Faster drilling with experience?*

Professor Petter Osmundsen
E-mail: petter.osmundsen@uis.no
Department of Industrial Economics, University of Stavanger, NO-4036 Stavanger, Norway

Associate professor Kristin Helen Roll**
Email: kristin.h.roll@uis.no
Department of Industrial Economics, University of Stavanger, NO-4036 Stavanger, Norway

Professor Ragnar Tveteras
E-mail: ragnar.tveteras@uis.no
UiS Business School, University of Stavanger, NO-4036 Stavanger, Norway

*We would express our thanks for rewarding conversations with and comments on the article itself from a number of key specialists in oil the Norwegian Petroleum Directorate, oil companies, rig contractors and oil service enterprises. We also thank Bernt Aadnøy at the University of Stavanger for valuable support. We are also grateful for useful comments from seminar participants at the University of Aberdeen, the University of Stavanger, and the 2010 IAEE international conferences in Rio and Vilnius. Funding from the Norwegian Research Council is appreciated.

**Address of correspondence: Kristin H. Roll, Department of industrial economics and risk management, University of Stavanger, NO-4036 Stavanger, Norway. Email: kristin.h.roll@uis.no Phone number: +47 51832258

Abstract

Drilling expenses has increased sharply in recent years. The productivity of drilling operations - in terms of meters drilled per day - significantly influences exploration costs. This study analyzes the effect of different types of learning on offshore drilling productivity. The econometric analysis employs a large data set on exploration wells from the Norwegian Continental Shelf. Many other industries have a steep learning curve. A central question here is if learning effects also contribute to increased productivity in petroleum exploration drilling. Furthermore, to what extent do diseconomies associated with reservoir depletion effects and limited acreage counteract learning effects on productivity?

1. Introduction

The future global supply of petroleum depend critically on sufficient investments in exploration drilling as the current discovered reserves are being depleted. Drilling costs is an important determinant of exploration drilling and thus the rate of produced reserve replacement because higher costs reduce the oil companies' incentives to undertake risky exploration investments. Drilling expenses have globally increased sharply in recent years. Key causes of this increase include declining drilling productivity and higher rig rates. Oil operations on the Norwegian Continental Shelf (NCS), as in other petroleum provinces, have recently been characterized by a shortage of rigs and very high rig rates. Rig rates on NCS increased from 75.000 dollar per day in May 2003 to 560.000 dollar per day in September 2008; an increase of 646 per cent. Understandably, the high rig rates instigated an enhanced focus on drilling speed.

At the same time as rig rates exploded, a decline in drilling productivity - measured by the industry standard *drilled meters per day* - has been observed and has caused much concern in the petroleum industry. As shown by Osmundsen, Roll and Tveteras 2010, the drilling productivity on the NCS in the four-year period 2005-2008 was on average 43 meters per day, significantly lower than the average 76 meters per day in the previous four-year period (2001-2004). Although there are not studies on drilling productivity available for many regions, anecdotal evidence suggests that a decrease in drilling productivity has been a global trend.[1] This may have a negative effect on the number of exploration wells that oil companies decide to drill, and thus the ability to discover new petroleum resources to replace the declining reserves in developed fields.

Building on research on drilling productivity (Aadnøy, 1999; Managi et al., 2005; Kaiser and Pulsipher, 2007; Kaiser, 2009; and Osmundsen, Roll and Tveteras, 2010) we will in this paper map out factors that are expected to influence drilling productivity. Our paper is complementary to Aadnøy (1999) and an extension of Osmundsen, Roll and Tveteras (2009). Where Aadnøy (1999) use qualititative evaluation methods to explore the relation between drilling speed and physical well characteristics, we employ an econometric approach on a large data set of individual exploration wells on the Norwegian Continental Shelf (NCS). Furthermore, where Osmundsen, Roll and Tveteras (2010) focus on the relationships between drilling productivity and physical characteristics of the well and well site, we extend the analyses by including the effect of different types of learning, or offshore drilling experience. We also propose that diseconomies associated with reservoir depletion effects and limited acreage may counteract learning effects on drilling productivity in a particular area over time.

In the literature is hard to find empirical statistical evidence of the effects of different types of learning on drilling productivity, with an exception for Kellogg (2009), who analyses inter-firm learning in Texas onshore drilling. Kellogg (2009) empirically examines the importance of relationship-specific learning, using high-frequency data from onshore oil and gas drilling in Texas. He uses the time necessary to drill a well as the measure of drilling productivity, accounting for the depth of the well being drilled. He argues that the measure of drilling speed parallels the way producers and engineers actually view drilling productivity. The analyses show that the joint productivity of a lead firm and its drilling contractor is enhanced significantly as they accumulate experience by working together.

In our paper we distinguish between the following types of learning in our econometric analysis: (1) Previous drilling experience in a given offshore area (quadrant); (2) previous experience of the drilling operator (oil company) on the NCS; and (3) previous experience of the drilling facility on the NCS. These three types of experience are measured by the cumulative number of exploration and production wells drilled before the current well. In addition, we control for several other factors, including the physical characteristics of the well and well site, technological change, and business cycles in the petroleum industry.

We analyze the effect of different types of experience or learning on drilling productivity, by estimating flexible econometric models of drilling productivity, using the common metric *meters drilled per day* as the dependent variable. This measure is widely used in the oil industry; for benchmarking of drilling performance, for evaluation of rig tenders, and as a performance indicator in incentive schemes.[2] We want to emphasize, however, that other measures also are necessary to identify value creation in drilling. First of all, requirements with respect to health, environment and safety (HES) must be fulfilled.[3] In addition to HSE and drilling speed, which affects the cost side, the amount of oil and gas which can be produced must certainly be taken into account. It is not only a question of drilling fast, but also of drilling correctly. A trade-off may need to be made here, at least in parts of the well path. In transport stages of the well, nevertheless, drilling speed is important. However, drilling speed in exploration should not come at the expense of the primary objective of gathering well information.

Previous literature has addressed petroleum reserve additions per unit of drilling effort - on US data by Iledare and Pulsipher (1999) and on British data by Kemp and Kasim (2006). Our approach is complementary to this research on exploration efficiency. Whereas the exploration efficiency approach also evaluates the productivity of geologists, geophysicists and reservoir engineers including the choice of drilling location, our measure of drilling efficiency is confined to evaluate the drilling process itself in terms of drilling speed.[4]

Iledare (2000) takes into the account the learning effect in explaining petroleum reserve additions per unit of drilling effort; in addition to factors like finding rates. The learning effect is modeled by cumulative drilling – an approach we also use in our model.

Farnsworth and Norgaard (1976) put forward hypotheses on the relation between learning effects and well depth which we will test on our well sample. We are also able to test for the relation between drilling speed and reservoir parameters put forward by Aadnøy (1999).

The paper is organized as follows: In section two we present the hypotheses to be tested on the different types of experience that may influence drilling productivity. Section three presents the econometric model of drilling productivity to be estimated and the data set. In section four the empirical results from the estimated econometric model is presented and discussed. Finally, section five concludes.

2. Exploration drilling experience hypotheses

Arrow (1962) pointed out the role of knowledge in economic growth, and its overwhelming importance relative to capital formation. He further stressed that learning - the acquisition of knowledge - is the product of experience (activity), as illustrated by learning curves.

Even though the physics of drilling is generally the same across wells, they may vary widely in complexity and type. The productivity in offshore exploration drilling is determined by a sophisticated interplay between physical well characteristics, site characteristics, drilling operator (oil company) competence, drilling contractor competence, and drilling facility technologies. Here we focus on how different types of experience in exploration drilling influence drilling productivity, and whether experience is important in certain situations.

Since Arrow's (1962) seminal paper the argument that production experience or learning improves efficiency is strongly supported by empirical evidence in many, primarily manufacturing, sectors, see for example Yelle (1979) and Balasubramanian and Lieberman (2010), and studies cited by these. It can be argued that, similar to many manufacturing sectors, offshore exploration drilling have several of the characteristics which cause learning-by-doing to be important for improving firms' productive performance: Several types of knowledge is difficult to acquire in a market, and production processes are complex and knowledge-intensive.[5]

However, unlike e.g. manufacturing sectors, for petroleum resource extraction there are also effects that may actually contribute to reduced productivity as cumulative production increases, in this industry as the cumulative number of drilled wells in a given area increases. First, the cumulative number of wells in an area can be used as an index of maturity. Maturity is essential as the least challenging wells in terms of geologic conditions usually are drilled first and the more complex wells later (*depletion effect*).[6] Second, there may be a negative *congestion effect* that increases with the density of wells in an area, e.g., relating to existing infrastructure and wells in the area. What we test is the effect of cumulative drilling from a given offshore area on drilling productivity - the sum of the experience, depletion and congestion effect. It is this overall effect that is crucial to the oil companies' profitability. Moreover, if this cumulative effect is positive, we can conclude that the learning effect dominates the combination of a depletion effect and a congestion effect, suggesting a considerable learning effect.

Below we present the three hypotheses to be tested. It should be noted that the first hypothesis may also involve learning from other firms' past production experience, i.e. inter-organizational learning, while the last two hypotheses concern learning solely from own past production experience.

We would like to test the hypothesis that increasing cumulative experience from a given offshore area (quadrant) on the Norwegian Continental Shelf should contribute to higher drilling productivity. From previous drilling experience in an area one should learn about (1) geologic conditions such as formation type and complexity, formation pressure and well temperature, (2) weather conditions such as waves, currents, and extreme conditions, and (3) logistical challenges, such as supplies of equipment, manpower and materials to the drilling facility. Learning about all these factors should contribute to increased productivity. However, the degree of learning from a given area may also depend on knowledge acquired by other operators and drilling facilities in the same area, as there may have been several operators and facilities which have drilled wells in the area. In other words, the degree of learning depends on the degree of inter-organizational learning. There are several mechanisms that may facilitate inter-organizational learning in a given area on the NCS: Different operators may use the same drilling facilities or *vice versa*, there is technical information on the area available in the public domain e.g. through the government agency *Norwegian Petroleum Directorate*, if there is petroleum production in the area this would typically involve a consortium of license partners which to some extent share information, and finally employees with area-specific knowledge may migrate between firms. One should expect considerable heterogeneity between different areas in terms of the availability of knowledge from previously drilled wells to the firms that are drilling the most recent well.

We also would like to test the hypothesis that the cumulative *drilling experience of an operator*, i.e. an oil company, on the Norwegian Continental Shelf should contribute to higher drilling productivity. It is a complex task to manage different stages of the well construction process – design, planning, execution and analysis. Usually drilling operations of multinational oil companies on the NCS are managed by a Norwegian subsidiary company. Since the start of offshore drilling on the NCS in the late 1960s most international oil companies have established local organizations in Norway. The use of a local organization is probably due to a number of factors that gives advantages to proximity – extensive and complex Norwegian government environmental, safety and working regulations, the often complex interaction with local suppliers of services and equipment, specific knowledge about physical characteristics of the NCS, etc. However, it takes time to develop an efficient offshore oil exploration organization consisting of teams of geologists, reservoir engineers, drilling engineers, project managers, contract managers, etc. There are reasons to believe that at least for the first wells the learning curve may be steep. It might be a challenge to maintain the drilling competence if drilling operations is few and spread over a long time period.

Finally, we test the hypothesis that higher cumulative drilling experience of a drilling facility on the NCS contributes to higher productivity. One should expect that the experience with the performance of the drilling facility increases with the cumulative number of wells drilled (*experience or learning effect*). Increased knowledge may be gained with experience of the conditions on the NCS, and the drilling facility's actual capacities and performance in relation to the requirements of wells, weather conditions, etc. on the NCS. The drilling operators that hire the drilling facility will also learn about its performance. Learning may lead to a more appropriate use of the facility in terms of which types of areas and wells it is hired for, and to adjustments of the facility and its equipments through upgrading investments. A factor that may counteract the positive learning effect on productivity is a negative *technological vintage effect*: the age of the drilling facility increases, and its equipment is worn out or become obsolete in relation to the requirements of new wells unless investments are made to upgrade it. Thus, we will test whether it is the learning effect or the vintage effect that is dominating.

3. Empirical specification and data

We estimate a transcendental logarithmic production (a so-called "translog") econometric model of drilling productivity introduced by Christensen et al. (1973). It is on log-log form for the continuous variables, which simplifies derivation of elasticities. The translog model is flexible in the sense that continuous variables are specified as second-order and interacted variables, and will therefore allow for a complete specification of substitution patterns among continuous variables. The unit of observation is an exploration well, which is observed from drilling is initiated to the drilling process is finished.

The translog econometric model is on a general form specified as

$$\begin{aligned}
\ln Y &= \alpha_0 + \sum_k \beta_k \ln x_k + 0.5 \sum_k \sum_l \beta_{kl} \ln x_k \ln x_l \\
&+ \sum_m \beta_m \ln r_m + 0.5 \sum_m \sum_n \beta_{mn} \ln r_k \ln r_l + \sum_k \sum_m \beta_{km} \ln x_k \ln r_m \\
&+ \beta_t t + 0.5 \beta_{tt} t^2 + \sum_k \beta_{kt} \ln x_k t + \sum_m \beta_{mt} \ln r_m t \\
&+ \beta_p p + 0.5 \beta_{pp} p^2 + \beta_{pt} pt \\
&+ \sum_{comp=2}^{4} \alpha_{comp} D_{comp} + \alpha_{P\&A} D_{P\&A} + \alpha_{disc} D_{disc} + \alpha_{wc} D_{wc} + \sum_{area=2}^{3} \alpha_{area} D_{area}
\end{aligned} \qquad (1)$$

where the dependent productivity variable, *Y,* is average drilled meters per day and represents drilling productivity. It is measured as total meters drilled from the sea bed to the bottom of the well, divided by the number of days from drilling activity is initiated until drilling is terminated, including days with no or little drilling activity (downtime). *x* is a vector of variables that represents physical characteristics associated with the exploration well, including well depth in meters (*dm*), water depth in meters (*wd*) and the litostatic pressure measured by the maximum (*md*) and the variation (*sd*) in the density of the drilling fluid. Subscripts *k* and *l* relate to these inputs.

Next, *r* is a vector of variables measuring different levels of experience, including drilling experience in a given area (*exq*), measured by the cumulative number of exploration and development wells drilled in the quadrant of licensed acreage previous to the current well. The experience of a specific operator and a specific drilling facility is measured by the total numbers of exploration and development wells drilled on the NCS by the given operator (*exog*) and drilling facility (*exf*).[7] Subscripts m and n relate to these inputs.

The terms with the time-trend variable t are included to control for unobserved technological change, and should capture the productivity contribution of numerous innovations in drilling that have been introduced during the data period. By interacting the time-trend variable with the above described observable well characteristics, we can measure the influence of these characteristics on productivity changes over time. The oil price variable p, represented by Brent Blend, is used as a proxy for the supply and demand conditions in the drilling market (market pressure), or the scarcity of productive labor, drilling facilities and other specialised inputs. One should expect greater scarcity of inputs in drilling processes as the oil price increases. The hypothesis is that high market pressure implies lower average quality of inputs.

The remaining right hand-side variables are dummy variables included to control for differences in properties of the oil companies, the drilling facilities and the wells. The D_{comp} dummy variable describes the types of oil companies, where the oil companies are separated into four groups based on their size. For categorisation we use the industry norm, with “mid caps am” (*comp3*), “three sisters” (*comp4*) and “mid caps euro” (*comp2*) as separate groups. For the remaining companies we create a “rest” (*comp1*) category.

The $D_{P\&A}$ variable controls for the wellbore status of the well. Most of the wells’ status is plugged and abandoned (P&A), but we also find wells categorised as junked, plugged, re-classed to development, and suspended in our data. We also control for discovery status of the well through the D_{disc} dummy variable, and for the purpose of drilling by specifying whether the well is a wildcat or appraisal (D_{wc}).[8] Furthermore, we control for the region where the well has been drilled by area dummies (D_{area}). The wells are drilled in the three major offshore regions on the Norwegian continental shelf – the North Sea (*area3*), the Norwegian Sea (*area1*) and the Barents Sea (*area2*). α_0 is the constant term representing the reference categories of the dummy variables. The default category consists of wells drilled by oil companies categorised as "rest", wells where the status are not P&A, well with no discovery, appraisal wells, and wells drilled in the Norwegian Sea.

As it may be difficult to interpret the parameters of the continuous variables individually due to interaction effects, it is more informative to calculate elasticities based on these parameters.[9] The elasticity of drilling speed with respect to the physical characteristics associated with the exploration well (water depth, well depth, max drilling fluid density, and variation in the drilling fluid density) is thus defined as;

$$\varepsilon_{Yk} = \frac{\partial \ln Y}{\partial \ln x_k} = \beta_k + \sum_l \beta_{kl} \ln x_l + \sum_m \beta_{km} \ln r_m + \beta_{kt} t \, . \qquad (2)$$

For the experience variables the elasticities are calculated as;

$$\varepsilon_{Ym} = \frac{\partial \ln Y}{\partial \ln r_m} = \beta_m + \sum_k \beta_{km} \ln x_k + \sum_m \beta_{mn} \ln r_n + \beta_{mt} t \, . \qquad (3)$$

The individual components of the elasticity might provide information that can give a more comprehensive understanding of the cumulative experience effect. The first term in Equation (3) measures the neutral experience effect (first order effect). The second component is the effect of a combination of experience and physical characteristics of the well (e.g., the effect that experience has on drilling speed in cases of deep wells), while the third measures the interaction effect with other types of experience. Finally, the last component measures changes in the experience effect over time.

The productivity elasticity with respect to time, or the rate of technological change driven primarily by new innovations, is defined as:

$$\varepsilon_{Yt} = \frac{\partial \ln Y}{\partial t} = \beta_t + \sum_k \beta_{kt} \ln x_k + \sum_m \beta_{mt} \ln r_m + \beta_{pt} p + \beta_{tt} t \,. \tag{4}$$

The productivity elasticity with respect to the oil price, which captures the effect of petroleum industry business cycles that may affect the scarcity of exploration drilling inputs, is defined as:

$$\varepsilon_{Yp} = \frac{\partial \ln Y}{\partial \ln p} = \beta_p + \beta_{pp} \ln p + \beta_{pt} t \,. \tag{5}$$

Our data set is retrieved from the data bases of the Norwegian Petroleum Directorate, which has collected and processed information and statistics on Norwegian oil and gas activities since the first well was drilled in 1965.[10] We have time series for all exploration wells and supplementary variables over the period 1965-2008, split between the three major offshore regions on the

Norwegian continental shelf – the North Sea, the Norwegian Sea and the Barents Sea. The long time span of our data allows us to account for several oil price cycles, as well as technological development. Average meters drilled per day over time are depicted in Figure 1.

(figure 1 approximately here)

Summary statistics of the estimating sample is provided in Table 1. We had to exclude some of the observations in the original data set due to missing observations on key variables in our econometric model, for example density variables. Some of the wells are sidestepping wells from the original exploration well. Including sidestep wells in the estimating sample leads to biased estimates, since these benefit in terms of reduced drilling time by partly utilising the original exploration well. Exclusion due to missing variable observations and sidestep wells lead to a reduction in the number of observed wells from 924 to 519. Given the challenging nature of large-scale offshore oil and gas operations on the NCS, all the major companies in the oil business is represented. The companies participating as operators on the NCS include most major and mid cap international oil companies, and major international oil service companies like Halliburton, Baker Hughes and Schlumberger.[11]

(table 1 approximately here)

As can be seen from table 1, the sample average drilling speed is 54 meters per day, ranging from a minimum of 3.7 to a maximum of 167 meters. There is considerable heterogeneity among the exploration wells in the data set with respect to physical characteristics. Sample well depth is on average 2986 meters, ranging from a minimum of 238 to a maximum of 5717 meters. Water depth is on average 254 meters, ranging from a minimum of 48 meters to a maximum of 1721 meters.

When we examine the drilling experience variables in table 1 we also find much heterogeneity. Average experience in each area (quadrant) - as measured by the cumulative numbers of wells - is 86, with a range from a minimum of 1 to a maximum of 785 wells. When we look at oil company drilling experience, we find that the average is 232 wells, ranging from 1 to 1341 wells. The average number of wells drilled by the facilities in the data set is 26, with a range from a minimum of 1 to a maximum of 173 wells.

4. Empirical results

This section presents the empirical results from estimation of the production model (1), together with associated elasticities.

(table 2 approximately here)

The production model (1) is estimated using OLS with White's heteroskedasticity-consistent standard errors (White, 1980). Before estimation, a classical additive disturbance term is appended to the production function. Symmetry of the continuous variables is directly imposed. Estimated coefficients with heteroskedasticity-consistent standard errors and associated t- and p-values are presented in Table 2. An R^2 of 0.60 suggests that the production function has reasonable explanatory power.

Our empirical findings correspond largely with the a priori expectations that we have derived from conversation with industry specialist. The company size dummy variables, D_{comp}, show that, while companies categorized as mid caps am (*comp2*) and mid caps euro (*comp3*) do not show significant difference in drilling productivity compared to the "rest" category, companies categorized as the three sisters (*comp4*) are - as a group - found to have significantly lower drilling productivity. One possible explanation is that these companies, in spite of a vast international experience, have a limited and discontinuous drilling experience on the NCS. This indicates that *local* experience, including supplier relations and knowledge of regulation and standards, is most important for drilling productivity.

Wells with discovery (*disc*) are found to be less productive than dry wells, while wildcats (*wc*) are more productive than appraisal wells. This is not surprising, as wells with discovery are slower to drill due to time spent on testing. The same is true for appraisal wells, where more tests are done while drilling.

We also find that drilling, when we have controlled for other characteristics of the well, is slower in the Barents Sea (*area2*), than in the North Sea (*area3*) and the Norwegian Sea (*area1*). Norwegian Sea wells are the most productive and North Sea wells are in between. Possible explanation to this is tougher climate conditions in the Barents Sea and larger logistic challenges due to longer distances from supply clusters. The lower number of wells in the Barents Sea also means that this region has travelled a shorter distance down the learning curve. The oil industry also faces tougher environmental standards in the Barents Sea, negatively affecting drilling speed.

It is not informative to interpret the continuous variables that appear in several terms in equations (1) individually. Sample mean elasticities are therefore calculated from the estimated parameters, using equations (2) to (5).

Table 3 reports the calculated sample mean elasticities of variables that represent physical characteristics associated with the exploration well. All the elasticities are significant at the 10% confidence level.

(table 3 approximately here)

Our results show that water depth has a negative effect on productivity. This is not surprising as our drilling meter measure starts at the sea bed. With deep waters it takes more time for the drilling company to undertake drilling. Drilling productivity is lower on average in deeper wells. This finding may have several explanations, e.g. technical problems like the drill bit going stuck, often takes more time to remedy in deeper wells. The litostatic pressure, measured by the maximal density of the drilling fluid, is also found to slow down drilling productivity. This result is supported by Santarelli and Dardeau (1992) who found that a high mud weight may result in loss of drilling circulation, and Aadnøy (1999) who argues that an increased mud weigh will lead to higher pressure overbalance and that the drilling assembly will be more easily subjected to differential sickening.[12] Furthermore, pressure variations, measured by the standard variation of the drilling fluid, are found to have a negative effect of productivity. This is in accordance with earlier studies which find that pressure variations may lead to a fatigue effect on boreholes, as the static pressure declines (Aadnøy, 1999).

Technological change and oil price elasticity are reported in table 4. We find a statistically significant technological change, with a yearly increase of 3%. The technological progress is a result of many innovations, which without doubt have substantially changed the drilling technology over time. Examples are the introductions of the top drive and real-time measurement technologies while drilling.

According to Table 4 a high oil price has a negative effect on productivity. This is as expected since high oil prices are associated with high activity levels and thus a scarcity of qualified labor, high quality drilling facilities and other specialised inputs. Less adequate rigs are being used at the margin, reducing average productivity. Moreover, at the peak of a business cycle for the oil industry it is more likely with scarcity of trained and experienced personnel and bottle necks at other crucial supply services in drilling, thus driving up the non-productive time.

(table 4 approximately here)

Since the main interest of this study is the effect and structure of previous experience, several hypotheses related to the included experience indexes are tested. In Table 5 Wald tests are reported for the null hypothesis of *no* effect on productivity associated with i) previous drilling experience in the license quadrant, ii) previous drilling experience of the oil company on NCS, and iii) previous drilling experience of the drilling facility on NCS. Furthermore, the flexible specification of the drilling production function allows us to test different hypotheses of the structure of experience effects. The significance of interaction terms between experience indexes and the physical characteristics associated with the exploration well iv) is tested. Finally, a null hypothesis of *no* time effect associated with experience v) is conducted to investigate the presence of change in experience effect over the sample time period.

(table 5 approximately here)

The null hypotheses i),ii) and iii) were rejected, thus supporting the presence of experience effects in exploration drilling. Furthermore, the tests support the specification of a flexible model, with interaction terms between experience effects and physical characteristics associated with the exploration well (hypothesis iv). The last hypothesis (v), which is testing absence of time effect associated with experience, is not rejected at 5% level of significance. At the 10% level, however, this hypothesis is also rejected.

From the estimated parameter estimates, sample average experience elasticities are calculated using equation (3). The calculated elasticities for the sample average well are presented in table 6. The mean elasticity of productivity in area experience (ε_{Yexq}) is calculated to be - 4.6%. This may seem counterintuitive, but may as argued earlier have reasonable explanations. The degree of learning from drilling experience in the area may depend on inter-organizational learning as other operators and drilling facilities may have drilled past wells. Furthermore, when increasing the drilling activity in a quadrant opposing effects over productivity occur: a positive effect for learning, a negative effect related to the fact that the least challenging wells are typically drilled first (negative stock effect), and an effect related to negative congestion externalities that increases with the density of wells in the area. Our empirical estimates suggest that the negative effects dominate. This is analogous to findings by Iledare (2000) on the effect of cumulative drilling on petroleum reserve additions per unit of drilling effort, in which learning effects - e.g., in seismic technology that made it possible to find smaller deposits - are dominated by diminishing returns in exploration. He concludes that the data is persuasive to support the hypothesis that technical progress has dampened quite significantly the adverse effects of effectiveness at adding new reserves on the Gulf of Mexico. However, technical progress has not significantly overshadowed the effects of depletion.

Previous experience of the operating company on the NCS is in our study found to have a positive effect on productivity, with an estimated elasticity (ε_{Yexog}) of 5.7%, while for previous experience of the drilling facility we find no significant effect as measured by the elasticity (ε_{Yexf}). An explanation of the latter is that the learning effect is offset by a negative vintage effect of the drilling facility.

(table 6 approximately here)

In the elasticities calculated in Table 6, we are not able to isolate the effect of experience, as it occurs jointly with depletion, congestion and vintage effects. The experience elasticities are calculated for the sample average well. But since most wells are not sample average – it is also interesting to look at the individual components of the estimated elasticites, to get a richer understanding of the effect of experience. By analyzing interaction terms, we are able to isolate instances where the effect of experience on drilling productivity is particularly important, i.e., cases where the learning effect dominates. Table 7 reports the individual components of the estimated elasticities (p-values in brackets). These are cross-terms between the *area experience*, *operator experience*, or eventually *facility experience*, and the other variables, and can therefore also be found in Table 2.

(table 7 approximately here)

For the experience effect in the area, we find a positive and significant interaction term with well depth. Experience in the quadrant therefore seems to be particularly important for drilling speed when drilling deep wells. This gives some support for the hypothesis put forward by Farnsworth and Norgaard (1976), that one would expect more rapid technological change to occur for deep wells than for shallow wells because the rate of increase in experience (which is related to technological change) is greater for deep wells than for shallow.

Contrary to this, we find a negative and significant interaction term between experience of the oil company and the well depth. In other words, the positive productivity effect of experience of the oil company is smaller when drilling deep. A possible explanation may be that deep wells have particular inherent characteristics such that the oil company's local experience in a particular area – which for the case of the NCS is dominated by shallower wells - has less value. We also find a significantly negative second order term, which indicates that there are declining learning returns from adding new wells in a quadrant.

Conversely, we find a positive effect of oil companies' previous experience on the NCS if the litostatic pressure - measured by the maximal density of the drilling fluid - is high.Furthermore, we find a positive interaction term with the previous experience of the drilling facility. This implies that a high level of experience for both the oil company and the drilling facility will generate higher drilling productivity. This gives some support for the findings of Kellogg (2009) from Texas onshore drilling. However, we have not been able to control for *joint* experience of contracting parties, which was the topic of Kellogg.

While the elasticity of previous facility experience shows no significant effect on productivity, as it also accounts for vintage of the facility, several of the individual components of the estimated elasticity are highly significant. The neutral component (β_{exf}), measuring the first order effect is positive and significant, and together with a negative second order term it predicts a positive but decreasing marginal effect on productivity with increased facility experience. Furthermore, we find a positive and significant interaction term with water depth, which indicates that facility experience is of importance when drilling in deep waters. The interactions with well fluid density variables are not clear-cut: while facility experience will increase the negative effect of high litostatic pressure, it will reduce the negative effect of pressure variations. Finally, we find a negative effect associated with the interaction terms between the time trend and facility experience. This suggests that facility drilling experience was more important previously.

5. Conclusions

This paper has focused on the effects of different types of experience (or learning) on exploration drilling productivity. Econometric models of productivity - in terms of meters drilled per day – were estimated to test hypotheses on experience, using well data from the Norwegian continental shelf. Unlike most other industries, in drilling of oil and gas we expect that a positive learning effect is counteracted by a negative depletion effect (the more easy prospects are being drilled first) and a negative congestion effect (conflicts with existing infrastructure). We find interesting results on two levels.

First, we examine how the change in overall activity levels affects the drilling speed over time. Our estimated elasticity measure of experience in a particular area (quadrant experience) - with experience measured by the cumulative number of wells drilled - shows a negative effect on productivity for the sample average well, suggesting that congestion externalities and depletion effects dominate learning effects. Similarly, the experience of the drilling facility is found to have no significant effect on productivity for the sample average well, i.e., on average the learning effect is offset by the vintage effect of the drilling facility.

Second, by analyzing the individual components of the elasticities, we are able to identify situations where learning effects are particularly important, to the extent that learning effect dominate negative effects of drilling activity. By investigating the different components of the activity elasticity we find that area (quadrant) experience is important when drilling deep. Previous experience on the NCS of the operating company is also found to have a positive effect on productivity. Conversely no such effect is found for international experience, indicating that only local oil company experience has a positive effect on productivity. This type of experience is found to be especially important when the litostatic pressure is high. Also, looking at the different components of the learning elasticity we find that drilling facility experience is important when drilling in areas with large water depth as well as in areas where there are challenges in terms of pressure variation.

We saw a dramatic drop in drilling speed at the Norwegian continental shelf following the 2004 gas blow-out at the *Snorre A* field, which could have resulted in a major accident with the loss of many lives. See Figure 1. The perceived negative effects on drilling speed from this incident may have some relevance for the current oil spill in the Gulf of Mexico.[13] A significant slowdown of drilling speed can be expected. In Norway drilling speed picked up three years after the incidence. A revised view of safety and drilling speed aroused at that time. According to industry specialists, there are certainly situations where there is a trade-off between safety and drilling speed, but this is not the case on a general basis. For instance, many of the success criteria for safe drilling, e.g., good planning and a clean drilling deck, also are important to secure drilling speed. Moreover, long duration of open well exposure can lead to various well problems, thus calling for a higher drilling speed. In a global perspective for the next years, the combination of changes in drilling environment (with the move to deeper waters and more complex reservoirs), changes in drilling technologies, and new safety requirements will probably make it more challenging to benefit from past experiences in exploration drilling.

Literature

Aadnøy, B.S., 1999. Modern Well Design. Balkema, Rotterdam.

Facts (2009), a general overview of information regarding the petroleum activities on the Norwegian continental shelf, published by the Ministry of Petroleum and Energy together with the Norwegian Petroleum Directorate; http://npd.no/en/Publications/Facts/Facts-2009/

Arrow, K.J. 1962. The economic implications of learning by doing. *The Review of Economics Studies* 29, 3, 155-173.

Balasubramanian, N. and Lieberman, M.B. 2010. Industry learning environments and the heterogeneity of firm performance. *Strategic Management Journal*, 31, 4, 390-412.

Farnsworth, R.L. and R.B. Norgaard. 1976. Technical change and petroleum drilling costs: comment. *Land Economics* 52, 1, February, 103-108.

Iledare, O. O. and A. Pulsipher. 1999. Sources of change in petroleum drilling productivity in onshore Lousiana in the US, 1977-1994. *Energy Economics* 21, 261-271.

Iledare, O. O. 2000. Trends in the effectiveness of petroleum exploration and development drilling in the U.S. Gulf of Mexico OCS region 1977-1998. Paper prepared for presentation at the 2000 SPE Annual Technological Conference and Exhibition, Dallas, Texas, 1-4 October, 2000.

Jovanovic B., and Nyarko Y. 1995. A Bayesian learning model fitted to a variety of empirical learning curves. Brookings Papers on Economic Activity Microeconomics 1995: 247–305.

Kaiser, M.J. and Pulsipher, A.G. 2007. Generalized Functional Models for Drilling Cost Estimatio". *SPE Drilling & Completion* 22(2), SPE 98401, June 2007, 67-73.

Kaiser, M.J. 2009. Modeling the time and cost to drill an offshore well. *Energy* 34, 1097-1112.

Kellogg, R. 2009. Learning by drilling: Inter-Firm Learning and Relationship Persistence in the Texas Oilpatch. NBER Working Paper Series, Vol. w15060.

Kemp, A. and S. Kasim. 2006. A regional model of oil and gas exploration in the UKCS. Scottish Journal of Political Economy 53 (2), 198-221.

Managi, S., Opaluch, J.J., Jin, D., and T. A. Grigalunas (2005), Technological change and petroleum exploration in the Gulf of Mexico. *Energy Policy* 33 (5), 619-632.

Mohn, K. 2008. Efforts and Efficiency in Oil Exploration: A Vector Error-Correction Approach. *The Energy Journal* 30 (4), 53-78.

Mohn, K. and P. Osmundsen. 2008. Exploration economics in a regulated petroleum Province. *Energy Economics* 30 (2), 303-320.

Osmundsen, P. 2009. Incentives for Drilling Contractors. Exploration & Production, *Oil &Gas Review* 7, 73-75.

Osmundsen, P. 1998. Dynamic taxation of nonrenewable natural resources under asymmetric information about reserves. *Canadian Journal of Economics* 31, 4, 933-951.

Osmundsen, P., Roll, K., and R. Tveteras. 2010. "Exploration drilling productivity at the Norwegian continental shelf", *Journal of Petroleum Science and Engineering* 73, 122-128.

Osmundsen, P., Sorenes, T., and Toft, A. 2008. Drilling Contracts and Incentives. *Energy Policy* 36, 3138-3144.

Osmundsen, P., T. Sorenes, and A. Toft. 2010. Offshore Oil Service Contracts - New Incentive Schemes to Promote Drilling Efficiency, *Journal of Petroleum Science and Engineering* 72, 220-228.

Osmundsen, P., Toft,and K. A., Dragvik. 2006. “Design of Drilling Contracts – Economic Incentives and Safety Issues”. *Energy Policy* 34, 2324-2329.

Santarelli, F.J., Dardeau, C., and Zurdo, C.: “Drilling Through Highly Fractured Formations: A Problem, A Model, and a Cure,” SPE 24592, presented at the SPE Annual Technical Conference, Washington, DC, October 4-7, 1992.

Sweeney, J.L. 1993. “Economic theory of depletable resources: An introduction”, in A.V. Kneese and J.L. Sweeney, eds. *Handbook of Natural Resource and Energy Economics,* Volume 3, 1993, 759-854.

White, H. 1980. A Heteroskedasticity-Consistent Covariance Matrix Estimator and a Direct Test for Heteroskedasticity. *Econometrica* 48 (4), 817--838

Yelle, L.E. 1979. The learning curve: Historical review and comprehensive survey, *Decision Sciences* 10, 302-328.

Tables:

Table 1. Summary Statistics of Variables in the Econometric Model

Description	Variable	Mean	Std. Dev.	Min	Max
Meters drilled per day	Y	54.284	27.394	3.710	166.563
Oil companies - Rest	*comp1*	0.168	0.374	0	1
Oil companies - Mid caps euro	*comp2*	0.566	0.496	0	1
Oil companies - Mid caps am	*comp3*	0.091	0.287	0	1
Oil companies - Three sisters	*comp4*	0.175	0.381	0	1
Wellbore status	*P&A*	0.854	0.359	0	1
Discovery status	*disc*	0.297	0.457	0	1
Purpose of drilling	*wc*	0.709	0.455	0	1
Norwegian sea	*area1*	0.329	0.470	0	1
Barents sea	*area2*	0.085	0.279	0	1
North sea	*area3*	0.586	0.493	0	1
Water depth	*wd*	254	210	48	1721
Well depth	*dm*	2986	1062	238	5717
Max drilling fluid density	*md*	1.565	0.392	1.030	8.330
Variation in drilling fluid density	*sd*	0.249	0.173	0.010	1.343
Quadrant experience	*exq*	86.541	122.358	1	785
Oil company experience	*exog*	232.416	300.846	1	1341
Facility experience	*exf*	25.967	24.794	1	173
Year	t	1993.073	6.857797	1976	2008
Oil price	p	35.831	13.978	16.69	72.39

Observations: N = 519.

Table 2. Estimated Parameters of the Econometric Model

	Coef.	Std. Err.	t-value	P-value
α_0	4.359	0.710	6.140	0.000
α_{comp2}	-0.020	0.050	-0.390	0.698
α_{comp3}	-0.005	0.064	-0.080	0.938
α_{comp4}	-0.145	0.056	-2.600	0.010
$\alpha_{P\&A}$	0.093	0.058	1.580	0.114
α_{disc}	-0.301	0.038	-7.970	0.000
α_{wc}	0.278	0.044	6.280	0.000
α_{area2}	-0.227	0.072	-3.150	0.002
α_{area3}	-0.120	0.052	-2.320	0.021
β_{wd}	-0.518	0.183	-2.820	0.005
β_{dm}	-0.607	0.389	-1.560	0.119
β_{md}	0.865	0.898	0.960	0.336
β_{sd}	-0.080	0.135	-0.590	0.554
β_{exq}	-0.056	0.085	-0.650	0.516
β_{exog}	0.118	0.079	1.500	0.134
β_{exf}	0.231	0.097	2.370	0.018
β_{wd-wd}	-0.195	0.110	-1.780	0.076
β_{wd-dm}	-0.326	0.136	-2.400	0.017
β_{wd-md}	1.201	0.278	4.330	0.000
β_{wd-sd}	-0.053	0.050	-1.060	0.289
β_{wd-exq}	-0.021	0.025	-0.820	0.414
$\beta_{wd-exog}$	-0.002	0.027	-0.090	0.927
β_{wd-exf}	0.053	0.021	2.490	0.013
β_{dm-dm}	-0.601	0.181	-3.320	0.001
β_{dm-md}	-0.093	0.418	-0.220	0.825
β_{dm-sd}	0.070	0.085	0.820	0.412
β_{dm-exq}	0.088	0.044	1.980	0.048
$\beta_{dm-exop}$	-0.117	0.060	-1.940	0.053
β_{dm-exf}	0.070	0.063	1.120	0.264
β_{md-md}	0.993	0.762	1.300	0.193
β_{md-sd}	-0.690	0.291	-2.370	0.018
β_{md-exq}	-0.067	0.102	-0.650	0.515
$\beta_{md-exog}$	0.171	0.098	1.750	0.081
β_{md-exf}	-0.312	0.156	-2.000	0.046
β_{sd-sd}	0.062	0.057	1.100	0.271
β_{sd-exq}	-0.024	0.018	-1.340	0.181
$\beta_{sd-exog}$	0.004	0.014	0.250	0.804
β_{sd-exf}	0.057	0.022	2.650	0.008
$\beta_{exq-exq}$	0.009	0.015	0.590	0.555
$\beta_{exq-exog}$	-0.008	0.008	-0.940	0.348
$\beta_{exq-exf}$	0.003	0.009	0.370	0.711
$\beta_{exog-exog}$	-0.033	0.017	-1.970	0.049
$\beta_{exog-exf}$	0.017	0.010	1.730	0.084
$\beta_{exf-exf}$	-0.083	0.027	-3.140	0.002
β_t	-0.073	0.048	-1.520	0.129
β_{t-t}	0.004	0.002	2.410	0.016
β_{wd-t}	0.009	0.005	1.770	0.077
β_{dm-t}	0.012	0.012	1.010	0.315

β_{md-t}	-0.045	0.027	-1.670	0.096
β_{sd-t}	0.000	0.004	-0.090	0.925
β_{exq-t}	0.000	0.002	0.000	0.997
β_{exog-t}	-0.001	0.002	-0.810	0.418
β_{exf-t}	-0.007	0.003	-2.530	0.012
β_{p}	0.346	0.210	1.650	0.101
β_{p-p}	-1.027	0.272	-3.780	0.000
β_{p-t}	-0.030	0.007	-4.430	0.000

N = 519. R-squared = 0.60

Table 3. Sample Mean Elasticity Estimates for Well Characteristics

	Elasticity	Std. Err.	t-value	P-value
ε_{Ywd}	-0.187	0.033	-5.660	0.000
ε_{Ydm}	-0.130	0.078	-1.680	0.094
ε_{Ymd}	-0.603	0.225	-2.680	0.008
ε_{Ysd}	-0.081	0.037	-2.210	0.027

Table 4. Estimated Sample Mean Rate of Technical Change and Oil Price Elasticity

	Elasticity	Std. Err.	t-value	P-value
ε_{Yt}	0.030	0.006	5.330	0.000
ε_{Yp}	-0.416	0.083	-5.000	0.000

Table 5. Wald Tests of Experience Effects

	Null hypotheses	F-value	Prob > F	Decision
i)	$\beta_{exq} = \sum_m \beta_{m-exq} = \sum_k \beta_{k-exq} = \beta_{exq-t} = 0$	2.35	0.0135	Reject H0
ii)	$\beta_{exog} = \sum_m \beta_{m-exog} = \sum_k \beta_{k-exog} = \beta_{exog-t} = 0$	2.24	0.0185	Reject H0
iii)	$\beta_{exf} = \sum_m \beta_{m-exf} = \sum_k \beta_{k-exf} = \beta_{exf-t} = 0$	5.08	0.0000	Reject H0
iv)	$\sum_k \sum_m \beta_{km} = 0$	2.25	0.0092	Reject H0
v)	$\sum_r \beta_{rt} = 0$	2.51	0.0585	Keep H0

Table 6. Sample mean elasticity estimates related to experience

	Elasticity	Std. Err.	t-value	P-value
$\varepsilon_{\mathrm{Yexq}}$	-0.046	0.015	-3.050	0.002
$\varepsilon_{\mathrm{Yexog}}$	0.057	0.026	2.150	0.032
$\varepsilon_{\mathrm{Yexf}}$	-0.010	0.021	-0.460	0.647

Table 7. The individual components of the estimated experience elasticities

	Experience area	Experience operator	Experience facility
	- 0.056 (0.516)	0.118 (0.134)	0.231 (0.018) *
Water depth	- 0.021 (0.414)	- 0.002 (0.927)	0.053 (0.013) *
Well depth	0.088 (0.048) *	- 0.117 (0.053) ’	0.070 (0.264)
Litostatic pressure	- 0.067 (0.515)	0.171 (0.081) ’	- 0.312 (0.046) *
Pressure variation	- 0.024 (0.181)	0.004 (0.804)	0.057 (0.008) **
Time-trend	0.000 (0.997)	- 0.001 (0.418)	- 0.007 (0.012) *
Experience area	0.009 (0.555)	- 0.008 (0.348)	0.003 (0.711)
Experience operator	- 0.008 (0.348)	- 0.033 (0.049) *	0.017 (0.084) ’
Experience facility	0.003 (0.711)	0.017 (0.084) ’	- 0.083 (0.002) **

** significant at 1% level
* significant at 5% level
’ significant at 10% level

Figures:

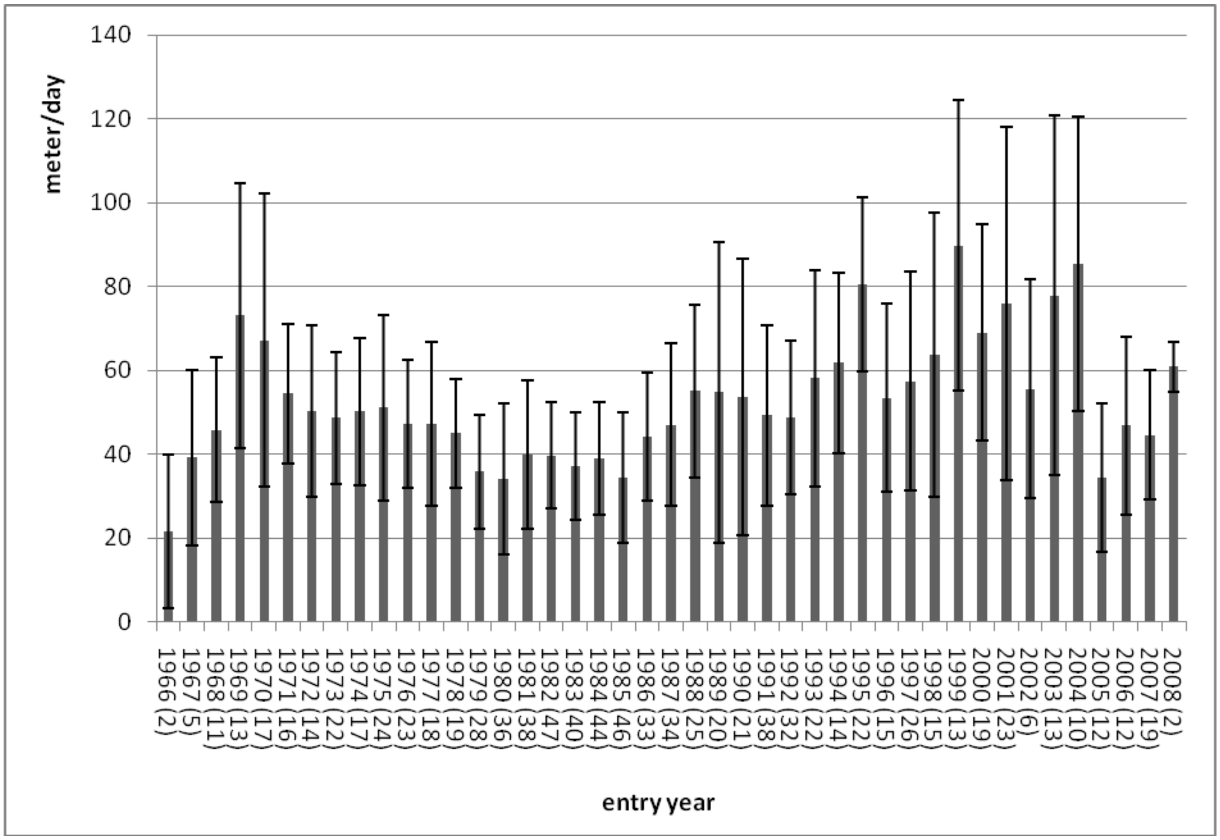

Figure 1. Average meters drilled per day. Exploration wells on the NCS, from 1966 to 2008. Annual number of wells in brackets. Black vertical lines indicate standard deviation. Data source: Norwegian Petroleum Directorate.

Notes:

---

[1] For instance, the Society of Petroleum Engineers (SPE) arranged a forum in Cadiz, Spain, September 20-25, 2009, "The Battle to Reduce Drilling NPT: Technology, Processes and People". The forum addressed reduced drilling productivity; "The number of meters drilled per day is falling dangerously and continuously."

[2] See www.RushmoreReviews.com, Osmundsen (2009) and Osmundsen, Sorenes and Toft (2008, 2010).

[3] For a discussion of the relationship between HSE and incentive systems in drilling, see Osmundsen et al (2006).

[4] When rig rates are high, efficient utilization of rig time becomes particularly important. The combined effect of high rig rates and low drilling speed threatens the exploration activity that is necessary to secure reserve replacement.

[5] See e.g. Jovanovic and Nyarko (1995) and Balasubramanian and Lieberman (2010) for a theoretical discussion and modeling of learning, including the factors that contribute to increasing the importance of own learning for productivity growth.

[6] See Sweeney (1993) and Osmundsen (1998).

[7] These variables are constructed by counting the cumulative number of exploration and development wells that have been conducted in the actual quadrant, or by the actual oil company and drilling facility at the wellbore entry time.

[8] Since there may be structural differences in productivity between wildcat and appraisal wells that are not captured by the "wellbore purpose" dummy variable, we also estimated a separate regression model only for the subsample of wildcats, which represent the majority of observations in the sample. Our empirical findings are overall fairly similar to those from the full sample. The results are available upon request to the authors.

[9] An elasticity is defined as the derivative of the log of the dependent variable with respect to the log of a continuous explanatory variable, measuring the percentage increase in productivity for a one percent increase in the actual explanatory variable, while holding all other variables constant.

[10] Parts of the dataset on exploration drilling on the NCS that is employed in this paper has been analyzed previously, to ascertain the determinants of variations in the overall exploration level and reserve generation. With well-count as the dependent variable, Mohn and Osmundsen (2008) specify and estimate an econometric model of exploration and appraisal drilling for the NCS. Explanatory variables include the oil price, cumulated discoveries and open exploration acreage. In a simultaneous error-correction model for drilling efforts, drilling success, and average discovery size, Mohn (2008) applies the same underlying data set to study reserve additions from NCS oil and gas exploration. Osmundsen, Roll and Tveteras (2010), used the data to investigate the relationship between drilling speed and physical characteristics for the well and well site.

[11] For details on NCS resources and participants, see Facts (2009).

[12] Another problem with high mud weight is related to the recording of excess gas while drilling. While the excess gas helps quantifying the pore pressure at the particular depth, high mud weight may suppress the high gas readings.

[13] The Deepwater Horizon drilling rig explosion, April 20. See http://www.bp.com/bodycopyarticle.do?categoryId=1&contentId=7052055&nicam=UK%20Oil%20Spill%20Response&nisrc=Google&nigrp=UK%20Oil%20Spill%20Response%20Brand&nipkw=bp&niadv=Text%20Ad and http://en.wikipedia.org/wiki/Deepwater_Horizon_drilling_rig_explosion