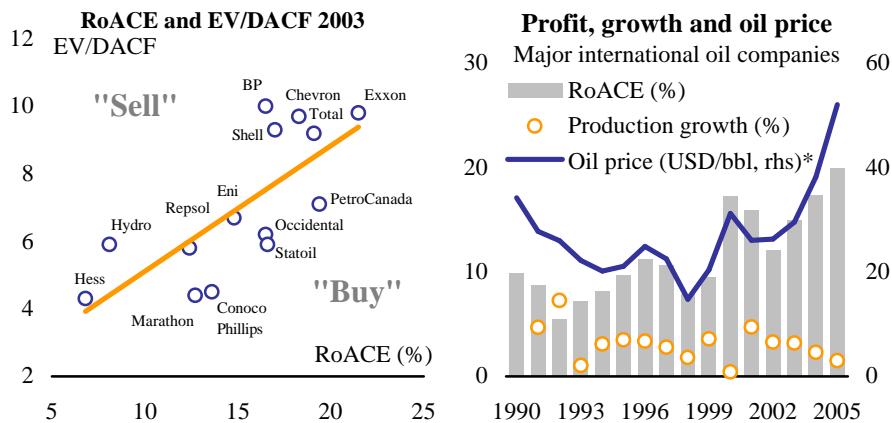
* in real terms (at 2004-prices).
Source: Deutsche Bank (2004; oil industry data).

Deutsche Bank (2004) reports that total investment expenditures among the major international oil and gas companies were cut by 16 per cent in real terms from 1998 to 2000, with a 38 per cent reduction in exploration expenditures over the same period. Mohn and Misund (2007) present econometric evidence of a structural break in IOC investment behaviour in 1998, implying that the investment response to the late rise in the oil price is significantly less than the estimated response for the period before 1998. An important reason is the implicit increase in the required rate of return on new investments among international oil companies, to secure improved capital discipline and RoACE performance.[6] Due to conservative valuation procedures,[7] RoACE will improve when investment rates decline, providing an additional argument for IOCs to bridle their capital expenditures.[8]

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[6] In spite of differences in terms of definition, there is a close economic relationship between the *ex ante* required rate of return (RRoR) measure and the *ex post* return on average capital employed (RoACE) indicator. See Antill and Arnott (2002) for a more comprehensive discussion of accounting standards, financial market behaviour and corporate investment strategies.

[7] This improvement in RoACE generated simply by reducing activity levels is mainly due to the system of depreciation (production unit method) and the most common way of treating exploration expenses (full cost method).

[8] For an IOC perspective on investment in the first years of the new century, see Smith (2003).

Thus, the emphasis on RoACE in valuation of oil companies curbed investments, implicitly representing a tacit collusion to support an increase in the oil price. In retrospect, maintaining the original investment rate (cheating) would have been beneficial for any one oil company, as earnings would have surged on both higher oil price and higher production. However, the general perception among oil company managers was that a lower ranking in the financial community would reduce the stock price, increase the takeover threat, and reduce the potential for profitable acquisitions.

Over the last couple of years, the tide has turned. Both investors and companies seem to have realised that reserve growth is required to sustain long-term production and activity growth. Accordingly, the pressure for short-term financial returns is relaxed. Spurred by advancing depletion of legacy fields of the past and limited access to new exploration acreage, management focus has shifted back to exploration and business development to access new oil and gas reserves. Our model scenarios are designed to capture both the rise and the fall of the RoACE era in the international oil and gas industry.
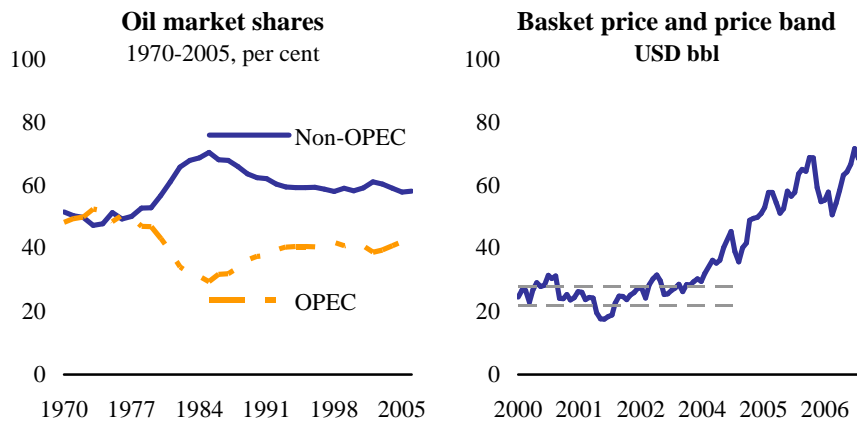
2.2 OPEC behaviour

Empirical studies of OPEC's role in the oil market have generally failed to establish firm evidence of stable cartel behaviour (e.g., Griffin, 1985; Dahl and Yücel, 1991; Griffin and Nielson, 1994; Alhajji and Huettner 2000a,b). However, recent studies acknowledge that some sort of collusion is taking place. The current discussion is more about which model of imperfect competition the oil price formation adheres to, and to stability issues of OPEC's market power. Böckem (2004) combines theories of new empirical industrial organisation (NEIO) literature with modern econometric techniques, and argues that a price-leader model provides the best description of OPEC behaviour. Hansen and Lindholt (2004) obtain similar results in an econometric study of monthly oil price data over the period 1973-2001. Smith (2005) provides a critical overview of empirical studies of OPEC behaviour, and concludes his own assessment with weak support for a "bureaucratic syndicate" model.

Traditionally, OPEC has collected data for a "basket" of different crude oil qualities, and the global oil market has been monitored through a reference price based on this basket (cf. Figure 2). In March 2000, OPEC established a price band mechanism to respond more automatically to changes in market conditions (Kohl, 2002). According to this mechanism, production would be adjusted at price levels below 22 USD/bbl and above 28 USD/bbl. The

mechanism was later adjusted to allow production adjustments at OPEC's discretion.[9] The price band mechanism was suspended in January 2005. Combining these observations with the oil price development, there are clear indications that OPEC's pricing power was significant at the turn of the century (Fattouh, 2001).

Figure 2. OPEC decision variables

| Oil market shares 1970-2005, per cent | Basket price and price band USD bbl |

Source: EIA, http://www.ecowin.com.

As argued by Haskel and Scaramozzino (1997), physical and financial capacity is likely to affect conjectural variations in an oligopoly. With a cartel strategy contingent on the ability of fringe producers to react, a variety of developments shed light on OPEC's self reliance. First, the outlook for non-OPEC supply was curbed by financial market pressures and strict capital discipline. Second, the oil price outlook was uncertain, and did not provide sufficient incentive for massive private oil and gas investment. Third, the domestic provinces of the IOCs were maturing rapidly,[10] with deteriorating exploration results and decaying reserves. Fourth, the Asian economic crisis demonstrated the importance of internal discipline when demand is insufficient to meet every cartel member's production ambitions. Finally, the global economy was recovering swiftly, with especially high growth in GDP and energy demand in non-OECD countries. Hyndman (2007) and Fattouh (2007) provide convincing evidence that agreements in a cartel like OPEC are easier to achieve when times are good then when times are bad. All in all,

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[9] By 2004 the price band mechanism had been activated only once; In October 2000, total OPEC production was increased by 500,000 barrels per day.
[10] USA, Canada, United Kingdom, and Norway.

OPEC regained strength during 1999, and entered the new century with increased market power – and a willingness to exploit it (Kohl, 2002).

We now turn to a detailed and model-based analysis of these developments, to reveal more precise implications in terms of investments, production growth and oil price formation.

3. Model scenarios

3.1 Overview of FRISBEE
The FRISBEE model is a recursive, dynamic partial equilibrium model of the global oil market.[11] Particular attention is paid to the oil industry's supply of oil, and the model accounts explicitly for discoveries, reserves, field development and production in four field categories across 13 global regions (including two OPEC regions). The model is calibrated based on market data for the base year 2000, as well as other relevant data and estimated parameters from the literature (e.g. demand elasticities, production costs, oil resources etc.). The global oil market is assumed to clear in each period (year). Regional supply, demand and trade flows are among the outputs of the model. The model does not intend to exactly replicate the historical development of the oil market, or forecast the future, as the oil market obviously is influenced by much more than economics. However, the model can still provide valuable insight into the effects of certain changes in the market, such as changes in the international oil industry.

In each region oil is demanded for transport and stationary purposes in three sectors of the economy: Manufacturing industries, Power generation, and Others (including household demand). Oil demand depends on user prices of oil products, and to some degree on other energy prices. In the end-user sectors the direct price elasticities are on average around -0.3 in the long run, and around -0.1 in the short run (cf., Liu 2004). Income growth is particularly important in the longer term, with (per capita) income elasticities on average around 0.6. Population growth and exogenous energy efficiency are also affecting energy demand. In the power sector oil competes with other fuels on a cost basis.

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[11] A more detailed, informal description of the model is given in Appendix A. For a more extensive presentation of the FRISBEE model system, see Aune et al. (2005). More recently, the model has been extended to include international gas and coal markets (see Rosendahl and Sagen 2007).

The development of non-OPEC production is influenced by initial production capacity and investments – in exploration, field development and efforts to increase oil recovery (IOR). Non-OPEC producers are assumed to behave competitively, as no single oil company has a market share above 3 per cent.[12] Thus, production volumes from developed fields are determined by the equalisation of marginal producer costs to producer prices in each region. Investments are driven by expected returns, and net present values are calculated for the four field categories in the 11 non-OPEC regions (i.e., 44 field groups), based on adaptive price expectations and a pre-specified required rate of return.

Oil companies form their investment strategies subject to an appropriate set of planning assumptions, reflecting expectations of relevant market developments. Their expected oil price trajectory will normally depict a gradual transition between the spot price and a constant long-term expectation for the real oil price.[13] Based on this trajectory, short-term projects will largely be influenced by near-term expectations, which will typically not be very different from the current oil price. As the investment horizon is extended for development and exploration activities, the role for long-term oil-price expectations also becomes gradually more important. For tractability reasons, we specify these ideas and mechanisms in terms of expected mean-prices for each investment activity, measuring the average price expected over the relevant time horizon for the investment activity in question:[14]

$$EP_{it} = \alpha_i P_{t-1} + (1 - \alpha_i) EP_{it-1} \;, \tag{1}$$

where EP_{it} is the expected (real) mean-price of oil applied for evaluation of investment activity i, P_{t-1} is the corresponding observed (real) price last year, and $\boldsymbol{a}_i$ are parameters that determine the speed of expectations adjustment for

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[12] It could be argued that a *country* like Russia, having a total market share of 12 per cent in 2006, can coordinate oil production from its domestic oil companies so as to influence the market. However, so far there have been few signs of such behaviour in Russia or other non-OPEC countries except in extraordinary situations.

[13] Previous empirical studies of oil price expectations provide firm support for the adaptive expectations hypothesis (e. g., Pesaran, 1990; Farzin, 2001). This implies an important role for historical memory in the formation of oil price expectations, and may be seen as a generalisation of the popular hypothesis of mean reversion. For a recent comparative investigation of alternative models for oil price expectations, see Prat and Uctum (2006), who reject the standard hypothesis of rational oil price expectations in favour of a combination of adaptive, extrapolative, and regressive expectations.

[14] In the model, the oil price differs somewhat across regions (due to transport costs), but this is disregarded in the equations here.

each of the three investment categories. The values of a_i in equation [1] are assumed to be respectively 0.60, 0.35 and 0.10 for IOR activities (*I*), field development (*D*) and exploration activity (*E*).[15] This reflects that IOR investments typically produce returns with a time lag of 0-2 years; field developments have a perspective of 2-5 years before start-up, whereas exploration projects are for the long term. Oil companies therefore adjust their IOR activities more rapidly than their exploration activities in response to oil price changes, as short-term price expectations change more rapidly than long-term expectations.[16] It takes time before the oil industry believe that a price adjustment is permanent, as illustrated by the slow pace of long-term investment response to the current price increase. Neglecting subscript *t* for simplicity of exposition, oil company investments in field development and IOR activities outside OPEC are derived from the following maximisation problem (Aune et al., 2005):

$$Max_{R_{ij}} \Pi\left(R_{ij},\ EP_i,\ r,\ CO_j,\ CC_{ij}, GT_j,\ NT_j, \vec{F}_j\right), \qquad [2]$$

where Π is expected discounted profits, R_{ij} denotes investment in new reserves (new field developments or IOR) in field group *j*, *r* is the required rate of return, CO_j and CC_{ij} operating and capital costs, respectively, GT_j and NT_j gross and net tax rates on oil production, respectively, and $\vec{F}_j$ is a vector of field characteristics that differ across field groups (notably production profile and time lags). Capital costs are increasing in investment activity, decreasing in undeveloped reserves (new fields), and increasing in the recovery rate (IOR). A simpler approach is applied for exploration investments, where we assume that the process for discovered reserves (R_{Ej}) is captured by the following function:

$$R_{Ej} = R_{Ej}(EP_E,\ r,\ U_j,\ \vec{F}_j)\ , \qquad [3]$$

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[15] This means that 90 per cent of the weights in the price expectation formation are based on the 3 last years' prices for IOR activities, 6 last years for field development, and about 20 last years for exploration activity. Other values of a_i would alter the investment activities somewhat. However, in terms of investment composition, our results are quite robust to changes in these parameters.

[16] When the oil price started rising around the turn of the century, volatility was high, and the longer term outlook was very uncertain. The company response was a redirection of investment toward activities with a short-term horizon, like IOR and (satellite) field developments, at the expense of longer term exploration investments, whose price expectations were not adjusted upward to the same extent (Osmundsen et al., 2007).

where EP_E is the expected oil price applied for evaluation of exploration activities, U_j denotes (expected) remaining undiscovered reserves, and subscript t is still subdued.

To summarise, oil companies outside OPEC choose optimal levels of exploration activities, field development, and IOR activities, based on expected prices, required rate of return, etc. A higher expected price and/or a lower required rate of return will increase the investments in new fields and IOR activities, and increase the level of discoveries. Because the time lag between capital outlays and revenues is highest for exploration and lowest for IOR, we should expect the required rate of return to be most important for exploration, and least important for IOR activities.

OPEC's behaviour is not easily depicted, and has certainly changed over time (see, e.g., Fattouh, 2007). However, as discussed above, several studies conclude that a price-leader model may provide a reasonable description. Since OPEC suspended its price band in 2005 because of the considerable upward pressure on the oil price, no official price targets have been announced. However, OPEC certainly considers the oil price development when production quotas are determined. Thus, the FRISBEE model assumes that OPEC searches for the price path that maximises its net present value of oil production until 2030 at a given discount rate,[17] and chooses a production profile consistent with this price path. However, we restrict the analysis to price paths on the following form:

$$P_{t+1}^{OPEC} = P_t^{OPEC} + \gamma^{t-t_0}\psi, \qquad\qquad [4]$$

where P_t^{OPEC} is the average producer price for OPEC, and ? and ? are parameters that determine the price path from an exogenous base year level (t_0 = 2000). The concave price trajectory illustrated in Figure 4 below is the result of a calibration with ? = 0.9, which is also applied in our further simulations.[18] The model now searches for the value of ? that maximises the

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[17] In the simulations presented in this paper, we use a discount rate of 7 per cent. Simulations with much lower (down to zero) or higher discount rates give almost the same conclusion when it comes to the relative price effects of changes in non-OPEC's investment strategy (if anything, the price effect is slightly stronger).

[18] Our choice of ? is of course a significant restriction of all the possible price paths OPEC can choose between. We have chosen a ? below unity (i.e., concave price path), as this seems to be in accordance with OPEC's mission statement: "OPEC's mission is to … ensure the stabilization of oil markets in order to secure an efficient, economic & regular supply of petroleum to consumers, a steady income to producers & a fair return on capital to those investing in the petroleum industry." (http://www.opec.org/home). In any case, for the purpose

net present value of OPEC's profit flow. As a comparison, Berg et al. (2002) and Yang (2007) simulate OPEC's behaviour through a dynamic optimisation model ala Hotelling (1931), but their modelling of the oil market is much simpler in other respects. On the other hand, Gately (2007) searches for an optimal strategy for OPEC that is robust to changes in uncertain future market conditions.

Note that we assume different expectation formation for OPEC and non-OPEC. Whereas non-OPEC producers have adaptive expectations about the future oil price, OPEC has (implicitly) rational expectations about future demand and how non-OPEC will react to different oil prices. Reasons for this could be that OPEC's behaviour has changed over time, and is therefore less predictable than non-OPEC's behaviour, which to a larger degree has been based on expected profit maximization (there are of course important exceptions to this generalisation).

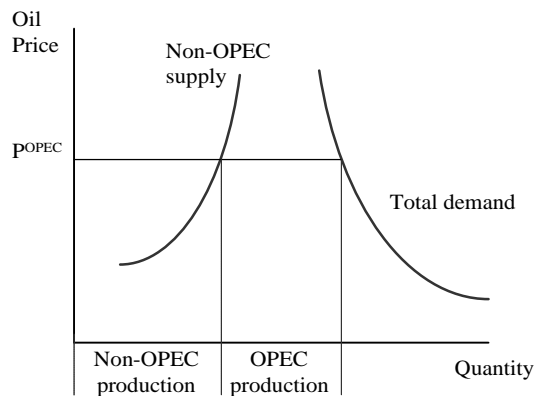**Figure 3. Oil price formation in the FRISBEE model**

Figure 4 provides a stylised overview of oil price formation in the FRISBEE model. Total demand and non-OPEC supply are based on neo-classical behavioural equations for oil and gas producers, other industrial companies and households in 13 regions across the world. The price set by OPEC (P^{OPEC}) clears the market, and implicitly determines both total oil production and the

of exploring the impacts of a change in non-OPEC's investment strategy this restriction is of minor importance since ? only determines the curvature of the price path. Simulations with other values of ? (including ?=1, i.e., linear and strictly convex price paths) indicate that the price differential in the long run (i.e., 2020-2030) is quite similar in relative terms.

market shares for OPEC and non-OPEC. For a given price chosen by OPEC, oil demand and non-OPEC production are determined independently, and OPEC supply is closing the gap. A credible defence of the price target will require surplus capacity. In our model, we therefore assume that OPEC will always invest sufficiently in new fields and IOR activities to maintain a capacity surplus of 10 per cent.

In summary, oil companies invest in exploration for new reserves, field developments and in efforts to increase oil recovery from producing fields. Non-OPEC production is profit-driven, whereas OPEC meets the residual "call on OPEC" at a pre-specified oil price path that is determined through an NPV maximisation process, subject to total demand expectations and conjectures for non-OPEC supply behaviour. A higher oil price path (compared to a reference path) will gradually increase production from oil producers outside OPEC. Extraction from existing capacities is fairly fixed, but the profitability of IOR investments is increased, leading to higher production capacity in the short to medium term. In the medium to long term oil companies develop more fields, and in the longer term new fields are discovered and appraised for development. A higher oil price path will also gradually reduce oil demand. The model scenarios below illustrate how the interaction between financial markets and oil and gas companies may affect the supply side of the oil market.

Figure 4. RoACE and oil price scenarios
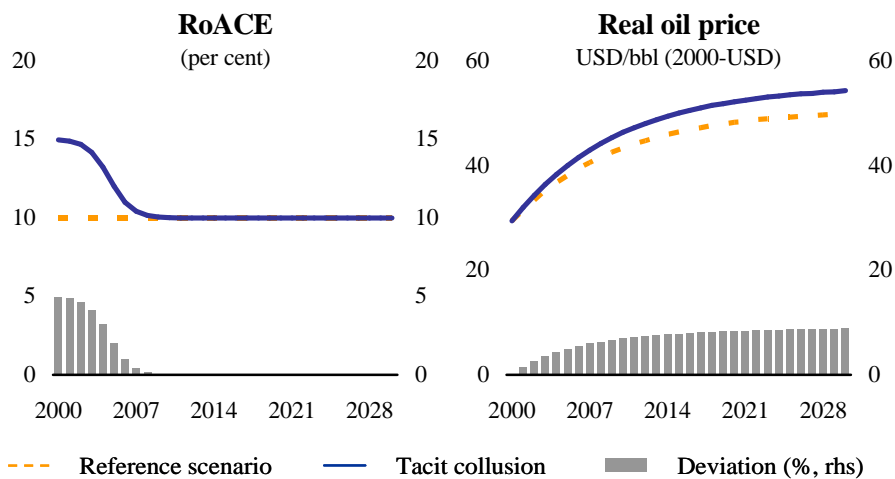
Source: Exogenous assumptions (RoACE) and *FRISBEE* Model (oil price).

3.2. Assumptions and calibration of two scenarios
Following the discussion in Section 2, we want to explore the market effects of change in non-OPEC's investment strategy observed in the oil market at the end of the last century. According to Deutsche Bank (2004), RoACE increased substantially among the IOCs in the 1990s, from 9 per cent in 1990-1997 to 16 per cent in 1998-2005. This indicates that the required rate of return on new investments was considerably raised in this period.

We will consider two different scenarios using the FRISBEE model. The first scenario, called the 'Reference scenario', assumes that the non-OPEC producers follow the attitude of the IOCs from the first half of the 1990s. That is, their required rate of return is assumed to be 10 per cent. The second scenario, called the 'Tacit collusion' scenario, assumes that the non-OPEC producers require a higher rate of return, i.e., 15 per cent, at the beginning of the new century. However, as discussed above, we have seen a gradual change among the IOCs over the last couple of years, with a gradual redirection of attention (and investment) from short-term profitability to long-term reserve and production growth. Accordingly, we allow the required rate of return to fall gradually from 15 to 10 percent towards 2010, as illustrated in Figure 4 (below we also consider the effects of a prolonged period with 15 per cent rate of return). In all other respects, the scenario assumptions are identical.[19]
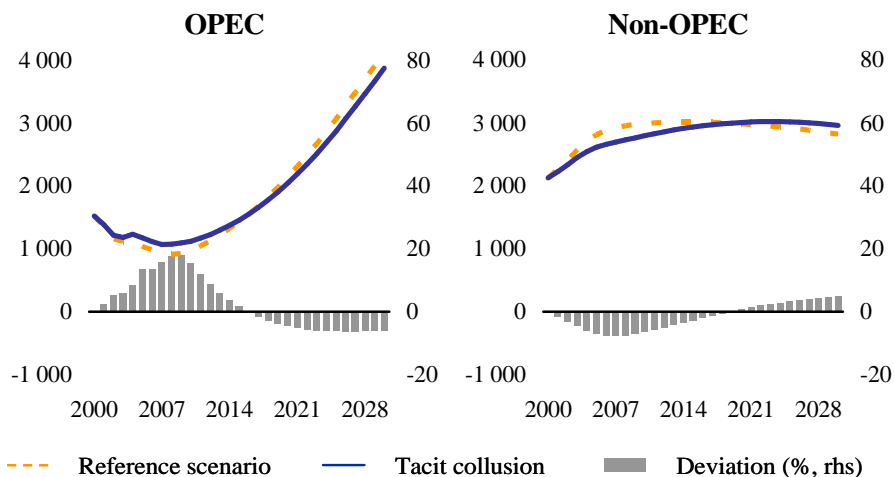
A higher rate of return in the 'Tacit collusion' scenario will induce less investment among non-OPEC producers compared to the 'Reference scenario', consistent with the observed behaviour of the IOCs after 2000. On the other hand, when the rate of return is gradually reduced in the former scenario, investment activities should pick up again. In fact, with more unexploited projects and possibly higher oil price, investment activities may surpass the activity level in the 'Reference scenario' after some years. In the next subsection we will investigate how this may have affected the oil market since 2000, and what impacts it may have on the future market.

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[19] We assume that OPEC has perfect expectations about the required rate of return in non-OPEC. Alternatively, we could assume that OPEC has adaptive expectations about the rate of return. In this case OPEC would choose a higher initial growth in the oil price in the 'Tacit collusion' scenario, assuming that non-OPEC producers would stick to a high required rate of return also in the future. Simulations indicate that this would lead to a significantly higher oil price level also in the long run.

3.3 Model results

In the 'Reference scenario', the oil price increases from 29 USD/bbl 2000 to 50 USD/bbl in 2030. Hence, it is clearly profitable for OPEC to settle on an increasing oil price path from the level in 2000. In the 'Tacit collusion' scenario, reduced investment activities among non-OPEC producers gradually reduce the supply outside OPEC compared to the 'Reference scenario', at least temporarily. This makes it profitable for OPEC to choose a higher oil price than in the latter scenario, cf. Figure 4. The short-term investment effect of the change in IOC strategy is substantial. As the difference in attitude for non-OPEC producers is fairly short-lived, we shouldn't expect a big change in the long-term oil price. However, the long-term oil price difference between the scenarios is not negligible (4.4 USD/bbl, or 9 per cent).

Figure 5. OPEC and non-OPEC oil supply (mtoe per year)

Source: FRISBEE Model.

Between 2005 and 2010, non-OPEC investment levels in the 'Tacit collusion' scenario surpass the levels in the 'Reference scenario' for all three investment activities. After 2005 the required rate of return is almost the same, whereas the oil price is higher in the former scenario. Moreover, the recovery rate in existing fields is lower, which means that there are more profitable IOR projects left. In addition, there are more undeveloped fields (despite fewer discoveries), which means that the oil companies have more profitable fields to develop. The (expected) amount of undiscovered oil reserves is also higher.
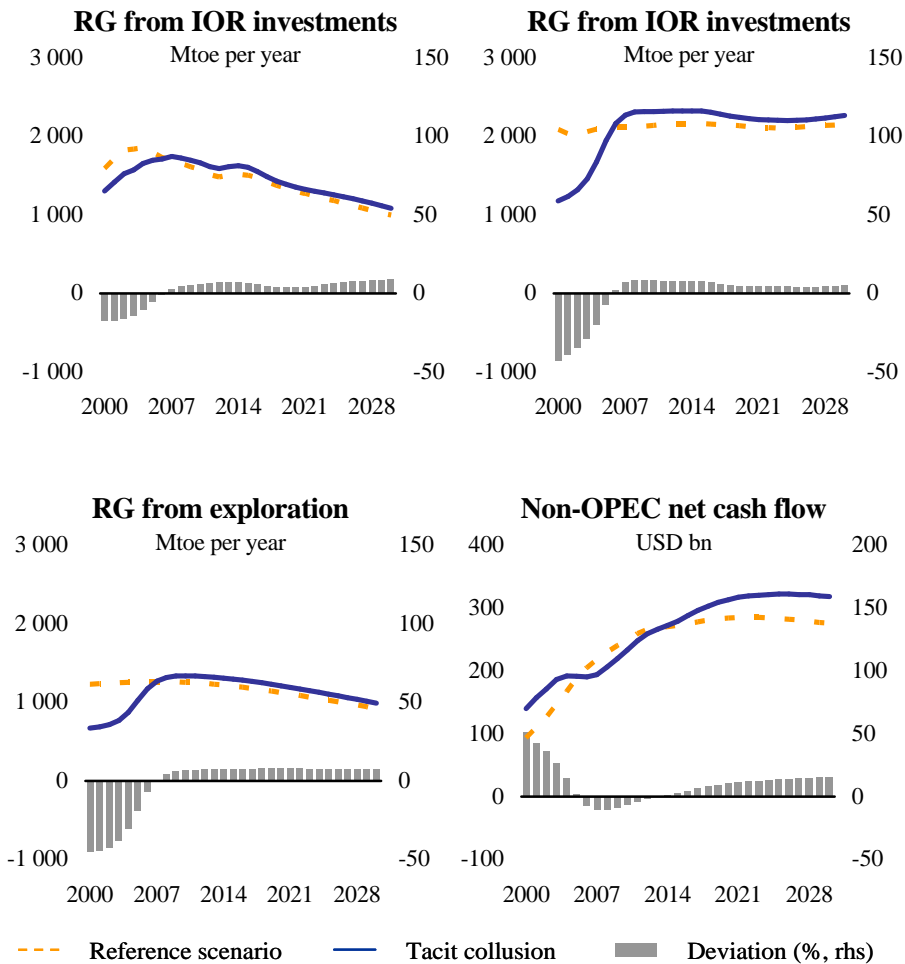
From Figure 5 we also see that non-OPEC supply is somewhat reduced in the 'Tacit collusion' scenario compared to the 'Reference scenario' in the first 15-20 years. Less investment gradually affects production levels. In the first couple of years this is driven by fewer IOR projects. After 5-10 years the effects of less development projects are perceptible, too. Gradually fewer discoveries also affect supply. However, as investment activity in non-OPEC starts to accelerate when the required rate of return is reduced, production levels outside OPEC gradually catch up with the 'Reference scenario'. From around 2020 non-OPEC supply is highest in the 'Tacit collusion' scenario.[20]

As explained in Subsection 3.1, a higher required rate of return among oil companies outside OPEC will affect new discoveries most and IOR projects least. This is because the time lag between investment expenditures and expected revenues are lowest for IOR activities and highest for exploration activities. Figure 6 shows how the different investment activities develop in the two scenarios. We see that IOR investments are least affected, as expected. They are reduced by up to 18 per cent in the 'Tacit collusion' scenario. New field developments are almost halved in the first couple of years, and so too are new discoveries.

Which scenario is most profitable for oil companies outside OPEC? Figure 7 shows how the net cash flow evolves, i.e., net revenues from oil production minus investment expenditures. We see that the 'Tacit collusion' scenario is clearly the most profitable one, whatever discount rate we apply. In the short run, non-OPEC producers gain from reducing their capital outlays. In the medium term, they gain from a slightly higher oil price, and lose from a slightly lower supply. Investment expenditures are about the same. In the longer term, both the oil price and non-OPEC production are higher, and these effects dominate the effect of higher capital expenditures. That is, non-OPEC's temporary restraint in investment activities is beneficial for both non-OPEC and OPEC producers, whereas the consumers stand to lose from higher prices.

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[20] If the oil price path was unchanged in the 'Tacit collusion' scenario, the investment levels would still surpass the levels in the 'Reference scenario' before 2010. However, the investment levels in the two scenarios would be more similar towards 2030, and non-OPEC supply would be highest in the 'Reference scenario' over the entire time horizon.

Figure 6. Reserve-generation (RG) by investment type and non-OPEC cash flow[21]

RG from IOR investments

RG from IOR investments

RG from exploration

Non-OPEC net cash flow

- - - Reference scenario — Tacit collusion ▬ Deviation (%, rhs)

Source: FRISBEE Model.

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[21] Unconventional oil (i.e., tar sands in Canada) is included in all graphs except for new discoveries. Within our time horizon, conventional oil discoveries are much more important for new field developments than unconventional discoveries, as reserves of tar sand are already huge and not really constraining field development in Canada. If we subtract unconventional oil also in the graph for new field developments, we will see a gradual but distinct decline after 2010 in both scenarios. In 2030 unconventional oil constitutes almost half of new field developments outside OPEC, according to our scenarios.

Figure 7. Oil price effects if the shock is permanent

Long-term oil price with varying degree of shock persistence (duration in years)
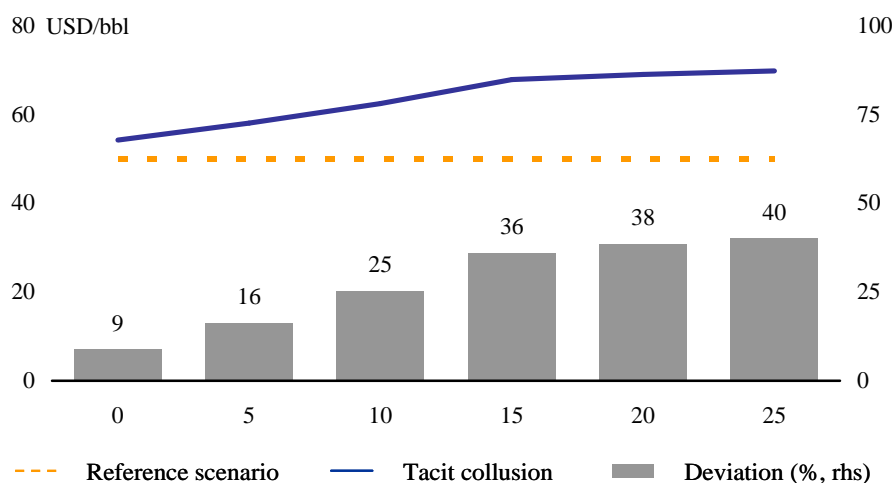
Source: FRISBEE Model.

Finally, what if the oil companies outside OPEC had required a higher rate of return (i.e., 15 per cent) for a longer period of time? Figure 7 shows the relative increase in the long-run oil price level when the decline in the rate of return is delayed by different number of years (e.g., 0 years is equivalent to the original 'Tacit collusion' scenario, whereas 25 years means that non-OPEC has 15 per cent rate of return over the entire time horizon). As the figure shows, the long-run effect on the oil price would be much stronger if the change in investment strategy in the oil industry was more than a short-lived phenomenon.

4. Conclusion

The process of capital formation in the oil and gas industry is an important part of the supply side dynamics in the oil market. Understanding how oil and gas companies think in terms of investment is therefore essential in order to develop and maintain the required insights for meaningful analyses of oil price formation. Over the last 10 years, international oil and gas companies have gone through a period of escalating market turbulence, restructuring and redirection of investment strategy. As the oil price dropped to a historical low in the aftermath of the Asian economic crisis, management focus shifted to short-term accounting returns, at the expense long-term field development and

215

reserve replacement. We explore the impact of this strategy redirection on oil price formation.

The temporary one-dimensional focus on RoACE forced the international oil companies to cut back on investments, thus generating higher oil prices. This change in strategy has clearly proved profitable for the international oil industry. Through the capital market analysts' RoACE-benchmarking of companies, an implicit coordination on lower investment levels was achieved. In retrospect, it can easily be demonstrated that deviation from the common strategy of low investment would have been profitable for any individual oil company. By maintaining its standard investment policy (e. g., a constant reinvestment ratio), it could have reaped the joint benefit of high oil prices and high production. However, tight co-operative capital discipline was maintained, as managers feared that a lower RoACE than the industry average would harm share prices in the short run, thus making it harder to raise capital and increasing the takeover probability.

This study demonstrates how increased focus on shareholder returns, capital discipline and return on capital employed (RoACE) have caused a temporary slowdown in investment and production growth among international oil companies. We find that the strategic redirection of the international oil industry towards the end of the 1990s had long-lasting effects on OPEC behaviour – and on oil price formation. Our scenarios suggest that the change in investment strategies of the late 1990s caused a lift of approximately 10 per cent in the long-term oil price. Both OPEC and non-OPEC producers gain from this development, whereas the cost is carried by oil-importers and consumers.

Industrial leaders and their companies do not operate in a vacuum. Rather, they respond continuously to changing political and market environments. Their models and ways of thinking may be stable for periods. However, their mindset will also be challenged by external forces from time to time. And sometimes these pressures even bring about deeper changes. This study demonstrates that such changes may have persistent effects on the oil market.

From the perspective of the investors, an adequate question is if strategies now have shifted too far away from accounting returns. The international oil industry has a history of over-investment at high oil prices (e.g., Jensen 1986). However, there are signs that the current situation is different from the traditional high price cycle scenario: The lack of adequate investment projects actually put an effective curb on investments, and reserve replacement levels

are low. On the other hand, some of the current investment projects in the oil industry have break-even prices considerable above historic oil prices. Company managers thus face some tough decisions. Traditional counter-cyclical asset trading (selling reserves at top of the oil price cycle) may not seem so tempting when the company is unable to replace its reserves. On the other hand, buying reserves in the current market sentiment may seem risky. Assets are traded at prices that entail a considerable downside risk. Part of this picture is the fact that the IOCs are competing for new reserves against NOCs that are not subject to the same capital market scrutiny.

An interesting direction for future research would be to study the stability of the investment process in the oil and gas industry in greater detail, preferably with micro-econometric studies of company data. Modern econometric techniques may reveal more exact information on how the process of capital formation in the oil and gas industry was altered in the late 1990s.

Appendix A. Description of the FRISBEE model

In this appendix we give a more detailed, informal description of the FRISBEE model, with emphasis on the oil market.[22] FRISBEE is a recursively dynamic partial equilibrium model of the global oil market. The world is divided into 13 regions (see Appendix B). In each region oil companies produce oil, which they sell on the global market. Three different end-users in each region consume oil products, which they buy at regional prices linked to the global market. We assume that the oil market clears in each period, i.e., total supply from all regions equals total demand in all regions, and all trade between regions goes through a common pool. The time periods in the model are one year, and the base year is 2000. Exchange rates are held constant over time.

Production of oil
In each of the 13 regions the model distinguishes between 4 field categories based on field size and geology (see Appendix B). Within each of the resulting 52 operational areas, there are developed and undeveloped reserves. New discoveries add to the stock of undeveloped reserves at the end of each year.

Both production and investment decisions are explicitly modeled. For each region and field category we apply a pre-specified production profile. This profile is taken for granted in the investment decisions, but can to some degree be altered during the lifetime of the field (see below). The profile is divided into four phases: The first phase is the *investment phase*, i.e., the time lag between the investment decision and start of production. The second phase is the *pre-peak phase*, i.e., when production builds up towards the peak level. The two first phases are quite short, varying between 2 and 6 years in total across regions. The third phase is the *peak phase*, when capacity is at a constant and pre-specified level. This phase lasts between 5 and 10 years. The fourth and final phase is the *decline phase*, when capacity declines at a constant rate per year until production is too low to be profitable. Thus, all developed reserves are divided into region, field category and vintage (phase). The initial allocation is based on input from an extensive database of global petroleum reserves in the year 2000.

At the end of each year, oil companies decide how much to invest in developing new fields and in improved oil recovery (IOR) from existing fields

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[22] A formal description is found in Aune et al. (2005), whereas Rosendahl and Sagen (2007) describes the gas market modelling in more detail.

(see below). When new fields are developed, the stock of undeveloped reserves is reduced. We assume that new discoveries are made each year in every region and field category. The volumes of new discoveries are assumed to be a concave function of the expected oil price, and a linear function of the expected remaining undiscovered reserves. This discovery function is calibrated for each region so that if the oil price stays at $40 per barrel, total accumulated discoveries over the time horizon (i.e., until 2030) equal USGS's (2000) mean estimate of potential new discoveries over a 30 years period.

The model includes supply of conventional oil (crude oil and NGL), and unconventional oil from Canada (tar sand) and Venezuela (extra heavy oil).

Production in non-OPEC
The oil production capacity in a region is by and large fixed at each point of time, and determined by investments in earlier years. However, production is not totally fixed, but can be above or below the pre-specified production profile if profitable. A short-term marginal cost function decides whether a deviation from the pre-specified profile is optimal. For non-OPEC regions we assume that oil supply is determined by equalizing the producer price of oil with the sum of marginal operating cost and gross sales taxes in each field category and vintage. The producer price of oil in a region is mainly determined by the global crude oil price and transport costs, but may also differ due to crude oil quality. We assume that the initial differences in producer prices across regions are unchanged over time.

In the pre-peak and peak phase we assume that marginal operating costs are fairly constant (and low) except when production is very close to capacity. Thus, there is only a slight possibility to adjust production in these two phases. In the decline phase, however, marginal operating costs increase more rapidly as production rises. This reflects that some of the declining fields are approaching the end of their lifetime, and extraction is falling for a given operational input. That is, costs per unit production get higher, and the oil price level will to a larger degree affect the optimal production level. Thus, production is more flexible in the decline phase. Marginal operating costs are based on detailed information about unit costs in different types of fields in the most important oil producing countries.

Production in OPEC
In the model OPEC chooses a fixed price path, and we search for the price path that maximizes OPEC's net present value (given some restriction on the form of the price path). The fixed price path assumption implies that demand

and non-OPEC supply are determined independently of each other, and that OPEC supply is solely determined by the residual demand (or call on OPEC oil). OPEC must therefore continually possess enough capacity so as to support the chosen price path (see OPEC's investment decisions below).

Investment decisions in non-OPEC
The basic incentive for oil companies is to invest in provinces and field types with the highest expected return. To sort out the most profitable among projects, net present value (NPV) is calculated for investments in each of the 44 non-OPEC provinces/field types over the entire project lifetime at a given discount rate. Linear capital allowances are made over 6 years (this seems to be a reasonable approximation over different fiscal regimes). As explained in the main text, non-OPEC producers have adaptive price expectations.

Oil companies continuously target the most profitable reserves. Reserves that are more costly to extract gradually enter as candidates for investment, and the cost of production will rise as the reserves are depleted. On the other hand, new discoveries and technological change reduce the costs of developing new fields.

Besides investing in new fields, oil producers have the option to invest in improved oil recovery (IOR) from fields in the decline phase. IOR investments generate additional reserves and open up for increased output in the short- to medium-term by lifting the tale of the production profile of a given field. The costs of IOR investments increase as the recovery rate becomes higher.

Risk is a factor that affects oil companies' investment strategies. Risk can be political, fiscal or related to exploration and production as such. FRISBEE incorporates an exogenous risk premium to account for variations in risk assessment in different provinces and field types. The risk premium is expressed in terms of additional costs per barrel that is required to make the investment project as attractive as a risk neutral project.

FRISBEE further incorporates other factors in the investment cost function, postulating that
- a large current production modifies the rising trend in field development costs (technical, institutional learning, "materiality")
- a large regional activity level modifies the rising trend in development costs (infrastructure, competitive subcontractors)
- few undeveloped reserves increase the rising trend in development costs

These factors make it more attractive to stay on in an area rather than enter new locations with a lower degree of reserve development, as long as the mature area still has much undeveloped fields left.

Investment decisions in OPEC
OPEC is a residual producer filling the supply gap necessary to keep the oil price at the preferred level. In FRISBEE, the operational rule for OPEC is to invest enough in new fields and IOR to maintain a current capacity surplus of about 10 per cent, in order to demonstrate the ability to increase production and control the price level. The distribution of investments between OPEC Core and Rest-OPEC, and between new fields and IOR, is exogenous.

Demand for oil
We distinguish between three end-users of oil products, i.e., Manufacturing industry, Power generation and Others (including households). Manufacturing industries and Others consume both transport oil and stationary oil (including processing), whereas Power producers consume fuel oil. All oil products are bought at a regional product price, which is determined by the global crude oil price, transport costs and refinery costs. The end-user prices of the different oil products must also cover distributional costs and taxes, and will generally differ across end users. End-user prices and regional product prices are generally taken from IEA, but other sources and some guesstimates have been used to fill the gaps. Transport-related costs, refinery costs and taxes are held constant in real terms over the time horizon. Stock changes are exogenous and are phased out over time.

Demand for oil in Manufacturing industries and Others are log-linear functions of population, income per capita, prices of other energy products and an autonomous energy efficiency improvement (AEEI), as well as demand in the previous year. This means that we distinguish between short- and long-run effects of price and income changes via an adjustment parameter. Between 30 and 55 per cent of the long-run effect is obtained after one year (varies between oil products and end-users), whereas the long-run price elasticity varies between -0.1 and -0.6 (weighted average is -0.19 for Manufacturing industries and -0.37 for Others). The price elasticities and adjustment parameters are mainly taken from Liu (2004). Prices of gas and coal are endogenous in the model, based on supply and demand in those markets. Demand for fuel oil in Power generation depends on unit costs for various power technologies.

Growth rates of GDP and population are exogenous in the model. Income elasticities are calibrated based on projections of energy demand, and vary between 0.1 and 1.1 in the long run (weighted average is around 0.6 for both Manufacturing industries and Others). Transport oil is generally about twice as income elastic as stationary oil. AEEI is set equal to 0.25 per cent per year in OECD and 0.5 per cent outside OECD.

Appendix B. List of regions and field categories in the FRISBEE model

Regions	Field categories			
	1	2	3	4
Africa	Onshore All	Offshore deep < 400 Mboe	Offshore deep > 400 Mboe	Offhore shallow All
Canada	Onshore All	Unconvention al All	Offshore < 400 Mboe	Offshore > 400 Mboe
Caspian region	Onshore < 400 Mboe	Onshore > 400 Mboe	Offshore < 400 Mboe	Offshore > 400 Mboe
China	Onshore < 100 Mboe	Onshore >100; < 1000 Mboe	Onshore > 1000 Mboe	Offshore All
Eastern Europe	Onshore < 100 Mboe	Onshore > 100 Mboe	Offshore < 100 Mboe	Offshore > 100 Mboe
Latin America	Onshore All	Offshore deep < 1000 Mboe	Offshore deep > 1000 Mboe	Offhore shallow All
OECD Pacific	Onshore All	Offshore deep All	Offshore shallow < 100 Mboe	Offshore shallow > 100 Mboe
OPEC core[*]	Onshore < 400 Mboe	Onshore >400; < 1000 Mboe	Onshore > 1000 Mboe	Offshore All
Rest-Asia	Onshore < 400 Mboe	Onshore > 400 Mboe	Offshore < 400 Mboe	Offshore > 400 Mboe
Rest-OPEC	Onshore < 400 Mboe	Onshore > 400 Mboe	Offshore deep All	Offhore shallow All
Russia/Ukraine/Belarus	Onshore < 400 Mboe	Onshore > 400 Mboe	Arctic < 400 Mboe	Arctic > 400 Mboe
USA	Onshore All	Alaska All	Offshore deep All	Offhore shallow All
Western Europe	Offshore deep < 400 Mboe	Offshore deep > 400 Mboe	Offshore shallow < 100 Mboe + Onshore	Offshore shallow > 100 Mboe

[*] OPEC core consists of Saudi Arabia, Iran, Iraq, Kuwait, UAE and Venezuela, whereas Rest-OPEC consists of the remaining OPEC member countries.

223

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Appendices

Appendix 1

Appendix 1

The neo-classical model of investment behaviour

Appendix 1

The neoclassical model of investment behaviour

Tobin (1969) gave rise to one of the currently most popular models of modern empirical investment research. The attractiveness of this specification of investment behaviour has at least two sources. First, the model is simple and has an intuitive appeal. Second, theory implies that Q represents a sufficient statistic for investment, a property that has been tested in a range of empirical applications. Consider the profit function of a representative firm, given by: [1]

$$\Pi_t(K_t, I_t, e_t) = p_t F(K_t) - p_t^I[I_t + G(I_t, K_t, e_t)] \qquad [1]$$

$F(K_t)$ is a well-behaved neoclassical production function, K_t represent the stock of fixed capital, and I_t is gross investment. Variable inputs are suppressed for simplicity of exposition. The firm puts its product at the market at the price p_t. $G(I_t, K_t, e_t)$ is an adjustment cost function, p_t^I is the price of investment goods, and e_t is a stochastic shock to the adjustment process. [2]

The neo-classical model of investment is subject to a range of standard assumptions of economic theory. To summarise, the model assumes that the firm's only quasi-fixed input is a single homogenous capital good and no adjustment costs associated with labour and other current inputs. The model also assumes the absence of financial policy issues and that the firm's only objective is to maximise returns to risk-neutral shareholders. Moreover, our firm operates in competitive input and output markets with symmetric information, and is allowed to issue unlimited amounts of equity at exogenously given required rates of return. [3] Finally, an implicit assumption of the model is separability between real and financial decisions (Modigliani and

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[1] See Bond and Van Reenen (2007) for a recent overview of microeconometric models of employment and investment.

[2] Observe that in a long-run approach to capital demand, we may treat capital as a variable input. This is equivalent to an assumption that capital services (k) can be leased in competitive markets at a rental price included in the vector of input prices w. Consequently, this user cost of capital (Jorgenson, 1963) will enter the profit function ($\Pi = \Pi(p, w)$), and the company's demand for capital services can readily be derived by Shephard's lemma as $\frac{\partial \Pi}{\partial w_k} = k(p, w)$.

Numerous studies have explored the estimation of this user cost, its sensitivity to regulation and tax, as well as its role for capital formation. Excellent surveys are provided by Chirinko (1993) and Caballero (1999). See Chirinko, Fazzari and Meyer (1999) and Ellis and Price (2004) for recent econometric applications.

[3] The implication is that internal sources of finance (retained profits) and external sources finance (new share issues) are perfect substitutes.

Miller, 1958).[4] Under these circumstances, the firm's dynamic optimisation problem can be stated as:

$$V_t = \max E_t \left[\sum_{i=0}^{\infty} \boldsymbol{b}^i \prod(K_{t+i}, I_{t+i}, e_{t+i}) \right] \qquad [2]$$

where V_t is firm value, $\boldsymbol{b} = \frac{1}{1+r}$ is a constant discount factor,[5] and $E_t[.]$ denotes the expected value conditional on information available in period t. Firm value as defined by Equation [2] is maximized subject the usual constraint on capital accumulation:

$$K_t = I_t + (1-\boldsymbol{d})K_{t-1} \qquad [3]$$

where d is an exogenous and fixed rate of depreciation for capital. First-order conditions are given by:

$$-\left(\frac{\partial \Pi_t}{\partial I_t} \right) = \boldsymbol{1}_t \qquad [4]$$

$$\boldsymbol{1}_t = \left(\frac{\partial \Pi_t}{\partial K_t} \right) + \boldsymbol{b}(1-\boldsymbol{d})E_t[\boldsymbol{1}_{t+1}] \qquad [5]$$

The Lagrangian multiplier $\boldsymbol{1}_t = \frac{1}{1-\boldsymbol{d}}\left(\frac{\partial V_t}{\partial K_{t-1}} \right)$ represents the shadow value of getting into one additional unit of capital in period t. According to Equation [4], profit optimisation requires the cost of acquiring additional units of capital in period t to be equated to the shadow value ($\boldsymbol{1}$). Equation [4] sets this shadow value equal to the marginal cost of acquiring additional units capital in period t. The first-order condition [5] describes the relation between shadow values in period t and future shadow values.

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[4] The validity of this assumption is the subject of another influential strand of the empirical investment literature over the last 10 years. See Schiantarelli (1996) for an overview of the early contributions on the investment cash-flow relation. More recent econometric studies include Bond et al. (2003), Baum et al. (2006) and Jin and Jorion (2006).

[5] Irreversibility options and uncertainty over price and demand could imply an increase in the required rate of return. Thus, both the irreversibility theory of investment (e.g., Abel and Eberly, 1999) and general CAPM principles (e.g., Mossin, 1966) can be embedded in our Q theory of investment.

Linear homogeneity of the profit function implies:

$$\Pi_t = K_t \frac{\partial \Pi_t}{\partial K_t} + I_t \frac{\partial \Pi_t}{\partial I_t} \qquad [6]$$

The first-order conditions [4]-[5] are now combined with Equation [3] to yield:

$$\boldsymbol{l}_t(1-\boldsymbol{d})K_{t-1} = \Pi_t + \boldsymbol{b}E_t\left[\boldsymbol{l}_{t+1}(1-\boldsymbol{d})K_t\right] \qquad [7]$$

Solving this equation forward we obtain for the value of the firm:

$$\boldsymbol{l}_t(1-\boldsymbol{d})K_{t-1} = E_t\left[\sum_{i=0}^{\infty}\boldsymbol{b}^i \Pi_{t+i}\right] = V_t. \qquad [8]$$

We now define marginal q_t as the ratio of the shadow value of capital to purchase cost $q_t \equiv \frac{\boldsymbol{l}_t}{p_t^I}$. Hayashi (1982) demonstrates that under linear homogeneity of the profit function marginal q equals average q.[6] A useful implication of the Hayashi conditions is that the unobservable shadow value of capital can be related to an observable average q ratio, namely the ratio of total asset value to its replacement cost:

$$q_t = \frac{\boldsymbol{l}_t}{p_t^I} = \frac{V_t}{p_t^I(1-\boldsymbol{d})K_{t-1}} \qquad [9]$$

Equation [9] presents marginal q_t as the ratio of V_t to the replacement cost value of the capital stock from the previous period. The numerator (V_t) represents the sum of discounted cash-flows from the existing capital stock, and captures changes in current and expected product prices, production plans, unit costs and discount rates. The denominator represents the cost of replacement for the capital stock. This ratio is known as Tobin's q (Tobin 1969), and suggests that companies with superior investment returns (high q) attract more capital and spend more on capital investment than underperforming firms. We follow the mainstream approach to adjustment

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[6] This is equivalent to constant returns to scale, a classical assumption for competitive market equilibria. As pointed out by Bond et al. (2005), failure of the Hayashi (1982) conditions will threaten the validity of the average Q model. See also Erickson and Whited (2000) for a thorogh discussion of problems concerning potential measurement errors.

costs, (e.g., Bond et al. 2005), and assume a quadratic adjustment cost function:

$$G(I_t, K_t, e_t) = \frac{b}{2}\left[\left(\frac{I_t}{K_t}\right) - a - e_t\right]^2 K_t \, , \qquad [10]$$

where b is a coefficient to represent the importance of adjustments costs. Equation [10] states that the unit cost of capital adjustment is a convex function of the investment rate, that adjustment costs kick in as soon as some investment threshold (a) is passed, and that the investment process is disturbed by stochastic shocks (e_t). With this specification, the first-order condition in Equation [4] can be modified into a simple relation between investments and the q ratio in company i:

$$\left(\frac{I}{K}\right)_{it} = a + \frac{1}{b}Q_{it} + e_{it} \, , \qquad [11]$$

where $Q_{it} = q_{it}\text{-}1$, and a and b are parameters of the adjustment cost function. Equation [A11] forms the basis for empirical specification in Chapter 6 of this dissertation, as well as wide range of other applied econometric studies of investment behaviour. See Bond and van Reenen 2007 for a recent overview.

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Investment and uncertainty: A two-period model with irreversibility

Appendix 2

Investment and uncertainty

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. This appendix offers a brief review of the literature on irreversible investments, with key results illustrated in a simple two-period model.

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 that the convexity of the profit function gives rise to a "desirability for price instability" (Oi, 1961) effect on investment in times of increasing uncertainty. With convex profits, which represent the standard assumption of neo-classical theory of producer behaviour, any price variation may be exploited for optimisation. Accordingly, any increase in uncertainty will also raise the marginal valuation of investment, yielding a positive link between capital-accumulation and 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) and others 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.

The idea of irreversible investment is truly relevant to oil and gas investments. Huge capital commitments, long investment lags and field-specific sequences of investment decisions involve a series of waiting options. This irrevocable character of investment expenditure is perhaps 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.

A two-period model of irreversible investment

Drawing on Dixit and Pindyck (1994) and Svensson (2000), we now illustrate some key points from the literature on irreversible investment in a more formal framework. We demonstrate how irreversibility of investment gives rise to a negative effect between investment and uncertainty due to the eal option value of deferral. Within this two-period model framework we will also identify, explain and discuss the asymmetric behaviour of investment implied by Bernanke's (1983) *bad news principle*.

Consider a
 company that has to decide on a capital investment $i > 0$. The investment is irreversible. For simplicity, we assume absence of operating costs, and instantaneous productivity of the investment, with a known instant profit $p_0 = p$. Future profit (p_t) can take two values: high profit ($p_t^h = fp$) which occurs with probability q, or low profit ($p_t^l = xp$) which occurs with probability $1-q$, where $f > 1 > x$. We also assume that investment return in the bad state is lower than the user cost of capital (ri), and that all uncertainty disappears after one period. The net present value of investing today may now be stated as:

$$V_0 = -i + p + \sum_{t=1}^{\infty} \frac{E_0[p_t]}{(1+r)^t} \qquad [1]$$

With irreversibility, $V_0 > 0$ is not a sufficient investment signal. The company may still not invest. The reason is that with uncertainty and irreversibility, the bad outcome ($p_t^l = xp$) may fall short of the cost of capital. No company wants to commit to unprofitable projects. With this potential outcome, the company may rather postpone the project to learn more about the determinants of future profits. The net present value of waiting one period and investing if future profits are high is:

$$V_1 = \frac{q}{1+r} \left[-i + \sum_{t=1}^{\infty} \frac{E_0[p \mid p = p^h]}{(1+r)^t} \right]. \qquad [2]$$

The company will invest today if and only if $V_0 > V_1$, i.e. if the net present value of investing today dominates the net present value of investing tomorrow, including the value of the waiting option. The implication is also that it takes more than a positive net present value to trigger an irreversible

investment decision. In other words, the real option value of waiting creates a wedge between the trigger value and the traditional net present value. To illustrate this more precisely, we note that the net present value of investing today may be stated as:

$$
\begin{aligned}
V_0 &= -i + \boldsymbol{p} + \sum_{t=1}^{\infty} \frac{E_0[\boldsymbol{p}_t]}{(1+\boldsymbol{r})^t} \\
&= -i + \boldsymbol{p} + q\sum_{t=1}^{\infty} \frac{\boldsymbol{fp}}{(1+\boldsymbol{r})^t} + (1-q)\sum_{t=1}^{\infty} \frac{\boldsymbol{xp}}{(1+\boldsymbol{r})^t} \\
&= -i + \frac{[(1+\boldsymbol{r}) + q\boldsymbol{f} + (1-q)\boldsymbol{x}]\boldsymbol{p}}{\boldsymbol{r}}
\end{aligned}
\qquad [3]
$$

Moreover, the waiting option has a value only for the case where investment should not have been undertaken in period 1. In other words, waiting has no value if immediate investment would have been profitable anyway. Therefore, the net present value of waiting one period and investing if future profits are high is given by:

$$
\begin{aligned}
V_1 &= \frac{q}{1+\boldsymbol{r}}\left[-i + \sum_{t=1}^{\infty} \frac{q\boldsymbol{fp}}{(1+\boldsymbol{r})^t} \right] \\
&= \frac{-qi}{1+\boldsymbol{r}} + \frac{(1+\boldsymbol{r})}{\boldsymbol{r}} q\boldsymbol{fp}
\end{aligned}
\qquad [4]
$$

The company will invest today if and only if $V_0 > V_1$, i.e. if:

$$
\begin{aligned}
V_0 - V_1 &= -i + \frac{[(1+\boldsymbol{r}) + q\boldsymbol{f} + (1-q)\boldsymbol{x}]\boldsymbol{p}}{\boldsymbol{r}} \\
&+ \frac{qi}{1+\boldsymbol{r}} - \frac{(1+\boldsymbol{r})}{\boldsymbol{r}} q\boldsymbol{fp} > 0.
\end{aligned}
\qquad [5]
$$

Equating V_0 to V_1 now yields:

$$
\left[\frac{(1+r)}{r} + \frac{(1-q)\boldsymbol{x}}{r} \right]\boldsymbol{p} = i\left[1 - \frac{q}{(1+r)} \right].
\qquad [6]
$$

Solving for p to gives us the critical level of profit (p^*) that will trigger investment:

$$p = p^* = i\frac{r}{(1+r)}\left[\frac{(r+(1-q))}{r+(1-q)x}\right], \qquad [7]$$

Equation [7] has a user cost interpretation, and illustrates that it pays to invest in the current period only if the first period return exceeds the user cost ($ir/(1+r)$) by a margin large enough to compensate for a possible irreversible unsuccessful investment. This decision rule illustrates not only the role of the waiting option in investment decision-making, but also the negative relation between investment and uncertainty. In our model framework, a mean-preserving increase in uncertainty will have to imply an increase in x. For investment to take place, this would require a higher current profit treshold, and investment would therefore tend down.

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. The bad news principle can also be illustrated in the above formal framework. Observe that news concerning the possible realisation of high profit ($E_0[p \mid p = p^l] = fp$) is irrelevant for the investment decision rule represented by Equation [7]. The economic interpretation is that the option to wait has no value in situations where direct investment would have been the optimal decision ($V_1 < V_0$). An appealing application to oil and gas exploration is that news about oil price increases are 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 activities. This is one of the hypotheses will that might be tested empirically in an econometric model of exploration activity (e.g., Mohn and Osmundsen, 2007).

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Appendix 3

A note on dynamic panel data estimators

Endogeneity issues in dynamic panel data models[1]

There are a variety of reasons for the development whereby application of panel data for empirical studies of producer behaviour has become widespread. As opposed to cross-sectional data for several firms, panel data includes information for multiple time periods, granting the opportunity for estimation of dynamic models. Compared to pure time series data, panel data models escape from potential aggregation bias (e. g., Nickell, 1981), and also allows for the investigation of heterogeneity at the firm level.

With panel data at hand, dynamic model specifications have a range of economic applications. Examples include empirical models of economic growth, Euler equations for individual consumption, and adjustment cost models of input demands at the firm level. Dynamic model specifications may also be required in the presence of autoregressive errors in the standard static model, and may therefore be applied even when the coefficient on lagged endogenous does not occur from the outset.

The below exposition provides a brief overview of the rationale behind the special estimators for dynamic panel data models, with a special emphasis on the generalised method of moments (GMM) estimators applied in Chapters 4 and 5 of this thesis. A comprehensive and rigorous survey is provided by Arellano (2003). This summary draws on Bond (2002), who provides a nice introduction to dynamic panel data methods, as well as a guide to contemporary methods and practice.

The point of departure for our formal discussion is the following simple AR(1) model:[2]

$$y_{it} = a y_{it-1} + h_i + v_{it} \ ;$$
$$|a| < 1 \ ; \ i = 1, 2, \ldots N \ ; \ t = 1, 2, \ldots, T$$

[A3.1]

where y_{it} is the variable we would like to explain, y_{it-1} is its value lagged one period, and a is an autoregressive coefficient, bound to [-1,1]. Unobserved (time-invariant) heterogeneity is captured by the individual-specific time-

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[1] For excellent comments and suggestions to this appendix, I thank (without implying) Frank Asche at the University of Stavanger and Terje Skjerpen at Statistics Norway.
[2] For simplicity of exposition, the key ideas are illustrated for this simple model without exogenous covariates (x_{it}). However, all results are robust to extensions in terms of additional explanatory variables.

invariant effect $\boldsymbol{h}_i$, and v_{it} is a genuine disturbance term with standard white-noise properties. Observe also that the typical panel data set for microeconometric studies involves a large number of individuals over a relatively small time period. Consequently, asymptotic properties are usually considered for a fixed T, with N approaching infinity.

In line with the standard panel data literature (e.g., Arrellano 2003, ch. 6), we treat the fixed-effects part of the error ($\boldsymbol{h}_i$) of our model as a stochastic variable. This means that fixed effects will be correlated with the lagged dependent variable (y_{it-1}). At the same time, we assume that the true disturbances (v_{it}) are serially uncorrelated. The implication is a correlation between the lagged dependent variable (y_{it-1}) and the gross error term ($\boldsymbol{h}_i + v_{it}$) which is quite robust to sample size. Standard *OLS* estimates are therefore inconsistent, and Bond (2002) demonstrates that an upward bias is implied by this misspecification, at least for large samples.

The standard approach is to remove this inconsistency by the application of the so-called *fixed-effects* estimator, whereby the model variables are measured as deviations from their unit-specific means. By this transformation the fixed effects are eliminated from the estimation. *OLS* is then normally used to estimate these transformed equations. However, a non-negligible correlation can be shown to prevail between lagged dependent variable and the error term also in the transformed fixed-effects equation. Based on the model in Equation A3.1, the transformed lagged endogenous variable is given by:

$$y_{it-1} - \tfrac{1}{T-1}(y_{i1} + \ldots + y_{it} + \ldots + y_{iT-1}),$$

whereas the transformed error term is:

$$v_{it} - \tfrac{1}{T-1}(v_{i2} + \ldots + v_{it-1} + \ldots + v_{iT}).$$

It follows that the component $\frac{-y_{it}}{T-1}$ of the first term will now be correlated with v_{it} of the second term. In a similar fashion, $\frac{-v_{it-1}}{T-1}$ of the second term is correlated with y_{it-1} in the first term. Other positive correlations will be dominated by these two negative correlations, implying that the correlation between the lagged endogenous variable and the error term in the transformed

model is negative (Nickell, 1981). Again, Bond (2002) demonstrates that the *fixed-effect* estimator produces estimates with a downward bias.[3]

A variety of instrumental variable techniques have been developed to handle the endogeneity bias of dynamic panel data models. Anderson and Hsiao (1981) propose a *2SLS* estimator for the differenced model transformation ($\Delta y_{it} = a \Delta y_{it-1} + \Delta v_{it}$), with instruments that are correlated with the transformed lagged dependent variable and orthogonal to the differenced error term. Lagged levels of the lagged dependent variables are valid instruments to obtain consistent estimates of the dynamic model, according to this approach. Applying the general method of moments (*GMM*) to a first-difference framework for labour demand, Arellano and Bond (1991) show that longer lags of the dependent variables are also valid instrumental variables.

A problem with the original Arellano Bond framework is that lagged levels of the dependent variable is a poor instrument for first differences of highly persistent time series, and especially for variables that are close to a random walk.[4] To make up for this deficiency, Arellano and Bover (1995) demonstrate that additional orthogonality conditions may be provided by the inclusion of the original level equations in the system of equations to be estimated, with significant efficiency gains. This estimator is referred to as the system *GMM* estimator, and is further developed by Blundell and Bond (1998), and Blundell, Bond and Windmeijer (2000). We continue our overview with a brief introduction to this class of *GMM* estimators.

The Generalised Method of Moments

The key idea behind the class of *GMM* estimators is that any statistical moment of the data sample has its counterpart in the population. This analogy is then applied to justify sample moments as estimators of underlying population parameters. A simple example may be applied to the random

---

[3] Observe that the bias is of order *1/(T-1)*, implying that the fixed-effect estimator is consistent for large *T* panels. This property is utilised in Chapter 2 of this Thesis, where dynamic panel data models for a narrow panel of exploration data is estimated by OLS.

[4] Persistent time series are defined by the role of history for their development, with positive correlation between current and lagged values. As an example, consider the simple *AR(1)* process: $y_t = a y_{t-1} + v_t$. Subtracting y_{t-1} from both sides now yields: $y_t - y_{t-1} = (a - 1) y_{t-1} + v_t$. Consequently, as the autoregressive coefficient *a* approaches 1, $Dy_t (= y_t - y_{t-1})$ will approach a random walk (v_t). In general, a random walk process (*I(0)*) for the difference implies that the level of the same variable is integrated of degree 1 (*I(1)*).

variable y_{it} of our model, as represented by Equation A3.1. Letting $\boldsymbol{m}$ represent the mean of the distribution of y_{it}, the expectation for this variable may be stated as:

$$E[y_{it}] = \boldsymbol{m}. \tag{A3.2}$$

To estimate the population average, we may now carry on by forming the sample analog to the population expectation:

$$E[y_{it} - \boldsymbol{m}] = 0. \tag{A3.3}$$

The empirical moment condition now turns out as the sample analog to the population expectation:

$$\frac{1}{N}\sum_{i=1}^{N}(y_{it} - \hat{\boldsymbol{m}}) = 0, \tag{A3.3}$$

and an estimator for $\boldsymbol{m}$ is provided by the value of $\hat{\boldsymbol{m}}$ that satisfies the sample moment condition of Equation A3.3.

A seemingly different example can be illustrated within the framework of the (biased) *OLS* estimator for the autoregressive parameter of Equation A3.1. A critical assumption for the *OLS* estimator to be unbiased is:

$$E[y_{it-1}v_i] = E[y_{it-1}(y_i - \boldsymbol{a}y_{it-1})] = 0, \tag{A3.4}$$

which also has its sample equivalent in:

$$\frac{1}{N}\sum_{i=1}^{N}y_{it-1}\hat{v}_i = \frac{1}{N}\sum_{i=1}^{N}y_{it-1}(y_{it} - \hat{\boldsymbol{a}}y_{it-1}) = 0. \tag{A3.5}$$

What Equation A3.4 illustrates is that the *OLS* estimator also may be viewed as a *GMM* estimator. However, I have already argued that a problem with dynamic panel data models is that both *OLS* and the *fixed-effects* estimator are biased, because the lagged endogenous variable (y_{it-1}) is correlated with the error term (v_{it}). Formally speaking, this implies a violation of a critical assumption for the *OLS* estimator, as implied by Equation A3.4.

The general response to this problem is a variety of instrumental variable techniques. Instruments typically include lagged levels (y_{t-2}, y_{t-3}, …) and/or changes ($\boldsymbol{D}y_{t-2}$, $\boldsymbol{D}y_{t-3}$, …) of the dependent variable. The *GMM* method was introduced for this purpose by Hansen (1982), whereas augmentation in a first-difference framework was provided by Holtz-Eakin, Newey and Rosen (1988) and Arellano and Bond (1991).[5] The set of instruments suggested Arellano Bond (1991) includes additional lags of the dependent variable. Drawing directly on the exposition of Bond (2002), the core of modern *GMM* estimators for dynamic panel data models involves a matrix of instrumental variables (Z_i) of the form:

$$
Z_i = \begin{bmatrix}
y_{i1} & 0 & 0 & \cdots & 0 & \cdots & 0 \\
0 & y_{i1} & y_{i2} & \cdots & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
0 & 0 & 0 & \cdots & y_{it} & \cdots & y_{iT-2}
\end{bmatrix}
\qquad \text{[A3.6]}
$$

The rows of the instrument matrix corresponds to the first-differenced equations for *t = 2, 3, . . ., T* for observation unit *i*. A requirement for the validity of the instrument matrix Z_t is given by the orthogonality condition:

$$
E[Z_i^{'}\Delta v_i] = 0 \quad for \;\; i = 0, 1, 2, \dots, N
\qquad \text{[A3.7]}
$$

where $\boldsymbol{D}v_i = (\boldsymbol{D}v_{i2}, \boldsymbol{D}v_{i3}, \dots, \boldsymbol{D}v_{iT})´$. This requirement also forms the moment conditions for the GMM estimator, which basically minimises the criterion:

$$
J_N = \left(\frac{1}{N} \sum_{i=1}^{N} \Delta v_i^{'} Z_i \right) W_N \left(\frac{1}{N} \sum_{i=1}^{N} Z_i^{'} \Delta v_i \right) ,
\qquad \text{[A3.8]}
$$

where the weighting matrix W_N is defined as:

$$
W_N = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Z_i^{'} \Delta \hat{v}_i \Delta \hat{v}_i^{'} Z_i \right) \right]^{-1} ,
\qquad \text{[A3.9]}
$$

---

[5] An alternative strategy to handle dynamic panel bias is proposed by Kiviet (1995), who recommends the fixed-effects estimator, followed by a correction for bias, which he finds can be predicted with surprising precision. However, as noted by Roodman (2006), this approach works only for balanced panels and does also not address the potential endogeneity of other regressors.

$\Delta\hat{v}_i$ represent estimates of the first-differenced residual from a preliminary consistent estimator. This approach is called the *two-step GMM* for dynamic panel data models. Observe that this estimator involves estimation uncertainty in both stages of the estimation procedure, first in the estimation of first-differenced residuals for the weighting matrix (cf. Equation [A3.9]), and then in conjunction with the estimation of the model parameters (cf. Equation [A3.8]) after having inserted the estimated of the weighting matrix. These sources of uncertainty are also erosive for the asymptotical properties of the *two-step* estimator. Simulation studies also suggest that the two-step estimator tends to produce standard errors with a downward bias, especially in small samples (e.g., Bond and Windmeijer, 2002).

In this context, it is therefore useful to note that homoskedasticity in the disturbance terms (v_{it}) allows an asymptotically equivalent *GMM* estimator to be obtained in one step, if the weight matrix in A3.9 is replaced with a simpler version:

$$W_N^* = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Z_i' H Z_i \right) \right]^{-1} , \qquad\qquad \text{[A3.10]}$$

where *H* is a (*T-2*) square matrix with *2*'s on the diagonals, *-1*'s on the first sub-diagonals, and zeros elsewhere. In this simplified approach, W_N^* does not depend on any estimated parameters, and hence there is only one source of estimation uncertainty. Simulation studies have shown that the costs of this simplified method are modest, and that the efficiency gains of the two-step approach are limited, even in the presence of substantial heteroskedasticity (Blundell and Bond, 1998; Blundell, Bond, and Windmeijer, 2000). Simulations on identical samples also indicate that one-step estimates produce more precise estimates than the above-mentioned two-step procedure.[6] Consequently, the one-step approach is the most popular one in empirical applications of *GMM* estimators for dynamic panel data.

Issues of over-identification arise when the number of instruments exceeds the number of parameters to be estimated (i.e., when *T > 2*). When this is the case, the assumptions made to obtain the moment conditions (A3.7) can be tested with a so-called *GMM* test of over-identifying restrictions (Sargan,

---

[6] A more comprehensive discussion of these issues is offered by Windmeijer (2005), who also propose a compensating small-sample correction procedure. This correction procedure is applied to calculate robust standard errors in Chapter 4 of this thesis.

1958; 2000). The basis for this test is the property that under the null that the over-identifying restrictions are valid, NJ_N (cf. A3.8) has an asymptotic c^2 distribution. However, as noted by Roodman (2006), the traditional Sargan statistic is sensitive to heteroskedasticity and autocorrelation, and tends to over-reject in the presence of either. An increasingly common approach is therefore to report the more robust Hansen (1982) statistic as a test for the exogeneity properties of the instrument matrix.[7] Note also that similar procedures are available for tests of no serial correlation in the disturbances. Alternative and supplementary approaches to hypothesis testing are discussed in more detail by Bond and Windmeijer (2002).

These *GMM* estimators are straightforward to compute, as the applied moment conditions (A3.8) are linear in the parameter of interest (a). Quite easily, they may also be expanded to include additional explanatory variables, for instance strictly exogenous variables. Consequently, the *GMM* estimator described above has become increasingly popular, and today it stands out as the standard work horse of contemporary studies of dynamic panel data. Again, interested readers are referred to Bond (2002) for a less compact introduction, and to Arellano (2003) for a comprehensive and rigorous overview.

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[7] In this context, the so-called Hansen statistic is the minimised value of the two-step *GMM* criterion function (Hansen, 1982).

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Appendix 3