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MODELING OF OPERATIONAL PARAMETERS TO SUPPORT THE EVALUATION OF THE OFFSHORE DRILLING PROCESS

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ABSTRACT

Oil exploration is one of the main industrial activities in the country, due to the variety of by-products and companies involved in the sector. In order to be able to extract such a product from the sedimentary basins, it is necessary to invest in large and high technology. Drilling platforms and services are among the main activities that represent significant costs for the execution of the exploration service. In order to enable the investment and commercialization of the oil barrel, these activities must be improved in order to attract investors to explore oil fields in an increasingly efficient and productive way, thus contributing to the generation of wealth and development of society. Within this scenario, the objective of this article was the application of data modeling in a set of operational parameters to support the evaluation of the efficiency of the offshore drilling process. Because it is a process involving different input and output variables, it is pertinent to analyze wells in homogeneous areas and to identify the main parameters that allow contributing to the best performance in the rate gain in perforated meters. In this sense, in the aspect of the methodological approach, the efficiency calculation was evaluated, based on the parameters pre-established by the drilling engineering, adopting, for the modeling, the classic, output-oriented model, used by the data wrap analysis. The results obtained, from the variables and the applied model, allowed a preliminary perception of the efficiency of the drilling system.

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1. INTRODUCTION

The area called pre-salt has large light oil reservoirs, which extend for 800 km of the Brazilian coast (Jones et Chaves, 2015). It is estimated that this area may contain 176 billion barrels of oil, a volume significantly higher than the current national reserves, which in 2014 were 16.2 billion barrels. This perspective makes the competitiveness of pre-salt projects take another step, with a primary focus on reducing drilling time. According to Guedes (2016), there are already more than 170 wells drilled in 10 years.

In this regard, the largest Brazilian operator stated its intention to invest approximately 74 billion dollars during the five-year period 2017-2021, 82% of which are directed to the exploration and production area (Petrobras, 2017).

Divided into different blocks and exploration fields, the pre-salt became an important reserve of resources for the country, even considering some obstacles, such as the drop in the price of a barrel of oil and the political-economic issues that affected the extraction of hydrocarbon in recent years. One of the main considerations is that the breakeven of ultra-deepwater exploration projects in Brazil (pre-salt) is on average above US$ 60 per barrel (Wood Mackenzie, 2016). That is, there were some well development projects that were considered viable under current economic conditions in 2014 (average price per barrel of US$ 101) and were no longer in the new context of 2015 (average price per barrel of US$ 54).

In this context, it is sought to analyze the efficiency of the drilling stage. According to Amorim Junior (2008), the metric cost is composed, among other factors, of the hourly cost of probe, expressed in dollars per hour (US$/hour), maneuver time (h) and drill operating time (h).

The choice of the input parameters in the system causes different results when the drilling rate is taken into account as output. In this way, the research seeks to compare and analyze the efficiency of wells related to a specific drilling area, in order to show better operational performance.

The efficiency of the drilling process of the oil wells involved in this research was obtained through the data envelopment analysis (DEA) method, based on the classic DEA-BCC model. The DEA method was initially proposed by Charnes et al. (1978), considering constant returns of scale, and designating DEA-CCR. Subsequently, Banker et al. (1984) presented a model for variable returns of scale, being denominated DEA-BCC.

The results analyzed from the SIAD software allowed identifying the drilling units considered efficiency references (Meza et al., 2005) in the use of essential drilling parameters, such as the weight on the drill and the rotation of the string. The calculations were made with the objective of maximizing the penetration rate in a certain stretch and depth of the rock formation, which will be kept confidential to preserve the data of the exploring company of the region, as well as the knowledge retained by it.

2. THEORETICAL REFERENCE

The oil from the pre-salt has an added value higher than the oil present in other regions, due to the concentrations of light hydrocarbons, denominated API degree. For Caldas et Amaral. (2015), this characteristic comes from the depth of the rocks of the reservoir and the presence of the salt layer, which prevented the development of bacteria responsible for the degradation of volatile petroleum fractions.

It is believed that only a third of the hydrocarbons present in the pre-salt have been discovered, albeit after eight years of production of the first oil in the region. For this reason, Pita (2014) points out that this locality is sometimes called the “Blue Ocean”, in reference to the bestselling book “Strategy of the Blue Ocean”, which teaches how to invest in unexplored markets.

The pre-salt region represents a new exploratory frontier for Brazil. The challenge of producing oil and gas in ultra-deep waters, below the salt layer, with a thickness of over 2000 meters, made it necessary to develop basic research in partnership with universities, research institutes and technology-based companies (Carneiro, 2016). In December 2013, Petrobras had 954 terms of technological cooperation with 88 Brazilian science and technology institutions. Among the participants, the Galileo Network and the Regional Competence Centers stand out.

There are a number of scientific challenges regarding the understanding of well behavior, as well as rock heterogeneity and the best strategy for hydrocarbon exploration. In addition, there is also a need for the training of skilled labor in the development of new strategies and machinery in the exploration and development of wells (Porto et al., 2013).

Prior to drilling, specialists, with field experience in the area where the well will be developed, propose benchmarks from a drilling program. When drilling a well, the inputs of these values are controlled by the surface driller and are related to the weight applied on drill bit and the speed of the string rotation (Carpenter, 2016).

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According to Mitchell et Miska (2011), the main functions of the drill string are as follows: to transmit the rotation of the rotary table to the drill and produce weight on the drill, so that the drilling is effective and delivered at the highest drilling rate possible, provided that it is within the operational limits in force.

The drilling through the rotary method is by the transfer of rotation to the drill in conjunction with the application of weight on it. In this way, the drill can grind the rock and drill the well towards its geological goal. In this method, the drill-generated cuttings are removed from the well and charged to the surface by the drilling fluid. This fluid is pumped from inside the drill string, and returns through the space between the string and the well walls (Mello, 2014)

2.1 Drilling parameters

2.1.1 Weight on drill bit

The weight on drill bit applied in drilling comes from the drill string, which, in turn, is composed of different pipes which, when connected to soil reading and well-targeting tools, are designed to drill and direct the well to its geological goal (Anjos, 2013). All of this material, connected to a rotary drilling system, provides a load that is suspended by cables. This load is responsible for transferring weight to the drill bit. As the operator suspends the rotating system, the weight on the drill bit is relieved; in contrast, when it releases the string, the weight is transferred to the bottom of the well.

The weight transferred to the drill bit is determined by technical specifications of the equipment, which must respect its mechanical limits so as not to cause future drilling problems such as early drill wear or buckling of drill pipe (Chieza, 2011). The analyzes of mechanical stresses, such as flow limits, among others, are analyzed in advance by specific drilling software to generate a work recommendation from the stipulated limits and safety margins.

The weight on the drill must also be analyzed, taking into account the type of drill and the formation that will be drilled. The study presented here deals basically with salt drilling, in which the drill used is the Polycrystalline Diamond Compact (PDC), because it allows a superior performance to the others, as it provides a higher penetration rate.

The interaction between drilling parameters is very important to achieve the best rates. A common mistake of the operators is to trust that maximum parameters necessarily imply the best performance. Siqueira (2011) warns that there is interference from one variable to another, where the best value adjustment between them allows for superior performance over the overall performance. When the weight on the bit, for example, is applied beyond what is necessary, it will affect the rotation of the column, generating vibrations and damaging the final objective of higher penetration rate.

2.1.2 Spindle rotation

The importance of the string rotation speed is the spin transfer to the drill bit. Through its inserts, the drill cuts the formation and removes parts of the rocks that are transported to the surface through the fluid. According to Hess (2016), string rotation is a parameter that controls the contact frequency of the drill string with the well wall.

The determination of the rotational value, applied to the drill string, is previously analyzed from the operational limit of the probe equipment, responsible for the rotation of the string, and by the technical specifications of the drill (Monteiro, 2012). The greater the number of rotations performed by the drill, the greater its wear and the reduction of the cutting surface, leading to the reduction of drill diameter and the reduction in drilling rate.

Rotation is also responsible for generating vibrations of different types in the drill string, and these are responsible for damage to well bottom tools. When the range of predefined rotational values is worked in harmony with the column weight, it is possible to minimize such undesirable effects in the column (Mattos, 2015). When these variables are optimally established, vibration is mitigated and weight transfer is not influenced by vibration, thus allowing drilling with a higher rate and less problems of failure and early drill wear.

2.1.3 Drilling rate

The drilling rate, in meters per hour, is a widely used measure in the oil industry to monitor the rate of advancement at which the drill string moves toward the geological goal or reservoir to be exploited. The drilling rate should be maximized, since its reduction implies a higher cost for the operation (Mohammadsalehi, 2011).

This performance may vary depending on several factors, including the type of training and the parameters used in the operation. Each type of geology has specific lithologic characteristics, as for example, its hardness and porosity, which directly influence the speed of the drill. This article concentrates on salt-derived formations that, because they

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have certain properties, make it difficult to drill. The type of formation to be drilled is an inherent factor in human will; however, drilling parameters can be conducted by specialists in order to identify the best combination of weight and spring rotation that provide the best rate.

Figure 1 shows the variables of the drilling model of oil wells. From the weight applied on the bit and the rotation of the string, the penetration rate is obtained as a result of the system. According to the literature discussed in this study, it is possible to understand how these inputs provide the expected result.

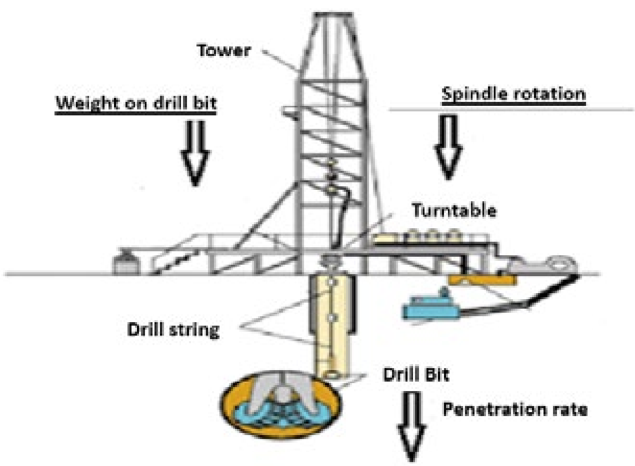

Figure 1. Drilling Variables
Source: Adapted from Freudenrich et Strickland (2001)

3. METHODOLOGY

3.1 Data envelopment analysis (DEA)

The DEA is a nonparametric method, based on linear programming, used for decision-making units (DMU) efficiency that converts multiple input variables into multiple output variables, (Cooper et al., 2011).

In the study that gave rise to the concept of DMU, Charnes et al. (1978) defined DEA as a model of mathematical programming, applied to the empirical estimation of relations that are pillars of the modern economy, such as the production functions.

The comparison between the different productivities makes reference to the concept of efficiency of the DMU, according to Figure 2. It is possible to verify that certain DMUs produce more, with less or equal amount of resources (Mello et al., 2005).

The objectives of the efficiency analysis performed with the DEA are summarized below: a) show the causes and the size of the relative inefficiency of each DMU compared; b) generate an efficiency indicator; c) determine new production targets that maximize the efficiency of DMUs (Jorge et al., 2010). There are two factors that significantly influence the results obtained when applying DEA: the model and orientation to inputs or outputs.

3.2 Classic models in DEA

As for the *models*, there are two that are most widely used: CCR and BCC. The first one has its acronym coming from the name of the authors who published the first article on the DEA (Charnes et al., 1978). The second is an extension of the first, as will be seen below and also has its acronym derived from the authors' names (Banker et al., 1984).

For Souza et al. (2016), the CCR model is used for Constant Returns to Scale (CRS), indicating the production relations of the DMU, taking into account the criterion of proportionality between inputs and outputs. However, there are contexts where there is no consistency of these returns to scale. Under these conditions, the CCR model can generate efficiency measures masked by the scale (La Forgia et Couttolenc, 2009). Due to this configuration of the CCR model, a later model, known as BCC, appeared. This model complements the CCR, allowing for variable returns to scale (VRS).

3.3 Output-oriented BCC model

The calculation of the efficiency was based on the parameters pre-established by the drilling engineering, in the well program delivered to the operators before each operation. From these values, we intend to find the most efficient combination between weight on drill, string rotation and drilling rate, in perforated meters. Considering that the DMU have different dimensions, represented by the scale of their variables, it was assumed that the appropriate model is the DEA-BCC, so that the input parameters in the system do not have a direct proportionality to the output values.

Associating the focus on the maximization of the outputs and the selected variables, it was verified the need to choose the output-oriented model. In this way, the output-oriented DEA-BCC meets the objective of evaluating drilling efficiency, with the best rates.

> The multiplier model assigns weights that are multiplied to the input and output parameters of the system so that the efficiency of a DMU is

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calculated by the ratio of the output of its outputs to their corresponding weights and the product of their inputs by their corresponding weights. This ratio expresses the efficiency of the analyzed DMU and the constraints of the problem work to ensure that there is no DMU with efficiency greater than 100%. The multiplier and envelope models make up a primal-dual pair (Calôba, 2003).

In order to be the best possible in relation to the others, each DMU chooses its weights to corroborate its efficiency; however, this can put other DMUs at the efficiency frontier, provoking a large number of units with 100%, thus reducing the discrimination between them, according to Equation 1, in the maximization of the outputs in the model BCC Primal (Envelope).

$$x_{i0} - \sum_{k=1}^{n} x_{ik}\lambda_k \geq 0, \forall_i$$

$$-\theta y_{j0} + \sum_{k=1}^{n} y_{jk}\lambda_k \geq 0, \forall_j \qquad (1)$$

$$\sum_k y_k = 1$$

$$\lambda_k \geq 0 \; \forall k$$

In which:

x_{ik}, y_{jk} – inputs i and outputs j of K;

x_{i0}, y_{j0} – inputs i and outputs j of the DMU 0;

λ_k – k-th coordinate of the DMU 0 on a base formed by the reference DMU.

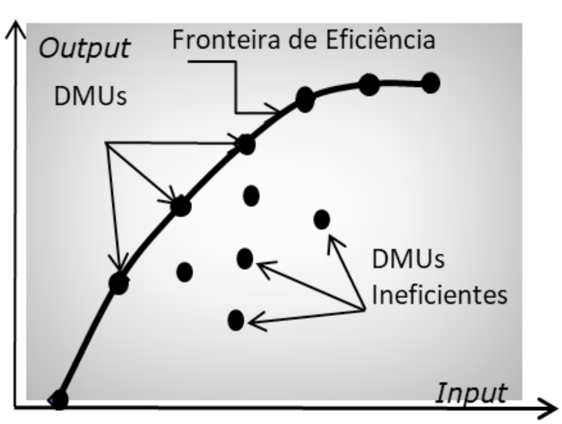

Figure 2. DEA basic chart diagram
Source: Author

3.4 inverted frontier

In order to improve the discriminating power of the model used, we can use the inverted frontier technique, which is based on considering what was input as output and vice versa. In this way an efficiency analysis is performed from the pessimistic point of view.

The inverse frontier calculations allow constructing a composite efficiency index (Effc), to simplify the analysis of the results (Pimenta et al., 2004; Meza et al., 2005; Mello et al., 2008). This index is equivalent to the arithmetic average between the efficiency in relation to the conventional DEA boundary and the complement of the efficiency in relation to the inverted boundary, as presented in Equation 2.

$$E_{ffc} = \frac{[E_{ffp} + (1 - E_{ffi})]}{2} \qquad (2)$$

In which:

E_{ffc} – Composite Efficiency

E_{ffp} – Standard Efficiency

E_{ffi} – Inverted efficiency

3.5 Critical factors in DEA modeling

In the use of DEA, Banker et al. (1984) indicate that the quantity of DMU must be at least equal to the product of the number of variables used in the input by the number of variables used in the output or, on the other hand, equal to three times the total of variables, using the result that provides the highest number of DMUs.

This proportion of DMU allows a greater discrimination of the results, avoiding that a significant amount of DMU is considered efficient.

4. COLLECTION AND TREATMENT OF DATA

The data were collected in daily drilling reports from each well, as shown in Table 1. The values of the drilling parameters and the penetration rate obtained are simultaneously sent to the client's office as drilling occurs. The reading of these values is done by means of sensors that report the results obtained to the monitoring software.

In order to maintain the integrity of the data and at the same time protect the confidentiality of the information, the identification of the drilled wells has been rena-

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med. In addition, the units of measure were also omitted, which does not detract from the calculations, since the DEA method is invariant to the scales of the variables (Barreto et Mello, 2012).

The input data for modeling the drilling process, as represented in Figure 3, correspond to the inputs, while the output data correspond to the outputs of the system.

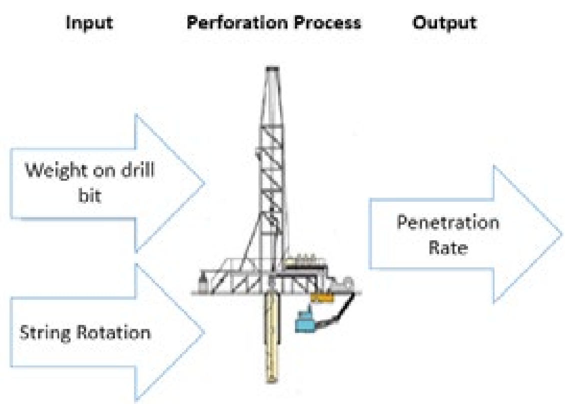

Figure 3. Drilling Modeling
Source: Adapted from Freudenrich et Strickland (2001)

Table 1. Modeling data for drilling

DMU	INPUT		OUTPUT
Wells	Weight	Rotation	Rate
pp1	51	99,3	5,2
pp2	56,1	166,8	5,4
pp3	41,5	195,9	26
pp4	36,8	195,6	26,4
pp5	34,5	180	40
pp6	29,9	158	2,1
pp7	61,8	97,8	1,1
pp8	19,6	82,1	29,5
pp9	64,6	199,8	35,4
pp10	30,3	33,6	1,4
pp11	19,4	60,6	33,5

4.1 Choose the DEA model

Based on the behavior of each variable and the analysis of the drilling process, the context points to the use of the output-oriented DEA-BCC model, considering the following characteristics:

- The obtained drilling rate does not keep proportionality with the input parameters in the system, reinforcing the concept of the BCC model (variable returns of scale).
- The inputs cannot be optimized in function of the drilling rate, since they are predetermined by the well engineering programs; this reinforces the output orientation, which should be maximized by reducing high operating costs, such as on-board platforms and equipment.

5. ANALYSIS OF RESULTS

The data collected from the input and output variables, inputs and outputs of the DMUs involved in the drilling process were applied to the output-oriented DEA-BCC model. To meet the objective function and considering the constraints of the linear programming problem, the SIAD software processed the information from the DMU, resulting in efficiency information that was the focus of analysis of this article.

6. BENCHMARK RESULTS

The results obtained by the mathematical model indicate which DMU were selected as references. The use of the inverted frontier allows identifying the least efficient DMUs and to calculate the composite efficiency, which will be the result of a tie between the standard efficiency and the inverted efficiency (Table 2).

Table 2. Efficiency results (SIAD)

	Efficiencies			
DMU	**Standard**	**Inverted**	**Composed**	**Composed***
DMU_1	0,15	0,22	0,46	0,47
DMU_2	0,14	1,00	0,07	0,07
DMU_3	0,65	1,00	0,33	0,33
DMU_4	0,66	0,98	0,34	0,35
DMU_5	1,00	0,37	0,82	0,83
DMU_6	0,06	1,00	0,03	0,03
DMU_7	0,03	1,00	0,02	0,02
DMU_8	0,88	0,04	0,92	0,94
DMU_9	0,89	1,00	0,44	0,45
DMU_10	1,00	0,79	0,61	0,62
DMU_11	1,00	0,03	0,98	1,00

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Then, the analyzed DMUs were sorted in order of efficiency. In Table 3, it is possible to visualize the wells that had better use of their available resources in the platform, such as the weight applied on the drill and the string rotation, to obtain a drilling rate as an output of the system.

Table 3. Composite Efficiency Rating (SIAD) in descending order

	Efficiencies			
DMU	**Standard**	**Inverted**	**Composed**	**Composed***
DMU_11	1,00	0,03	0,98	1,00
DMU_8	0,88	0,04	0,92	0,94
DMU_5	1,00	0,37	0,82	0,83
DMU_10	1,00	0,79	0,61	0,62
DMU_1	0,15	0,22	0,46	0,47
DMU_9	0,89	1,00	0,44	0,45
DMU_4	0,66	0,98	0,34	0,35
DMU_3	0,65	1,00	0,33	0,33
DMU_2	0,14	1,00	0,07	0,07
DMU_6	0,06	1,00	0,03	0,03
DMU_7	0,03	1,00	0,02	0,02

The study allowed identifying the DMU_11 as the most efficient in the gain of drilling rate, from the parameters analyzed. Although it does not have the highest drilling rate among the wells, its use of resources in a moderate way, associated to a satisfactory rate delivery, guaranteed the positioning of this DMU among the most efficient of the research.

The DMU_8, although not at the standard efficiency frontier, obtained the second place, favored by the low value calculated at the inverted efficiency frontier, since, using moderate drilling parameters, it has obtained an expressive rate as a result.

In the case of DMU_5, it is possible to notice that, although it was responsible for the higher rate of perforation obtained, it was ranked third, since the high consumption of spins in the string hampered its performance in the comparison between the analyzed DMUs.

The DMU_9 case is interesting because, even if it possesses one of the highest perforation rates (2nd position), it has one of the highest inefficiency rates calculated by the inverted boundary, due to its high consumption of the input parameters, which, in the end, was responsible for its downgrading in the overall efficiency ranking.

DMU_7 was considered to be less efficient among the analyzed ones. Its extremely low drilling rate has caused it to be lowered; although the input parameters used are not out of the standard, it is believed that the well must have presented some type of technical problem, thus damaging its final performance.

7. CONCLUSIONS

Given the performance of the perforations analyzed, it was pertinent to apply the DEA method to obtain the relative efficiency between the studied wells.

From the parameters and rates considered it is possible to have a new perspective of recommendations on parameters and drilling rates for future correlation wells, in order to motivate the best performance and lower operating cost.

It is important to note that, although the homogeneity of the DMU is justified by similar drilling resources and pre-salt sections, the intercalations of other types of formation were not taken into account, which may justify the lower efficiency of some DMUs.

As suggestions for unfolding the research, it could be pointed out the evaluation of other variables that could have been addressed to measure the efficiency of well drilling, such as time between phases, which would allow a more comprehensive view of drilling performance from the first to the last stage, when the well is delivered for production.

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