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Concave drilling curve[1]

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Abstract

Drilling expenses have increased sharply in recent years. Average meters drilled per day significantly influences exploration costs. Hence it is important to understand the factors that determine this drilling metric. In this study we analyse the effect of drilling depth on meter per day. There are various physical and technical characteristics that enhance and decrease meter per day as drilling depth increases. Factors that reduce meter per day are present at depths way above depths of high pressure and high temperature. The counteracting effects on meter per day are described and analysed on a large number of exploration wells on the Norwegian continental shelf.

Keywords: Meter per day, drilling cost

[1] 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 Per Bu, Andre Fjelde, Terje Løvereide, Harald Syse, Stein Tonning and Stein Vårlid, and from seminar participants at the Norwegian Petroleum Directorate. Funding from the Norwegian Research Council is appreciated. Address of correspondence: Petter Osmundsen, Department of industrial economics and risk management, University of Stavanger, NO-4036 Stavanger, Norway. Email: Petter.Osmundsen@uis.no, Home page:WWW.UiS.no/Osmundsen

1. Introduction

When deciding where to explore, reservoir characteristics are the main driver. An additional significant factor to consider is explorations costs. The latter is to a large degree determined by geological conditions, rig rates and average meter per day (m/d). Over the last couple of years, with the presence of high rig rates[2], m/d has become more important to keep down drilling cost. We demonstrate in this paper that m/d is strongly related to drilling depth, with counteracting effects. Drilling depth is defined as meters drilled measured from the sea bottom.

Since the trend is to drill deeper wells, much focus is on drilling challenges in high temperature high pressure wells (HTHP). This often occurs around 4000 metres drilling depth. Our sample well depth from the primary mid water Norwegian continental shelf is on average almost 3000 meters, ranging from a minimum of 109 to a maximum of 5717 meters, with a standard deviation of 1091 metres. Thus, drilling depth is relatively homogeneous and there are just a few HTHP wells in our sample. Nevertheless, drilling depth plays a vital role. We show that drilling depth slows down m/d also at lower levels of pressure.

In this paper we analyze the effect of well depth on m/d, by estimating flexible econometric models of drilling, using the common metric *average 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.[3] 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.[4] In addition to HES and m/d, which affects the cost side, the amount of oil and gas which can be produced is obviously the primary factor to be taken into account.

The paper is organized as follows: In section two we review literature on drilling productivity. In section three we present the hypotheses to be tested on the different factors that may influence m/d. Section four presents the econometric model of m/d to be estimated and the data set. In section five the empirical results from the estimated econometric model is presented and discussed. Section six concludes.

2. Literature

Building on previous research (Aadnøy, 1999; Managi et al., 2005; Kaiser and Pulsipher, 2007; Kaiser, 2009; and Osmundsen, Roll and Tveteras, 2010), we will in this paper analyse factors that are expected to influence m/d, with a particular emphasis on drilling depth. Our paper is complementary to Aadnøy (1999) and is an extension of Osmundsen, Roll and Tveteras (2010). Where Aadnøy (1999) uses qualitative evaluation methods to explore the relation between m/d and physical well characteristics, we employ an econometric approach on a large data set of exploration wells on the

[2] Rig rates on the Norwegian continental shelf for floaters 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 (data source: RS Platou). This high level of rig rates has persisted until 2013. Understandably, the high rig rates instigated an enhanced focus on m/d.
[3] See www.RushmoreReviews.com, Osmundsen (2009) and Osmundsen, Sorenes and Toft (2008, 2010).
[4] For a discussion of the relationship between HES and incentive systems in drilling, see Osmundsen et al (2006).

Norwegian continental shelf. Furthermore, where Osmundsen, Roll and Tveteras (2010) focus on the relationships between m/d and a wide range of economic and physical characteristics of the well and well site, this paper is has a more narrow focus. We only examine technical parameters and the model is set up so as in detail examine the relationship between m/d and well depth.

Previous literature on drilling productivity has addressed petroleum reserve additions per unit of drilling effort - on US data by Iledare and Pulsipher (1999) and Iledare (2000), and on British data by Kemp and Kasim (2006). Our approach is complementary to this research on exploration efficiency. But 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 m/d. The combined effect of high rig rates and low m/d currently threatens the exploration activity that is necessary to secure reserve replacement.

3. Factors affecting m/d as drilling length increases

Average meters drilled per day is the industry standard for measuring drilling performance.[5] Our time measure for a well is from drilling is initiated to the drilling process is finished, i.e., we include non productive time. We believe this to be the correct timeframe in an economic context, e.g., it corresponds to the time period for which rig rates are paid. By meetings and discussions with drilling experts, we were able to form a priori expectations as to how different physical factors affect m/d as the drilling depth increases. When drilling of a well starts there are offsetting effects on m/d. The following factors call for enhanced m/d as the well gets deeper (dominating in the increasing part of the curve in Figure 1):

- Start up time - placing the conductor at the seabed - slows down m/d. This is not surprising, as it takes time without contribution to the key performance indicator - meters per day. The start up can be seen as a fixed time that is depreciated over the metres drilled; the higher the number of metres, the lower the fraction of lost time.
- Top hole is commonly performed in low consolidated formation. To avoid it to cave in, drilling must be cautious and thereby slow. The same applies to the fact that blowout preventor (BOP) is not in place initially. Once BOP is in place and one reaches firm rock, m/d can increase.
- M/d is low during drilling of the top hole. One has to be careful to avoid too large inclination at this stage, since the drill bit and BOP is to be placed here afterwards; 1 degree is maximum.
- It takes time before proper return of liquids has been established. When this is in place, salt water can be replaced by drilling mud. .
- High weighting agents and optimal torque increases m/d as drilling gets deeper.
- Initially, when drilling with a large diameter drilling bit, there is danger of breaking the drill string. Thus, one has to drill slowly. M/d enhances when the diameter of the drill bit becomes smaller. Similarly, the large diameter of the initial drill bit requires a lot of energy. Reduced

[5] Osmundsen et al. (2008, 2012).

dimension as drilling proceeds reduces the energy demand end enhances m/d. Moreover, m/d picks up at reduced dimension of the drill bit due to reduced amount of cuttings.

The following factors call for reduced average m/d as the well gets deeper (dominating in the decreasing part of Figure 1):

- It takes more time to evacuate the cuttings as the drilling length increases. The cuttings need to be pumped over a larger distance.
- When many drill pipes are coupled together, as the drilling length increases, the rotation is subject to more friction, resulting in reduced drilling power.
- Much time is spent on circulation to lower temperature to avoid damage to down hole electronics and batteries. This also applies to non-HTHP wells.
- The longer the drilling distance, the longer time it takes to change the drill bit (tripping) and more time is spent on maintenance.
- When the well gets deeper, there is higher well pressure. This requires higher mud weight, which implies slower drilling.

4. Exploration drilling analysis

As a first logical step, in Figure 1, m/d - measured as average meter drilled per day - is plotted against the depth measure. The dots show average m/d for the sample wells, and the red line shows a line fitted to these points. As illustrated by the figure, average m/d initially increases with well depth. As explained in Section 3, there are several factors that contribute. For example, it takes time before proper return of liquids is established. When this is in place, salt water can be replaced by drilling mud, and m/d picks up.

M/d increases until it reaches a peak around 3000 meters and then gradually falls again. The decline in m/d can be explained by increasing temperature and formation density as the well depth increases. This is supported by the result in our model below that a 1% increase in density, all other factors in the model kept constant, leads to a 1.08% decline in m/d. In other words, as the well is getting deeper, the positive effect is being offset by the negative effects. The positive effects dominate up to approximately 3000 meter. After this point the negative effects dominate. From the summary statistic in table 1 below, we see that the average well is 2958 meter. Thus, m/d is highest at the average well depth. This is a result one would expect. Drilling equipment and procedures are designed for the average well, and deviations from average well depth cause suboptimal operations.

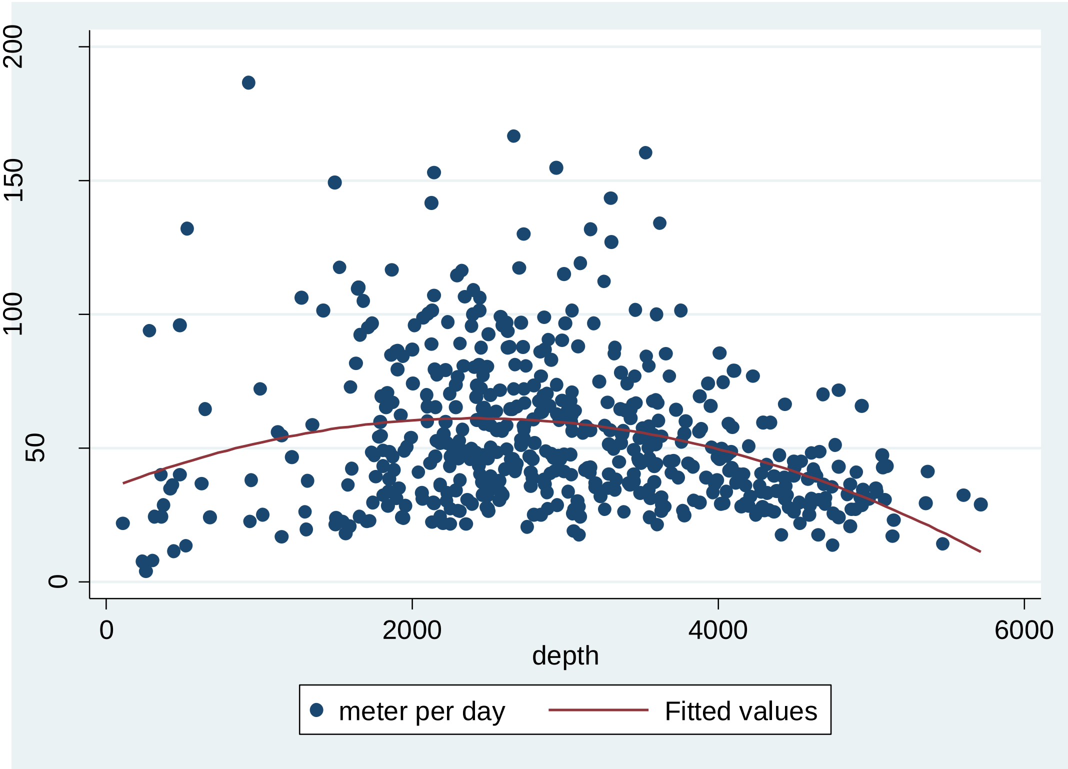

Figure 1: m/d (average meter drilled per day) plotted against drilling depth, for exploration wells on the Norwegian continental shelf, in the period 1965-2008. Data source: Norwegian Petroleum Directory.

While looking at a plot can be valuable as a first shot to understand a relationship between deep and m/d, a full multivariate model is necessary to understand the full picture. We therefore establish a multivariate model of m/d that enables us to isolate the main effects that improve and reduce m/d.

4.1 Empirical specification and data

The data used for estimation 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.[6] We have time series for all exploration wells and supplementary

[6] Parts of the dataset on exploration drilling on the Norwegian continental shelf that is employed in this paper have 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

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. Given the challenging nature of large-scale offshore oil and gas operations on the Norwegian continental shelf, all the major companies in the oil business is represented. The companies participating as operators include most major and mid cap international oil companies, and major international oil service companies like Halliburton, Baker Hughes and Schlumberger.[7]

The estimated econometric model of m/d is on a log-log form for the continuous variables, which simplifies derivation of elasticities. The model is on a general form and is given by:

$$\ln(m/d) = \beta_0 + \beta_{depth} \ln Depth + \beta_{density} \ln Density + \beta_{120} Hightemp + \sum_f \beta_f Tech_f + \beta_{purpose} Purpose + \beta_{trend} Trend \qquad (1)$$

where the dependent variable, *m/d,* is average drilled meters per day. The unit of observation is an exploration well, which is observed from drilling is initiated to the drilling process is finished. To be more specific: in the dataset drilling time commences when the first penetration equipment enters the sea bed (30” conductor or 36” hole opener enters the sea bed). The drilling operation ends when first anker is lifted.[8] The *Depth* variable represents the well depth in meters measured from the sea bottom, while the *Density* variable represents the litostatic pressure measured by the maximum density of the drilling fluid. As illustrated in Figure 2 these two variables are highly correlated. While the variables are strongly correlated, they measure different aspects of a well, as the depth of the well also is a proxy for different physical elements that positively and negatively affect m/d. Density is expected to slow down m/d. Without including the *density* variable in the model, the *depth* would reflect the negative effect from higher density as drilling gets deeper. By including as many relevant variables as possible we try to separate each single effect to see how it affect m/d. I.e., with the parameters for density and temperature capturing the negative effect, the parameter for drilling depth now captures the effect of depth for a given temperature and density.

estimate an econometric model of exploration and appraisal drilling for the Norwegian continental shelf. 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 dataset to study reserve additions from Norwegian continental shelf oil and gas exploration. Osmundsen, Roll and Tveteras (2010), used the data to investigate the relationship between m/d and physical characteristics for the well and well site.

7 For details on resources and participants, see Facts (2012).

[8] The time span in the Norwegian Petroleum Directorate data corresponds with the time scope in drilling contracts. The meter per day compensation starts from the first spudding. Before the point of spudding the rig is compensated for mobilisation time, but this is paid by lump sum; see Osmundsen et al. (2008).

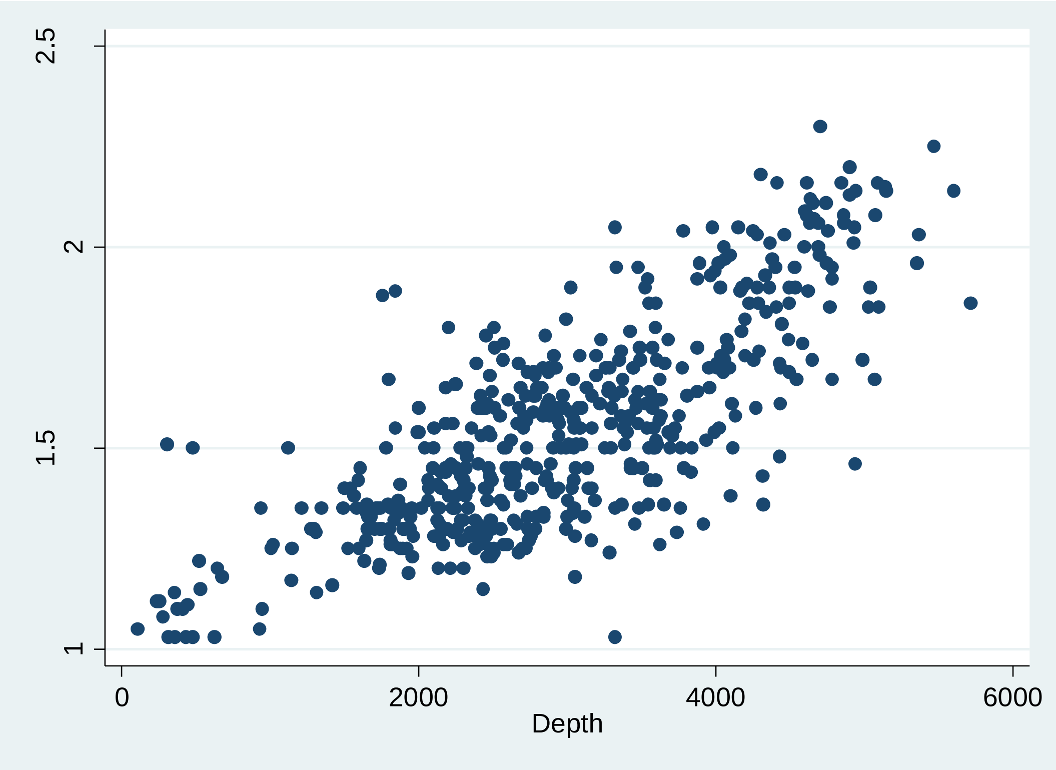

Figure 2: Density (litostatic pressure) plotted against drilling depth, for exploration wells on the Norwegian continental shelf, in the period 1965-2008. Data source: Norwegian Petroleum Directory.

Collected data indicates that m/d decreases rapidly above 120 degrees. From conversations with industry experts we learn that this corresponds with harder formations and higher failure rates of equipment.[9] Thus, the operators normally implement HPHT procedures with reduced m/d at these temperatures and corresponding depths, before entering the reservoir, e.g., the companies apply HPHT procedures from the bottom of the 12 ¼" hole section to ensure not to enter the HPHT reservoir unintentionally.

To control for this we have included a dummy variable that is one if the bottom hole temperature exceeds 120 degree Celsius (*Hightemp*). Differences in drilling technology are accounted of by including dummy variables (*Tech*) that separate between the following technologies: semi-submersible, jackup and vessel; where the subscript *f* reflects the different technologies. Semi-submersible is used as reference category, since this is the technology that is mostly used. Since there may be structural differences in m/d between wildcat and appraisal wells, mainly due to more testing time in appraisal wells, we control for the purpose of drilling by including a dummy variable that is one if the well is a wildcat and zero if the well is an appraisal well (*Purpose*). Finally, a time-trend

[9] Note that the 120 degrees generally apply to the time span of our analysis; 1965-2008. In recent wells drilling challenges start at higher temperatures - 150 and even 200 degrees are mentioned by our industry reference group.

variable *Trend* 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.

Summary statistics of the sample variables are provided in Table 1. The sample average m/d is 54.3 meters per day, ranging from a minimum of 3.7 to a maximum of 186.6 meters. Sample well depth is on average almost 3000 meters, ranging from a minimum of 109 to a maximum of 5717 metres.

Originally the dataset consisted of 924 observations, but we had to exclude some of the observations due to missing observations of key variables in our econometric model, for example density variables. Furthermore, we exclude some of the wells that are sidestep 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 utilizing the original exploration well. Exclusion due to missing variable observations and sidestep wells leads to a reduction in the number of observed wells from 924 to 524.

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
m/d	524	54.30	27.99	3.71	186.60
Depth	524	2958.09	1090.70	109	5717
Density	524	1.55	0.26	1.03	2.30
Hightemp	524	0.29	0.46	0	1
Semi-submersible	524	0.93	0.26	0	1
Jack-up	524	0.05	0.23	0	1
Vessel	524	0.02	0.13	0	1
Purpose	524	0.70	0.46	0	1
Time trend	524	27.04	6.87	10	42

Table 1: Summary statistics for exploration wells on the Norwegian continental shelf, in the period 1965-2008. Data source: Norwegian Petroleum Directory.

Empirical results

The production function is estimated using statistical regression analysis; ordinary least squares (OLS).[10] Before estimation, a classical additive disturbance term is appended to the model. Estimated

[10] Stata (11) software was used for estimation.

coefficients and associated *t*- and *p*-values are presented in Table 2. Since the model is specified as a log-log model the coefficients can be regarded as elasticities.

	Coef.	**Std. Err.**	**t**	**P>t**	**[95% Conf. Interval]**
Jack-up	-0.17	0.09	-1.81	0.07	-0.35 0.01
Vessel	-0.10	0.16	-0.64	0.52	-0.41 0.21
Purpose	0.10	0.05	2.31	0.02	0.06 0.19
Time-trend	0.02	0.00	5.05	0.00	0.01 0.02
High temp	-0.23	0.05	-4.35	0.00	-0.33 -0.13
Depth	0.38	0.06	6.72	0.00	0.27 0.50
Density	-1.08	0.16	-6.05	0.00	-1.43 -0.73
Const	3.48	0.09	38.50	0.00	3.30 3.65

Table 2: Empirical results: estimated coefficients and associated *t*- and *p*-values, standard error and confidence interval.

Except for the variables that control for different drilling technologies, all parameters are significant at 5% level, indicating that they are important in explaining m/d. Although not significant at 5% level, we find that at 10% level the jack-up technology is slower on average than both the semi-submersible and vessel technology. On the other hand we cannot find any significant difference in m/d between semi-submersible and vessel. This result, however, is uncertain, since almost all of the wells were drilled by a semi-submersible technology. The dummy variable that specifies whether the well is a wildcat or an appraisal well (*Purpose*) shows that wildcats are more productive than appraisal wells. This is as expected since appraisal wells are slower to drill due to time spent on testing. The trend variable that is a measure of technological change is significant and shows a yearly increase of 1.6%. 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. As expected both density and temperature are found to have a negative effect on m/d. Increasing the density by one per cent will on average reduce the m/d by 1.1 per cent and as temperature exceeds 120 degree Celsius the m/d will decrease an additional 0.23 per cent. This indicates that wells with bottom hole temperature above 120 degree Celsius are on average slower to drill than wells that have temperatures less than this. The effect depth has on m/d is one of the main findings in this paper. Since the estimated coefficient is positive and significant we find that an increase in depth will increase m/d, keeping other explanatory factors like density and temperature constant. A 1% increase in well depth leads to a 0.38% increase in m/d, everything else kept equal. This accounts, e.g., for the fact that high weighting agents and optimal torque increases m/d as drilling gets deeper.

How does this correspond with Figure 1, showing concave m/d with respect to depth? Whereas the regression estimators show average effects for the sample, the plot shows the variation in the sample data. Remember also the arguments for slower m/d in Section 3. Most of them were related to higher pressure and higher temperature. As illustrated in Figure 2, depth is strongly correlated to density (this is also true for temperature), were density (and temperature) gets higher as the well gets deeper. Since we do not have the opportunity to separate out the effect of density in a plot, a lot of the deceasing part of Figure 1 is a consequence of higher density. In other words, since we do not control for other variables, all the different factors that simultaneously affect m/d are displayed. In the regression model, on the other hand, we manage to separate the effects. The elasticity in our model with relation to depth is calculated in a multi variate model where we already have accounted for the negative effect of depth and temperature. Thus, in our model the estimated coefficient for drilling depth accounts for the arguments that are not controlled for explicitly. Together this complied effect has a positive effect. Our results hence demonstrate why it was important to specify a multi variant regression model when investigating this problem. Only focusing on the plot might give the impression that depth has a more negative effect on m/d than what is actually true.

5. Conclusion

We analyse average meter per day (m/d) for exploration wells on the Norwegian Continental Shelf, in the period 1965-2008. A plot of m/d (average meter drilled per day) against drilling depth, for exploration wells on the Norwegian continental shelf, in the period 1965-2008, shows a concave relation between m/d and depth. Through conversations with drilling experts we form a priori hypothesis as to factors affecting m/d. Factors like high temperature and density are likely to slow down drilling, whereas other factors like reduced dimension of the drill bit are likely to increase m/d at higher well depth. By applying a multi factor regression model we are able to isolate the main factors that affect m/d. The findings confirm the hypotheses. By increasing density by one per cent, m/d is on average reduced by 1.08 per cent, and as temperature exceeds 120 degree Celsius the m/d decrease an additional 0.23 per cent. This is partially offset by an increase of 0.38 per cent due to positive effects associated with an increase of the drilling depth by 1 per cent. We find a positive average time trend of 1.6 per cent per year that accounts for technological development. Appraisal wells have lower m/d than wildcats due to more time spent on testing. We also account for differences in m/d due to different categories of facilities.

As there is an inverse relation between drilling cost and m/d, the concave drilling curve of Figure 1 would correspond to a convex drilling cost function. This would be an interesting topic for future research.

While *meters drilled per day* is the industry standard for measuring drilling productivity, other measures than m/d are necessary to identify value creation in drilling. In addition to m/d, 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. M/d in exploration can to some extent come at the expense of the primary objective of gathering well information. According to industry sources, however, the pure transport phase in exploration wells comprises more than ninety per cent of the drilling time. Moreover, when rigs are scarce and rates are high, efficient utilization of rig time becomes particularly important. Another trade-off is between m/d and matters of health, environment and safety (HES). Whereas in some cases such a trade-off certainly exists, it is also the case that some of the success criteria for high m/d – like good planning and a tidy working environment – are also crucial to an improvement in the HES-performance. Moreover, long duration of open well exposure can lead to various well problems, thus calling for a high m/d.

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