

## A statistical solution for cost estimation in oil well drilling

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### Abstract

Drilling operations must be preceded by adequate planning, fulfilling the path to produce hydrocarbons at low and competitive costs. Conventional well planning is based on the personal experience of project engineers, which use information from offset wells to estimate the performances in future wells. This article reviews and discusses a published statistical methodology for planning upcoming oil wells. The statistical approach incorporates uncertainties of the process, reducing the relevance of personal decisions and supporting the staff with more realistic cost estimations. A reliable project can reduce unexpected expenditures in a long-term campaign and shorten the learning time, resulting in improved cost prediction and a better-fitted calendar. An expressive database, containing information from an onshore field in Brazil, yields a case study to demonstrate the benefits of this approach for the development of new drilling projects. The solution presented supports a more precise planning of costs, the improvement of technical limits and the development of different technologies in drilling operations in future wells.

**Keywords:** geosciences; cost per meter; least squares; Amorim curve.

### 1. Introduction: Drilling a well

Drilling bits are used until the moment they wear out and become ineffective, being pulled out of the well and replaced by a new one. At the end of a section, the bit connected to the bottom end of the drill string is pulled out from the hole, being a casing string run and cemented. Drilling will continue until the production zones are reached, when they are abandoned or completed to start producing. Some wells are drilled with the casing itself replacing the conventional

drill string, disclosed as economic by saving time circulating, running casing and reducing non-productive time (Patel, D. *et al.*, 2018).

The operational information of the wells is registered in a Bit Record. Its heading includes name of field and well, spud-in date, operator and relevant rig information. Each line contains the unique information that specifies each bit: serial number, running sequence, pullout date and depth, bit type and diameter, length

drilled, rig hours and rate of penetration. Additional space is included for the eight *IADC codes* to report the bit wear and remarks (McGehee, D.Y. *et al.*, 1992), inclination of the well, size of jet nozzles, drilling parameters and some mud properties. Unfortunately, a most desirable *Increase in Cost per Meter* IADC code was not included in the IADC 1992 reviews to report that a bit had become economically inefficient (Brandon, B.D. *et al.*, 1992), needing to be replaced.

#### 1.1 Planning a drilling campaign

The preparation of a drilling program is performed by experienced people, being desirable knowledge about the area of the upcoming wells. A project engineer analyzes geological information (Bera, 2010) and operational data from offset wells (Simmons, 1986), estimating future performances of the drilling operations based on existing

information and personal knowledge.

Traditionally, the poor bit performances are discharged, understood as being the result of bad practices that shall not be repeated. A handful of good runs are elected as results to be repeated or improved. As the dataset used in a conventional analysis (Devore, 2010) is different from a statistical set, since

only some good drilling performances are considered in the former approach, uncertainty is brought to the costs of the future wells.

Intervals of the planned well are divided by the expected rate of penetration (ROP) by depth, generating the Drilling Hours seen in a Bit Program (Table 1).

Bit	Section	Bit	Bit	Depth	Length	Drilling	ROP	Acc.	WOB	RPM	Mud	Remarks
nº	nº	size	type	Out	Drilled	Hours	-	Hours	-	-	Weight	-
-	-	(in)	-	(m)	(m)	(h)	(m/h)	(h)	(ton)	-	(sg)	-
1	1	26	115	1000	950	60	15.8	60	6-15	80-140	1.2	IADC 115
1	2	17.½	115	2100	1100	110.0	10.0	110	10-18	120-160	1.4	IADC 115
2	2	17.½	115	3300	1200	120.0	10.0	230	10-15	80-160	1.5	IADC 115
3	3	14.¾	PDC	4150	850	100.0	8.5	330	2-3	120-130	2.0	Bicenter Bit
4	3	14.¾	PDC	4500	350	33.0	10.6	363	2-3	120-130	2.0	Pilot bit 8.5
5	4	12.¾	PDC	5260	760	95.0	8.0	458	2-4	80-120	1.9	Pilot bit 8.5
6	4	12.¾	PDC	5370	110	30.0	3.7	488	3-5	70-100	1.9	Pilot bit 8.5
7	4	12.¾	PDC	5500	130	35.1	3.7	523	3-5	70-100	1.9	Pilot bit 8.5
8	5	8.½	537	5610	110	70.0	1.6	593	8-10	80-100	1.0	Metal seals
9	5	8.½	537	5720	110	70.0	1.6	663	8-10	80-100	1.0	Metal seals
10	5	8.½	517	5830	110	70.0	1.6	733	6-8	80-100	1.0	Metal seals
11	5	8.½	517	5940	110	70.0	1.6	803	6-8	80-100	1.02	Metal seals
12	6	6	517	6090	150	90.0	1.7	893	4-6	80-100	0.67	Metal seals
13	6	6	517	6237	147	90.0	1.6	983	4-6	80-100	0.67	Metal seals
14	6	6	517	6384	147	90.0	1.6	1073	2-5	80-100	0.67	Metal seals
15	6	6	517	6531	147	90.0	1.6	1163	2-5	80-100	0.67	Metal seals

Table 1  
Example of a proposed Bit  
Program for an onshore well in Mexico.

Fixed costs: expenditure with inventory of replacement parts, wellhead elements etc. are predictable and have negotiable prices. Some costs are related to the measured depth, such as the cost of casing string, volumes of cement slurries, mud additives, time to log, run casing and wait for cement hardening. Most of the variable costs that compose CAPEX (capital expenditure) are predictable within good precision by using statistical models developed for the petroleum industry (Samuel, 2010).

Variable costs: can be significantly affected by variations in the drilling

speed, non-productive (NPT) and lost time (York, *et al.*, 2009). Since time estimations for the OPEX (operational expenditure) are mostly based on personal experience, different results can be expected from different project engineers. In a conventional planning, where only good results of the offset wells are selected and the poor runs rejected, costs might end up higher than planned. Imprecision can significantly influence the variable costs of a well, especially considering that rig costs can escalate to US\$1,000,000/day.

Drilling bit manufacturers and

tool rental companies, willing to sell or rent their products and beat competitors, will propose the least expensive solutions that match the estimations made in the proposed well program. Marketing and the desire to improve performances influence the process, sometimes generating objectives of low probability to happen or even to be repeated in a same field. Imprecise projections will also affect the logistics of subsequent wells in a drilling campaign, resulting in additional standby fees of tools and equipment, anticipation of purchases and potential hurried orders.

## 1.2 Pros and cons of each method

A great advantage of the conventional planning process is that the experience of the project engineer can overcome poor data or lack of information. However, all useful information should be included in a larger database so that the proper statistical analysis is made. *“Being able to effectively organize and categorize information will ultimately deliver more intelligence into the business by enabling better and faster decision-making”* (Stevens, 2016).

In the authors' view, some weaknesses of the conventional process are:

- The performances of the best bits are analyzed, instead of their costs per meter;
- Marketing might affect the selection of more conservative and adequate options;
- Development of technology is affected by enthusiasm and prices, not costs;
- Restrictions from management might result in purchasing of bits of low price;

• Neglected poor performances represent an obstacle to knowing which needed bit protection has failed, or was insufficient, to face the challenges;

• Projections vary significantly, depending on the experience and optimism of the project engineer;

• Risk analysis normally is not shared, being delegated to an independent process;

• More backup bits are needed to comply with uncertainties.

## 2. Materials and methods: a statistical approach for well planning

This article discusses a solution published in a thesis in 2008 (Amorim Jr., D. 2008), developed to mathematically estimate the cost of any interval drilled in an oil well, and updates the Case Study of the thesis. The research started in 1985, plotting operational results in paper, being later improved with Lotus 1-2-3 and Excel.

Conceived to be a statistical approach to increase the reliability of drilling operations, it has demonstrated to be

a valuable tool to determine the OPEX of drilling a well with greater precision. *“Common sense well construction evaluation processes used in conjunction with validated conventional and new technologies have proven their worth by reducing expenditures and risks”* (York, *et al.*, 2009).

Pilar is an onshore field in the northeast of Brazil, selected due to a difficult environment, where regionally fractured abrasive sandstones, interbed-

ded by hard shale and limestone layers, seen in Figure 1, demand special features and protections to be used at the drilling bits. In a challenging environment, where wells can surpass 5,000 m of measured depth, the quest for long bit runs is mostly desired to reduce drilling costs. An extensive database of 1164 bit runs from 138 wells, drilled from 1981 to 2010, was used to produce the *Amorim Curve* (Amorim Jr., D., 2008) shown in Figure 5.

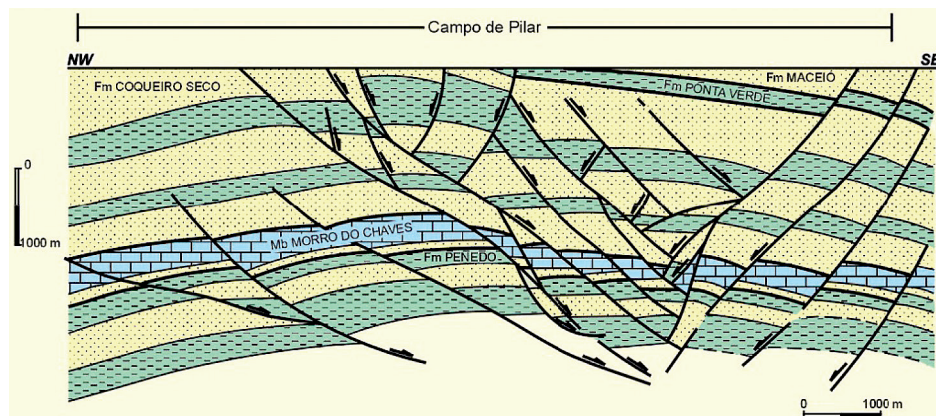


Figure 1  
Geological profile  
of Pilar field, 2003. Source: ANP.

## 2.1 Collecting and organizing data

The first step of the well planning discussed is to survey *all* existing information related to the drilling operations in that field. Data is organized in a spreadsheet and duplicate entries

are disregarded. The key indicators of the process, tied to a date, are the **bit serial number** and **bit running order** in that well. The cost per meter (**CM**) is the variable modeled in the optimiza-

tion process, intending to predict and to minimize drilling costs of any upcoming well. The traditional formula for cost per length for any bit run is used to calculate the **CM** (Eq. 1):

$$CM = \frac{CB + CH \times (TT + HR)}{MD} \quad (1)$$

where: **CM** is the cost per meter at the depth that the bit was pulled; (US\$/m), **CB** is cost of the bit; (US\$)<sup>1</sup>, **CH** is cost of the drilling operation per hour; (US\$/h)<sup>2</sup>, **TT** is the time spent in a round trip to replace the bit; (h)<sup>3</sup>, **HR** represents time spent in the drilling operation; (h)<sup>4</sup>, **MD** is the length drilled by the bit; (m).

<sup>1</sup>Bits using additional protection or better technology are more expensive and might be used multiple times. **MD** is adjusted after new runs are made; the bit cost is shared with the total length drilled, modifying the *Amorim curve* in the optimization process. The conventional calculation of **CM** using 100% of **CB** in first run does not reflect the true costs of developing new technologies.

<sup>2</sup>**CH** must include cost of rig, tools, logistics, diesel, standby of equipment, office support and any cost that would not exist if the drilling process was not taking place. Conventional calculations underestimate **CM** by using only rig rental

and diesel costs.

<sup>3</sup>**TT**: the trip time has been traditionally estimated as a linear function of **DO** (Depth Out): **TT** = 0.003 × **DO** + 1 (Amorim Jr., D. & Iramina, W., 2008). **TT** can be adjusted by linear regression using actual rig data (Lee, S.S. *et al.*, 2018).

<sup>4</sup>**HR** registered in Bit Records has embedded time spent in drilling, connections and quick repairs. The usage of the true drilling time in the process introduces a difficulty of surveying data, but it is a most valuable refinement to the optimization process.

The cost per meter achieved at the end of each bit run is a non-linear and non-stochastic event (Van Kampen, 1992), affected by the well depth and complex aspects:

In deeper wells, the trips to replace bits are longer, more complex and should be minimized by longer bit runs (Kaiser, 2009);

A progressive and variable increase in non-linear rock strength, that

reduces the rate of penetration and demands increasing drilling energy levels (Barton, 1976);

Underbalanced and overbalanced mud weights affect the rate of penetration (Bjelm, 2006);

Abrasiveness is a non-linear factor that accelerates dulling of cutters, increasing the number of trips and trip length per run (Grimes *et al.*, 2007);

Pipe addition increases the elasticity of the drill string, slowly changing its resonance modes and modifying the drilling efficiency (Christian, 2017). A negative scenario of drilling vibrations will affect the number of trips, increase the drilling hours, accelerate bit wear and reduce the length drilled per run (Amorim, *et al.*, 2012);

Certain well trajectories increase the total area of the elements of drill string contacting the walls, with significant increment in friction, reduction in drilling efficiency and rates of penetration (Ghasemloonia, A., 2012).

## 2.2 Preparing the database

As the drilling operations go on, it is ideal that the **CM** be calculated and the chart updated, shown in Figure 2. It

initially presents a quick decay - as the cost of the bit is still being shared by a shorter extension drilled, slowly stabiliz-

ing. The objective of this procedure is to minimize the **CM**, pulling the bit at its minimum drilling cost:

$$\frac{dCM}{dCD} = 0 \quad \text{or} \quad CM = CM_{min}, \text{ which occurs when } CM < CM_{n+1}$$

Such an economical flag cannot be strictly taken into consideration to pull a bit as **CM<sub>n+1</sub>** is calculated only if an additional length is drilled. If **CM<sub>min</sub>** has

been achieved but drilling continues, the overall cost of the section (Eq. 2) will gradually increase. As the **CM** is increasing, improvements in ROP are needed to

justify maintaining the present bit at the bottom. Other actions are then taken: check the drilling parameters, lithology changes and mud conditions; and

perform an evaluation of the total cost of drilling over the remaining length by running a new bit.

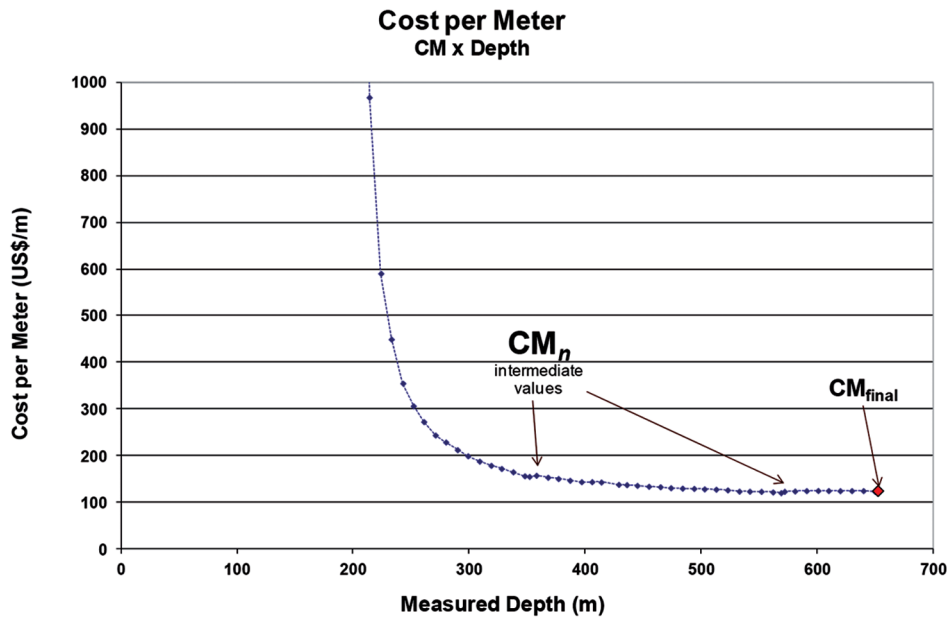


Figure 2  
Cost per meter calculations performed until the bit was pulled.

In Figure 2 a small increase in the **CM** is seen at 350 m, but drilling continued; **CM<sub>min</sub>** was achieved at 570 m, but the bit was replaced only at 650 m. The well continued after the replacement of the first bit, such that two more bits were needed to reach the total depth of the section. The cost of

the section is the sum of the *n* operational costs, expressed by Formula 2 and represented in Figure 3 by the sum of the shaded areas:

$$CostSection = CM_1 \times MD_1 + CM_2 \times MD_2 + \dots + CM_n \times MD_n \quad (2)$$

$$CostSection = \int_{DepthIn}^{DepthOut} CM_i \times MD_i = \sum CM_i \times MD_i \quad (3)$$

### 3. Results: estimating operational results

When planning a new well, predicting the value of **CM** versus depth is almost a guess exercise. In the chart of the **CM** for the Pilar field, shown

in Figure 4, it is noticeable that for depths less than 2000 m, the dots are concentrated under the value of US\$200/m. In the conventional plan-

ning process, the project engineer will pick an average of a couple of good runs, hoping they are repeated during the drilling operations.

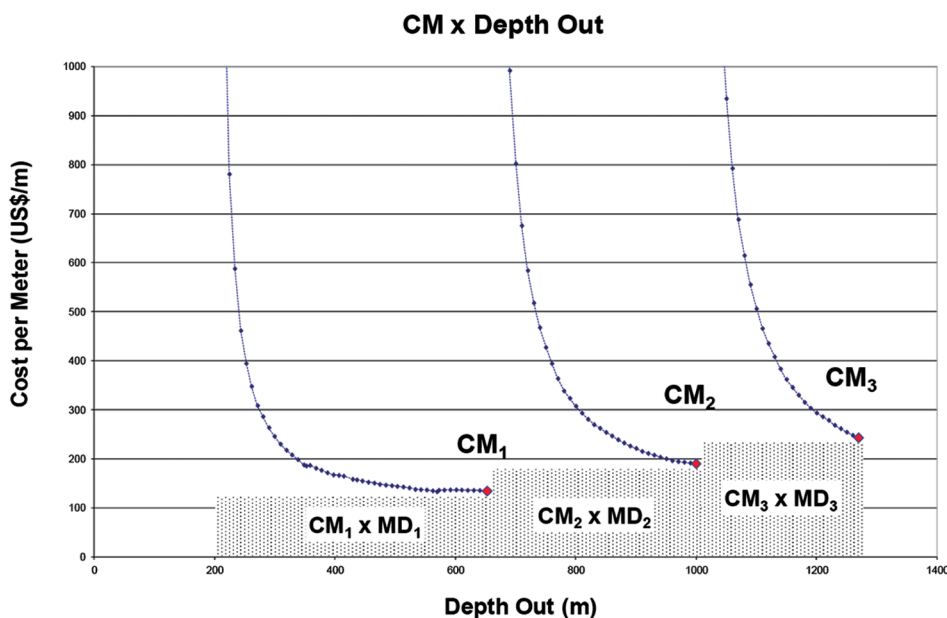


Figure 3  
Total cost of the section for the three bits used in a section.

It is noticeable that the vertical spreading of **CM** is different in function of the well depth. Drilling costs are the result of crossing different geological

formations, trouble zones and of overcoming operational hazards (York, *et al.*,



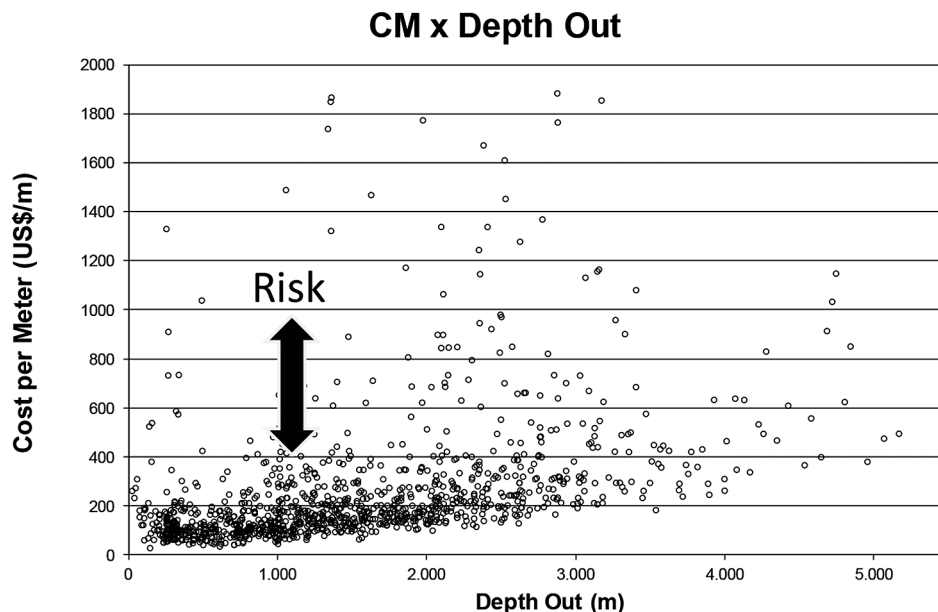
2009), unique in each field. This is a solid argument against the usage of averages to plan future performances.

Risk will be reduced in proportion to how close the points are about the

curve in a determined depth (Devore, 2010). The distribution in the y-axis, shown by the arrow in Figure 4 is a useful estimation of risk, illustrating the chances of *not repeating* planned per-

formances: around 4000 m the dots are less spread and more likely are the chances to achieve similar performances; the opposite is expected in the range of 2500 - 3000 m.

Figure 4  
Plotted CM values  
of all bit runs in Pilar field.



### 3.1 Cost of any section or interval

The principle of least squares, developed by the German mathematician Carl Friedrich Gauss (1777–1855), is used to treat the database, representing an evolution to the conventional planning procedure, which selects

the best performances of a handful of selected results.

The measure of the goodness of the fit is improved by minimizing the sum of the squares of the deviations from the *Amorim curve*. By applying

the principle of Least Squares to pairs of  $(X_i, Y_i)$ , where  $X_i$  is *Depth Out* of the bit and  $Y_i$  is *Cost per Meter* at the end of each run (Almeida, 2015).

The *Amorim Curve* is the exponential equation produced by the database:

$$CostSection = \int_{DepthIn}^{DepthOut} K_1 x e^{K_2 \times D} \quad (4)$$

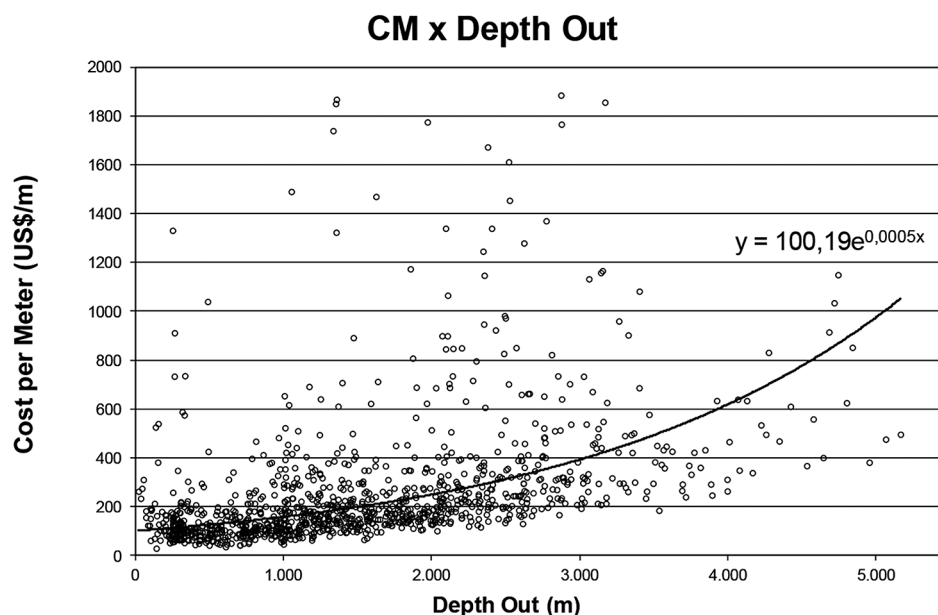
The regression that best fits the deterministic values (Freitas, 2003) will be

the solution to the formula for any given interval. This value will be used for the

CAPEX of each well section, achieved by filtering each bit diameter in the database.

$$CostSection = K_1 \times \{ (e^{K_2 \times D_2}) - (e^{K_2 \times D_1}) \} / K_2 \quad (5)$$

Figure 5  
Amorim curve and equation  
of CM versus MD for the Pilar field.



### 3.2 Cost per meter of any section or bit run

The cost per meter of any interval is determined by dividing the total cost of the

interval by the length of the section. This value is useful for planning the bit runs:

$$CM_{interval} = \left( \int_{DepthIn}^{DepthOut} K_1 \times e^{K_2 \times D} \right) / MD \quad (6)$$

### 3.3 Solution for the case study

The equation that expresses the

Amorim curve for the Pilar field, seen in

Figure 5, is:

$$CM = K_1 \times e^{K_2 \times D} = 100.19 \times e^{0.005 \times D}$$

The results can also be calculated and plotted in  $\ln(CM) \times \text{Depth Out}$  (Figure

6). Using Eq. 5 for a hypothetical interval of Depth in = 1000 m and Depth out =

2000 m, the cost of the planned section can be determined with accuracy:

$$CostSection = 100.19 \times \{ (e^{0.005 \times 2000}) - (e^{0.005 \times 1000}) \} / 0.005$$

$$CostSection = US\$214,318 \text{ or } CM_{1000,2000} = US\$214/m$$

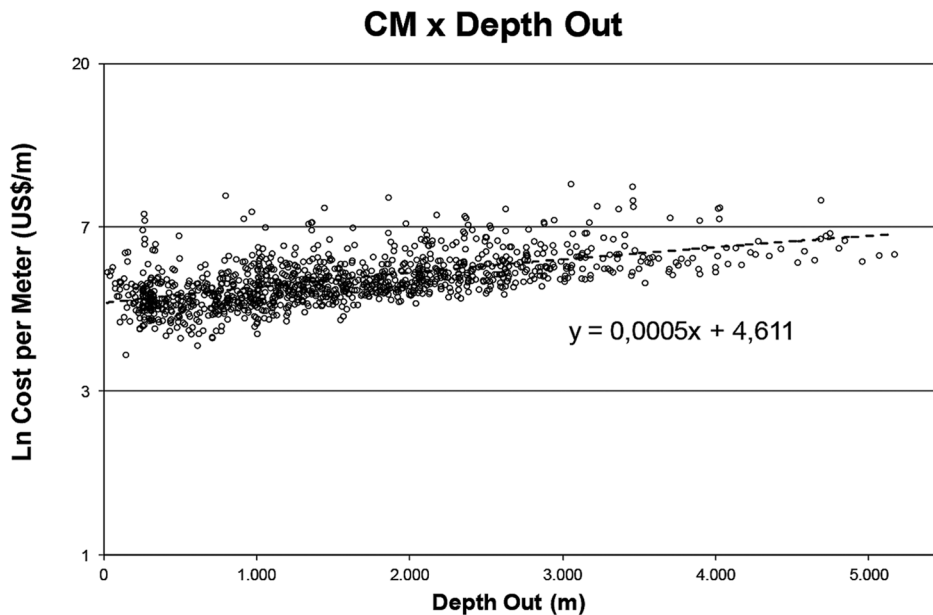


Figure 6  
Ln (CM) versus Measured  
Depth Out for the Pilar field.

## 4. Discussion: analysis of the results

### 4.1 Interpretation

• Dots sitting on the *Amorim Curve* are the most probable result to happen in a future well, representing the benchmark of the existing results in the database.

• Dots below the curve are the *best in class runs*, desirable to be repeated in similar depth out and geological formations in the area.

• The lowest values of **CM** represent the *Technical Limits* at a depth

range, within the resources used in the operation;

• Dots above the curve represent the *poor performances*, and the highest values of **CM** represent operations that demand investigations;

• Vertical distribution of **CM** is a graphical estimation of risk for any depth range;

• *Lessons Learned* for each depth

range, geological formation or bit diameter can be extracted and registered in the field documents. This action will support the new project engineers, reducing the dependence of more expensive specialists;

• Reverse engineering can be applied to any desired result by entering **CM** versus depth out in the database, spotting the bit type and the operational conditions that lead to such results.

### 4.2 Defining fair remuneration for the development of new technologies

A complex subject when performing technical tests is defining which values validate economically a test, as it remunerates fairly the parts involved in the research and development of long-

term solutions.

By using the methodology presented in this article, the partners, when joining a new project, will know the expected results versus depth in ad-

vance, being able to estimate risks and potential issues. The technical proposals can be based at predicted costs versus depth, being offered a fair bonus for a technical solution.

### 4.3 Reverse engineering for the development of solutions

Specific filters can be applied to different drilling conditions, generating the *Amorim curve* achieved by each specific technology. Figure 7 shows values of CM achieved using PDC and rollercone bits in

the Pilar field. Despite a small number of runs, PDC bits achieved two expressive results and the *Technical Limits* for less than 1000 meters.

Above 1000 m, the curves reverse

and PDC bits show to be uneconomical. In testing new technologies, the *Amorim curve* for rollercone bits for that bit diameter can be the basis of a proposal to pay a PDC bit supplier for drilling an interval.

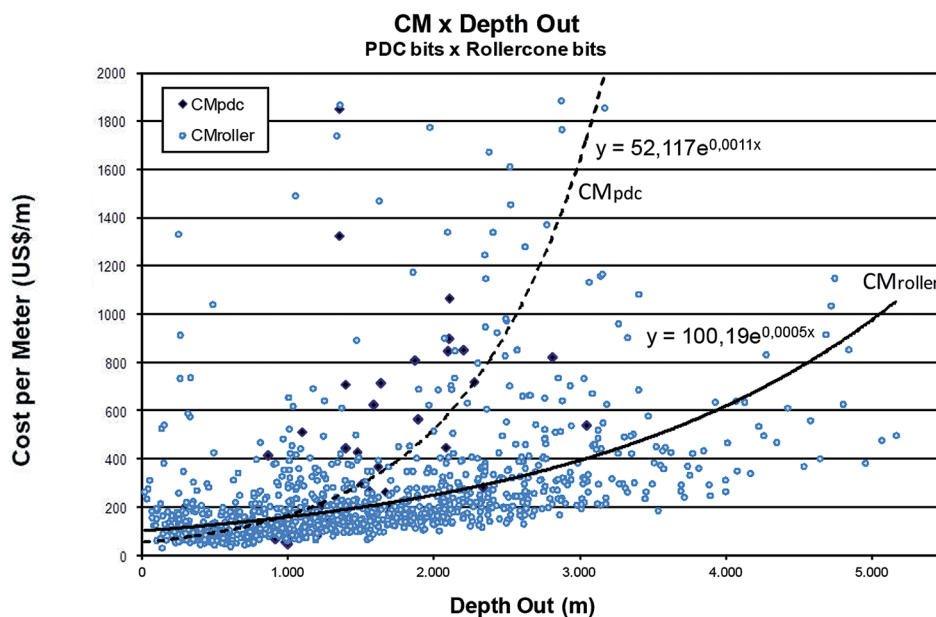


Figure 7  
Comparing performances of  
PDC and rollercone bits versus depth.

Examples of technical filters to work as lines of research: bit hydraulics (Ramsey, 2019); tools and procedures to

mitigate drilling vibrations (Bailey, J. *et al.*, 2013); types of directional drilling bits and tools (Barton, S. *et al.*, 2008); MSE (Berg

& Tveit, 2016); drill string with roller reamers replacing stabilizers (Sowers, F. *et al.*, 2009) etc.

## 5. Conclusion

In the conventional planning, the personal experience of project engineer is irreplaceable in exploratory wells or in areas with lack of operational information. The planning method discussed in this article is based on statistics, and gets more precise as information is gradually gathered and processed, bringing indisputable advantages:

- Projections of future performances come from mathematical calculations;
- The most probable results are expressed by formulas of simple solution;

- Poor performances, statistically detected to produce higher costs per meter, will support the determination of needed bit protections and operational changes;
- Manufacturers will work objectively on demands from project engineers;
- The experience of the project engineer will be useful in refining the selection of bit type and tools from the offers made by manufacturers and suppliers;
- The purchase of bits of lower prices is one of the outputs of the process.

The process discussed is a valu-

able tool to support the development of solutions and improve technical limits. By applying reverse engineering, the conditions that lead to specific excellent results can be traced, repeated or overcome.

Bit manufacturers and tool suppliers will be able to present proposals supported by trustable targets and traceable conditions, receiving fair payments to develop a win-win partner relationship based on a well-defined budget.

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