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Selections of oil-well configurations at design phase: proposal of integrity and production indicators.

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This article intends to approach a method of identifying and calculating indicators for evaluating configurations of oil wells in ultra-deep waters; during the design phase, when the decision will take place, the proposed indicators may contribute to managerial decision-making. After the introduction, the article briefly presents the adopted methodology, the results obtained in the literature review, the suggested indicators and their calculation methods. Suggested indicators are: unreliability and availability of barries elements, downtime due to repairs, repair costs, probability of ceasing production or injection, and expected reduction in nominal flow due to degradation of production components. The conclusions are: a) that a robust and well-established methodology was adopted for the bibliographic review, b) unexpectedly, the subject indicators for oil well evaluation are little explored in the literature, c) that the process using several sources of information allowed the research to reach an interesting set of indicators, and d) these indicators must now be validated and tested.

Keywords: Oil Well, Oil Well Indicators, Oil Well Design, Indicators Quantification.

1 Introduction

According to the Oil and Natural Gas Production Bulletin, published by the Brazilian Oil and Gas regulator (the National Agency of Petroleum, Natural Gas and Biofuels – ANP), in November 2022, Brazil produced 3,978 million barrels of oil equivalent. About 97% of this production comes from offshore operations. The pre-salt areas stand out among the offshore fields, with an oil flow of 2.964 million barrels of oil equivalent per day, which means about 74.5% of Brazil's total production. Given the importance of the pre-salt fields, an analysis of the offshore operations carried out in this location is in order. The pre-salt fields are located approximately 290 km from the coast, at a depth of over 2,000 m. The reservoirs in this field are located about 7,000 meters from the sea's surface. It is possible to understand the enormous risks of this operation. A blowout in a pre-salt well could leak an average of 20,000 barrels per day (62% of the average flow that occurred in the Macondo well in the accident that occurred in 2010). The technological and logistical challenges involved are also evident. In the first case, corrosion, pressure, and temperature, among others. In the logistical case, the distance from the coast makes any repair or replacement of equipment difficult and expensive. A vital element in these fields is the oil wells. The design of these wells represents an important phase of their life cycle since the project entails operating and maintenance conditions that cannot be easily changed later. Its operation must be safe and profitable to justify the costs incurred in its construction and operation. During the field development, various configurations are presented as alternatives in the design phase of the well. Such configurations are then compared to choose the one that is expected to have the best performance throughout the entire life cycle. However, in the absence of objective criteria, the decision-making process can be impaired and dominated by subjectivity. To avoid this problem when evaluating design proposals, an interesting approach relates to the development of quantitative indicators that portray the evaluators' expectations about the quality of the well concerning several aspects. Two relevant factors are related to production and the integrity of the proposed configuration. This article presents the results of a research of production and integrity indicators for offshore oil wells. Following this introduction, the second section will summarize the methodology adopted. The third section describes the insights obtained from the literature review. The fourth section will introduce a proposal of the indicators, showing their formulations. The last section of the paper will present its conclusions and recommendations for future works.

2 Methodology

Figure 1 shows an overview of the methodology adopted for identifying the indicators. This methodology aims at combining the knowledge of experts and best practices reported in scientific papers to derive quantitative indicators for oil well design, focusing on production reliability and integrity issues. The sources of information had four origins: bibliographic research, strategic objectives of the oil and gas operator, experience and knowledge of the oil and gas operator, and experience and knowledge of LabRisco team. By combining bibliographic research with the expertise of the team, we can reduce the impact of biases and subjectivity.

2.1 Bibliographic Research

The methodology used in the Bibliographic Review was proposed by Thome, Scavarda e Scavarda (2016). Briefly, the method adopted consists of seven steps: keyword identification; search in the databases using the chosen keywords; grouping of pre-selected articles in a single file, removing redundant articles; selection of articles for full reading; reading and evaluating complete articles; verification; and results.

The selection of articles for full reading has three phases for article exclusion: evaluation by the title of the article; assessment by reading the abstracts; and removal of unavailable articles.

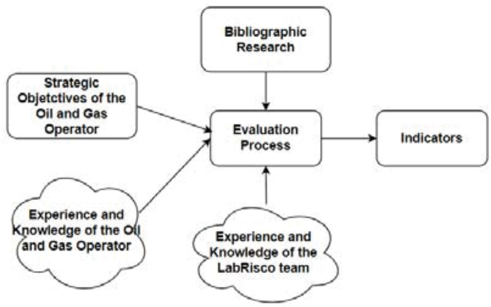

Figure 1. Methodology overview

2.2 Keywords Identification

The project team – consisting of one member from oil & gas industry with experience in well integrity management and seven LabRisco researchers with experience in risk analysis and reliability engineering – conducted brainstorming meetings to identify words that interest the project. With the identified words, the research team performed preliminary searches in the Scopus and Web of Science databases. After preliminary searches, keywords were identified using bibliometric methods, such as: keywords clusters, tree map of most common terms, and histogram of the frequency of the most common terms.

After identifying the keywords, it was decided to create two main branches of research, called Research Factors (RF), which constitute groups of references with common themes and help understand the topics most discussed in the bibliography of an area of knowledge (Patriarca, et al. 2020). One is related to production, and the other is to integrity. For each of them, a search pattern was defined in the Scopus and Web of Science databases.

2.3 Search in the databases using the chosen keywords.

Figure 3 (Section 2.4) presents the search for keywords and the results of searches in the two

2.4 Grouping of pre-selected articles in a single file, removing the redundant.

The third step of the bibliographic review process was grouping articles, joining the results of the two databases, and removing redundant

databases for RF Production and RF Integrity. Notably, the many references found, mainly in the Scopus database, indicate that the two surveys have a broad scope.

ones. This process was done using Mendeley software. Figure 3 (Section 2.4) shows the articles remaining at this step's end for each RF.

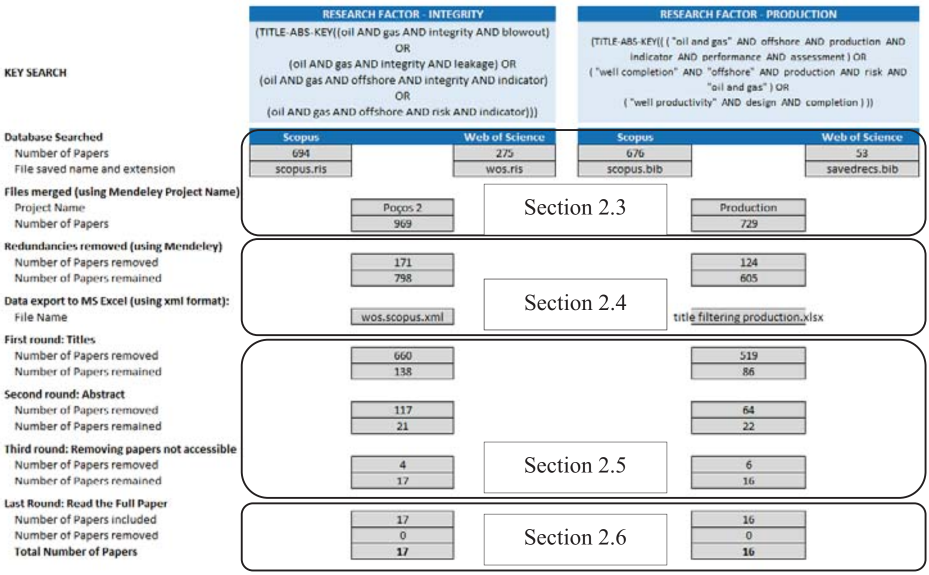

Figure 2. Evolution of the bibliographic research

2.5 Selection of articles for full reading

Figure 3 (Section 2.5) shows the result of the fourth step of the Literature Review.

The task of selecting articles for complete reading was carried out in three phases: evaluation of the article by reading the title, evaluation by reading the abstract, and removal of unavailable articles.

In order to avoid bias, the selection process for the three exclusion criteria was always based on reading by two team members. Each member individually assessed whether the article should remain in the research. After this initial analysis, there were meetings to compare the results.

In cases where the opinion of the team members coincided – "article should be included" or "article should not be included" – the decision was immediately implemented – article excluded or selected for the next evaluation phase. In cases of disagreement, the two members justified their position and discussed their opinions. In cases where opinions converged, the article was immediately excluded or included in the bibliographic review following the pair's decision. In the evaluator keep their opinion, the article would undergo a third evaluation, which a senior engineer would make. In the research for this project, there was no need for evaluation by a senior engineer.

2.6 Other phases of the bibliographic review.

All articles selected in the previous step were read for both RF. The results obtained for each RF were cataloged and are presented in Appendix A of this report. Before finishing the work of this stage of the project, a verification of the robustness of the results obtained using

Google Scholar was carried out, using the same method presented.
The Google Scholar search had two main objectives: to cover all possible information sources and run a robustness test on the previous process. As the databases chosen for research do not include theses and dissertations, it was decided to expand the research to this database. The result of this robustness check was positive since no new references were found.

3 Insights from the literature Review

The research group divided the literature review into two Research Factors: integrity, and reliability of production equipment. The following sections show the most relevant references and insights.

3.1 Insights for Integrity Indicators

The most relevant papers found by the research team related to the Integrity Indicators were:
Barriers Management:

- Mendes, Fonseca and Miura (2016)
- Hopkins (2011)
- Øien (2013)
- Zhen, et al. (2022)

Process Safety:

- Animah e Shafiee (2016)
- Gutierrez, et al. (2019)

Despite the importance of the theme, during the review process, the research team identified a need for more exploration of indicators related to the integrity of the elements of barriers to evaluating and comparing different configurations.

The fact that the indicators are appropriate in the production phase but not for the selection of configurations was frequently presented to the barrier management research factor. However, the work by Mendes, Fonseca e Miura (2016) is one of the articles that helped confirm the work being done previously and brings insights on how to continue the development complementing the indicators obtaining new insights on the configurations being evaluated. They are:

- The number of critical components for good integrity can be a suitable proposal for a new indicator. Taking the oil well configuration as input and calculating the configuration cut sets, it is possible to determine the system's critical components according to the number of components existing in the cut sets obtained. This information can be useful for comparing different configurations.
- The failure detection probability of the different methods is information that can be used as an indicator or to improve the well-life simulation. To obtain this information, it is necessary to associate the different failure detection methods with detection probabilities.

3.2 Insights for Production Equipment Reliability Indicators

The analysis from the perspective of the reliability of production equipment identified two topics most addressed by the literature: production costs, and reliability and availability of the production equipment.
The most relevant papers found by the research team related to the Production Equipment Reliability were:
Production Costs:

- Wetzel, et al. (1999)
- Kharghoria, et al. (2018)

Reliability and availability of the production equipment:

- Wetzel, et al. (1999)
- Chitale, Blosser e Arias (2010)

The research made it possible to understand and compare the different variables that the authors propose to quantitatively assess the question of production in the oil and gas industry. In this sense, this section presents insights obtained after evaluating the analyzed works. The different insights found are presented independently for each research factor.
The insights for the production cost indicators are as follows:

- Well productivity is an important factor and must be taken into consideration when selecting completion types and considering project costs.

- Costs are usually measured in terms of cost per volume produced (e.g., US$/bbl).
- Sand production is undesirable for a well and therefore measures to contain this production must be considered.

The insights found for the reliability and availability of the production equipment indicators are as follows:

- Hydrate formation inhibitors are important to ensure continued production from the well.
- Wells are subjected to sand production, which could be avoided by using sand containment screens. There are several types of screens. In one article, for example, a performance comparison is made between gravel pack (GP) and stand-alone screen (SAS).
- The reliability of production equipment can be used for benchmarking between different suppliers. Other parameters include risk and intervention costs for equipment replacement.
- Collapse of the production column is an essential factor to be evaluated, as it can stop production and affect oil well safety.

4 Proposal of Indicators

The research made it possible to understand and compare the different variables that the authors propose to quantitatively assess the question of production in the oil and gas industry. In this sense, this section presents insights obtained after evaluating the analyzed work.
In this section, we introduce the formulation for three sets of indicators: integrity, production (or injection), and indicators for both integrity and production.

4.1 Unreliability of barriers elements

The purpose of this indicator is to assess the probability of loss of oil well integrity during the first five years of operation. It considers only the events arising from the known failure modes of the barrier elements. Its importance stems from the fact that, typically, after five years, wells undergo repair interventions.
The calculation of unreliability is supported by a fault tree model, with loss of oil well integrity as the top event. The basic events of the tree are the failure modes of the barrier elements. The minimum cut sets are determined, and considering the failure probability distributions, the probability of each basic event of the tree can be calculated.
The expression in Eq. 1 calculates the probability of each minimum cut set.

$$\Pr(C_i) = \prod_{j=1}^{N_i} \Pr(B_j^i) \qquad (1)$$

Where:

- C_i is the i-th minimal cut set.
- N_i is the number of basic events that make up the o i-th minimal cut set.
- B_j^i is the j-th basic event that make up the i-th minimal cut set.
- $\Pr(B_j^i)$ is the probability of B_j^i calculated considering a mission time of five years.

Knowing the minimum cut set probabilities allows us to calculate the probability of the top event, as shown in Eq. 2.

$$\Pr(T) = \Pr(C_1 \cup C_2 \cup \ldots \cup C_M) \qquad (2)$$

Where:

- T is the top event.
- M is the number of minimal cut sets for the fault tree.

4.2 Availability of Barriers Elements

This indicator aims to assess the expected availability of the physical elements that make up the barrier elements. In addition to the previous indicator, it considers the characteristics of the oil well configuration and how it fits into the repair and maintenance system.
Availability calculation is also supported by fault tree modeling of the oil well barrier element system. For each failure mode, a multiphase Markovian model is developed, which allows for estimating the unavailability of each component over time, based on their individual failure rates, repair rate, and intervals between tests (Colombo, Abreu e Martins 2021). Then, the calculated values are combined using fault tree model logic to estimate the expected unavailability of the barrier system. At each minimum cut set, the expression given by Eq. 3.

$$\mathrm{U}(C_i) = \prod_{j=1}^{N_i} \mathrm{U}(B_j^i) \quad (3)$$

Where:

- C_i is the i-th minimal cut set.
- $\mathrm{U}(C_i)$ is the expected unavailability for the system considering only the i-th minimal cut set..
- N_i é o número de basic events that make up the i-th minimal cut set.
- B_j^i is the j-th basic event that is part of the i-th minimal cut set.
- $\mathrm{U}(B_j^i)$ is the unavailability associated with the failure mode handled by the basic event B_j^i, calculated from the multiphase Makovian model.

The knowledge of the unavailability associated with each of the minimum cut sets allows us to compute the expected availability for the system by Eq. 4.

$$\mathrm{A} = 1 - \mathrm{U}(C_1 \cup C_2 \cup \ldots \cup C_M) \quad (4)$$

Where:

- A is the calculated availability for the well barrier system.
- M *is the number* of minimal cut sets for the fault tree.
- $U(C_1 \cup C_2 \cup \ldots \cup C_M)$ is the unavailability calculated for the well barrier system.

The expression $\mathrm{U}(C_1 \cup C_2 \cup \ldots \cup C_M)$ can be calculated analogously to calculate the probability of occurrence of the top event of a fault tree. In this case, the probabilities of the basic events are given by their respective instantaneous unavailability.

It is important to note that the availability calculation can be performed for each instant of time. The expected availability for the well is given from the average for the mission time, according to the Eq. 5.

$$\overline{\mathrm{A}} = \int_0^t t' \mathrm{A}(t') dt' \quad (5)$$

Where:

- $\overline{\mathrm{A}}$ is the average availability of the well barrier element system.
- t is the mission time considered for the productive life of the well.
- $\mathrm{A}(t')$ is the availability calculated at the instant of time t'.

4.3 Downtime due to repairs.

The purpose of this indicator is to classify the oil well configuration in terms of the expected number of days of production/injection downtime due to interventions to repair physical components that affect the integrity of the well. Equation 6 shows how to calculate downtime due to component repairs.

$$d = \sum_{i=1}^{M} n_i \cdot ART_i \quad (6)$$

Where:

- d is the calculated value for the expected downtime of the well due to interventions motivated by component failures that affect the integrity.
- M is the number of different workover scopes considered for a given configuration;
- n_i is the expected number of occurrences of the i-th scope of repair over the productive life of the well;
- ART_i is the expected active repair time for the i-th scope of repair.

The value of n_i, $i = 1, \ldots, M$ can be obtained by different approaches. One can calculate n_i based on the expected number of failure occurrences according to a Poisson process by the formulation given by Eq. 7.

$$n_i = t \sum_{j=i}^{Q_i} \lambda_j \quad (7)$$

Where:

- t is the mission time considered for the productive life of the well..
- Q_i is the number of failure modes repairable by the i-th workover scope.
- λ_j is the failure rate associated with the j-th failure mode among those repairable by i-th workover scope.

4.4 Repair Costs.

The purpose of this indicator is to qualify the oil well configuration in terms of expected repair costs due to component failures that affect both integrity and production/injection capacity. The calculation of this indicator depends on the downtime calculation presented in the section 4.3. Once the downtime is known, we apply the formula in Eq. 8.

$$CI = \sum_{j \in \mathrm{WI}} \left(DI_j \cdot csd + cseI_j + ocrI_j\right) \quad (8)$$

Where:

- CI is the expected cost due to interventions motivated by component failures that affect well integrity.
- WI is the set of workover scopes applicable to integrity repairs for the evaluated well configuration.
- DI_j is the downtime due to component repairs that impact the integrity of the well covered by the j-th workover scope.
- csd represents the cost of renting a rig to carry out intervention in the well per unit of time.
- $cseI_j$ represents the cost of replacing equipment for the$j$--th workover scope of components that affect the integrity.
- $ocrI_j$ represents all other repair related costs for the j--th workover scope of components that affect the integrity.

4.5 Probability of ceasing production or injection.

The purpose of the indicator is to evaluate the configuration considering the probability that the failure of physical components of the well interrupts the flow of production (or injection) during the first five years.
The formula for calculating the probability indicator of ceasing production or injection is given by Eq. 9.

$$\mathrm{P_c} = 1 - \prod_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{R_i} \quad (9)$$

Where:

- $\mathrm{P_c}$ is the probability of ceasing production or injection due to failure of physical well components.
- $\mathrm{R_i}$ is the probability of $\mathrm{i}-\mathrm{th}$ failure mode does not occur during the considered mission time.
- N is the total number of identified failure modes capable of causing the cessation of production.

The calculation is performed from the complement of the probability that no failure mode capable of ceasing production occurs over the considered mission time. The determination of a mission time for the well is implicit in the calculation of this indicator.

4.6 Expected reduction in nominal flow due to degradation of production components.

This indicator aims to assess the expected impact on nominal production/injection (reduction of production/injection flow) of the well due to equipment failures related to production/injection. Eq. 10 gives the formula for calculating the production/injection degradation probability indicator.

$$\nabla_{\emptyset} = \sum_{i=1}^{N} (1 - R_i) * P_i \quad (10)$$

Where:

- $\nabla_{\emptyset}$ is the expected reduction in production or injection flow due to the failure of physical well components.
- R_i is the probability of th $\mathrm{i}-\mathrm{th}$ failure mode does not occur during the considered mission time.
- P_i is the reduction factor caused by the failure of component i in the production or injection flow.
- N is the total number of identified failure modes capable of causing production/injection degradation.

5 Conclusions and Further Work

The first point to be concluded is that the research was conducted using a well-established and rigid methodology, ensuring good coverage of published articles. Despite this broad coverage and the importance of the topic, it was surprising that only some scientific articles dealt with the subject of indicators.
The research process added results of the survey on the oil and gas operator's strategic objectives and their knowledge on the subject to the results of the literature review and the research team's knowledge; an interesting set of indicators was arrived at that assess safety aspects,

maintenance, and costs. The data needed to compute these indicators would be based on the reliability statistics of typical subsea oil well equipment and estimates of repair times and costs.

The following research steps will be towards testing the proposed indicators to validate them in a project, studying the need to include new indicators, reviewing those already identified, or implementing the suggested ones.

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