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ORIGINAL PAPER

Integrated risk management: a Petrobras application in offshore well construction safety to minimize critical emergency disconnections

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Abstract

In order to avoid mistakes and to save a great deal of time in analysis, an innovative methodology was developed that can analyze the well operations and rig characteristics involved to define the best emergency disconnect sequence (EDS) available. A solution was developed based on the characteristics of the rigs and blowout preventers (BOPs), and six variables were considered that directly affect the choice of EDS. All possible combinations of 64 scenarios were analyzed, and the priority of choice of the EDS was defined empirically. This paper presents an approach to EDS risk management and examples of exposure time (time without riser safety margin and shear capability) for the same well, which can be lowered from 13% to 0.1%. The impact of this reduction is related to the ability of the BOP to cut some of the heavy casings, in addition to improved availability of EDS modes. This implementation opened up many possibilities for the performance of risk exposure analysis, enabling comparison of several BOP configurations of contracted rigs and selection of the best options. This innovative approach allowed a better management of the rig schedules, prioritizing safety aspects and making it possible to allocate the fleet in a systematic way.

Keywords Well safety · Safety barriers · Emergency disconnect sequence (EDS) · Well control · Kick · Well design

Abbreviations

BOP	Blowout preventer
BSR	Blind shear ram
CAPEX	Capital expenditure
CSR	Casing shear ram
EDS	Emergency disconnect sequence
LBSR	Lower blind shear ram
LMRP	Lower marine riser package
MPD	Managed pressure drilling
RSM	Riser safety margin
SEEDS	System of emergency disconnect sequence
UBD	Underbalanced drilling
UBSR	Upper blind shear ram

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1 Introduction

Petrobras is the biggest Brazilian oil operator, currently operating worldwide in the energy sector, primarily in the areas of exploration, production, refining, marketing and transportation of oil, natural gas and their products. In recent years, Petrobras has made several significant oil field discoveries in the Brazilian Pre-Salt layer, with an impressive production potential in deepwater. However, the development of production from these new fields presents many technological and logistical challenges demanding intensive optimization of the work processes and an increasing number of operational activities, including offshore well construction. An important aspect to consider in the future of these projects is sensitivity to the environment, as during well construction operations, many problems can occur. Oil spills can result in the most catastrophic events in terms of cost, loss of assets, environmental damage and personnel safety when their occurrences and escalations are not handled properly (Januarilham 2012). Although large-scale oil spills are generally rare, distinct events can account for most of the cumulative oil spill volume (Ji et al. 2014), spills from oil production can also be very large, and pollution from blowouts and other incidents sometimes exceeds that caused by major tank accidents (Nihoul and Ducrotoy 1994). From the drilling perspective, well design and construction require the addressing of safety issues, especially those associated with well control operations. Personnel training and certification, as well as the proper well control operation, require reliable computational tools, such as kick simulators (Avelar et al. 2009). Petrobras' major concern is to develop its reserves under the best safety conditions, in order to preserve the environment, its people and its assets. Thus, it has been necessary to focus more on the ability to perform safe disconnection regardless of the operation occurring in the well (Paula and Fonseca 2013).

The construction of petroleum wells is becoming more and more complex and challenging, especially in regard to drilling and completion in deep and ultra-deepwater, which requires the use of increasingly sophisticated dynamically positioned rigs (Paula and Fonseca 2013). In normal drilling operations, the primary well control is the hydrostatic pressure exerted by the drilling fluid in the well, which can be adjusted to specific conditions through variations in the fluid density. Proper well planning requires that the pressure inside the wellbore should overbalance the formation pressure by a certain safety margin. This can be attained by the hydrostatic head of the drilling fluid or the combination of applied surface backpressure and the hydrostatic head of the drilling fluid (managed pressure drilling—MPD scenario). As a secondary barrier during drilling, the blowout preventer (BOP) is designed to close the well annulus or the drill pipe (Cai et al. 2012). In deepwater and ultra-deepwater drilling operations, the BOP is latched onto a wellhead, situated on the seabed (Huse and Alme 2013).

Blowout preventers have several functions, but the most important is the ability to prevent large blowouts of hydrocarbons from the well (Østby 2008). Kick is described as the unwanted influx of formation fluid into a wellbore during drilling operation as a result of pressure differences in the wellbore. This influx is unwanted because it can flow to the surface and create a blowout, harming people, the environment and causing property damage (Januarilham 2012). Kicks are early signs of potentially disastrous blowouts (Ajienka and Owolabi 1991), and there are several cases where such blowouts may occur, including high pressure in the well and platform drift-off (Østby 2008). In the event of primary control loss resulting from a sudden increase in formation pressure or lost circulation, it becomes necessary to seal off the well by some other means to prevent uncontrollable flow, or blowout, of formation fluids (Vujasinovic 1986). The blowout preventer (BOP) is one of several barriers in the well to prevent kicks and blowouts and is the most important and critical piece of equipment as it is the last line of protection against blowouts during well interventions (Januarilham 2012). It may be defined as one or more valves installed at the wellhead to prevent the escape of pressure, either in the annular space between the casing and the drill pipe or in the open hole during drilling or completion operations (Huse and Alme 2013).

The BOP is a structure with a large set of valves and rams placed on the top of the well, which can be closed when the drilling crew have uncontrolled flow of formation fluid in the wellbore (Januarilham 2012). Often the expression "BOP" is used for "BOP stacks," which is an assembly of many blowout preventers (annular preventers, pipe ram preventers, shear or blind rams) and other well control equipment such as the kill and choke lines (Huse and Alme 2013). The subsea BOP system consists mainly of the subsea BOP control system and the subsea BOP stack. A typical subsea BOP system is illustrated in Fig. 1 (Cai et al. 2012). During normal operation, the BOP valves are operated with fluid power from the rig through an umbilical. In the event of an emergency where the umbilical may be accidentally cut, the BOP must therefore contain the necessary energy to operate the rams without a topside connection (Østby 2008). BOP configurations vary because of differences in drilling regions, ocean depths, and so on. Until now, no definitive configuration standards have been established (Cai et al. 2012).

Different preventer configurations provide different levels of performance for subsea BOP systems. Specifically, a blind shear ram preventer, which is regarded as an emergency device, is used to shear the pipe and seal the well. As shown in Fig. 1, the typical subsea BOP is equipped with two annular preventers and four or five ram preventers, including two blind shear rams and two or three pipe rams. The configuration of the stack is dependent on the expected operations, redundancy, flexibility and the trade-off between the advantages and disadvantages of each configuration (Januarilham 2012). Besides the annular preventers, ram preventers, connectors and other components such as the flexible joint, choke/kill valves and choke/kill lines are integrated to form the whole subsea BOP stack (Cai et al. 2012). There are several types of rams which have different tasks in addition to sealing the well. One may be designed to grip and hold equipment lowered into the well, while others are designed to cut equipment and pipes which are blocking the ram. The latter is the shear seal ram (Østby 2008). The subsea BOP stack is usually equipped with two hydraulic connectors, the LMRP connector and the wellhead connector. The LMRP contains the control system of the BOP and one or two annular preventers, depending on the BOP configuration. The LMRP connector enables retrieval of the control

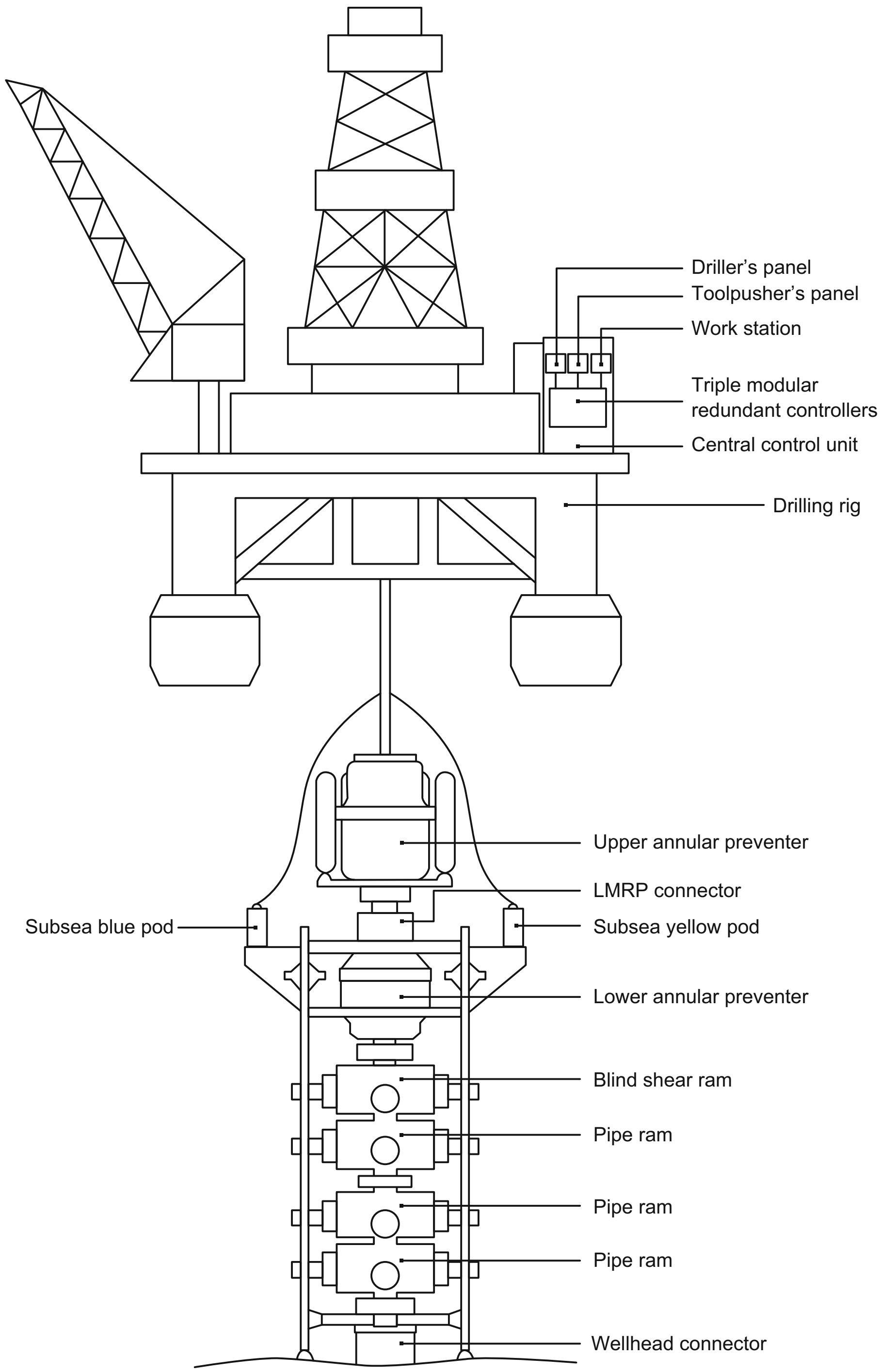

Fig. 1 Typical architecture of a subsea BOP system. Reproduced with permission from Cai et al. (2012)

system, and the annular preventer enables maintenance without the necessity of removing the whole BOP stack, therefore saving time and making it safer, besides being used to connect the LMRP to the BOP stack. The wellhead connector is used to connect the BOP stack to the wellhead (Cai et al. 2012).

Loss of position of the dynamically positioned rig without safe disconnection could result in critical damage to the well barrier, as well as to exposed subsea equipment. The ultimate consequence could be a blowout and/or severe damage to subsea production systems like production templates, resulting in risk to personnel, environmental damage, financial loss and harm to the reputation of the company (Paula and Fonseca 2013). Currently, all dynamically positioned rigs are equipped with an emergency disconnect button which initiates a pre-programmed sequence of functions designed to secure the well in a minimal amount of time prior to disconnecting the LMRP riser connector (Sattler and Lewis 2004). An emergency disconnect sequence (EDS) is a sequence of actions, events and interlocks that are automatically initiated once the EDS button is pressed on any BOP panel in the rig. These actions will activate the mechanism or equipment responsible for disconnecting the rig from the well (Paula and Fonseca 2013).

One of the problems is that each rig has a different combination of EDS, even when they have similar BOP configurations. It is interesting to note that some functions are activated even though they should already be in a particular position. This is done to ensure the well is secured upon disconnecting (Sattler and Lewis 2004). Despite extensive technology, an emergency disconnection may occur at any time in dynamically positioned drilling rigs, sometimes surprisingly so, be it through human error, adverse environmental conditions or blackouts. The prior selection of proper EDS, followed by well-thought-out operational decisions, is essential for reduction in potential damage caused by disconnections (Paula and Fonseca 2013). The operating philosophy behind the emergency disconnection guidelines, as shown graphically in Fig. 2, is that decisions which have been previously considered and planned should be initiated as soon as possible.

Based on this philosophy, Petrobras adopted the "degraded status" concept. It considers that, when the rig has lost any of its backup systems, such that a single failure in any of the dynamic positioning (DP) system equipment causes the rig to lose its capability of maintaining position, it is considered to be in "degraded status." From the "degraded status" to the "yellow status," the crew may have some time to think and perform pre-planned actions. The moment the "red alarm" sounds, the only thing left to be done is disconnect the rig as fast as possible or risk

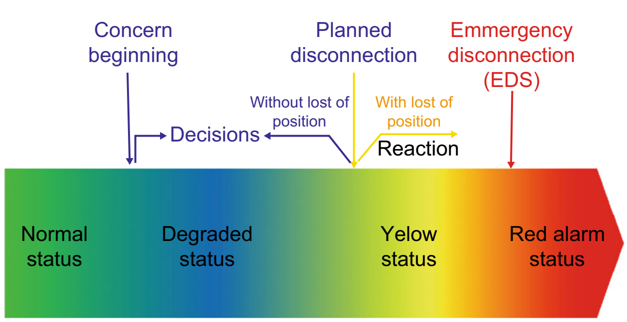

Fig. 2 Operational philosophy of emergency disconnection guidelines. Reproduced with permission from Paula and Fonseca (2013)

getting stuck to the wellhead, thereby putting the well and the rig at risk.

This paper is organized in six sections, as follows: Sect. 2 presents the EDS bibliography survey. Section 3 describes the automatic generation of operational sequences with EDS. Section 4 presents the SEEDS methodological approach. Section 5 shows the results and applications. At last, Sect. 6 presents the conclusions and future steps.

2 EDS state-of-the-art survey

To investigate what is known on the subject, it was necessary to see what is already available in the literature. Thus, a bibliographic search was conducted from 1980 to October 4, 2015, taking as reference the SCOPUS database, which is significant in several fields of knowledge. Initially, the key words used were: "emergency disconnect sequence" or "system of emergency disconnect sequence" or "emergency disconnection" or "disconnection emergency guidelines" or "system of emergency disconnection." The 113 results were found with articles and conference papers, considering only the "physical sciences" category. A new filter was applied, where the "computer science," "earth and planetary sciences," "physics and astronomy," "social sciences," "materials science," "mathematics," "medicine" and "environmental science" areas were removed, due to the fact that the subject is specific to the oil and gas industry. Using this filter, it was possible to obtain 69 documents. In a more detailed analysis of these articles, 21 documents were then selected to form the core of the bibliographic research. It is concluded that the subject presented here is innovative, very current and it is still developing.

In the literature, important works are found on the construction of offshore wells, using risk analysis techniques, such as Bayesian network, fault tree, event tree and bow tie (Bhandari et al. 2015; Khakzad et al. 2013; Abimbola et al. 2014). Such studies help to determine the probability of blowouts, facilitating the preventive and mitigating actions for undesired events. Also described in the literature is the impact on the operation risk by the introduction of new drilling techniques, such as MPD (managed pressure drilling) and UBD (underbalanced drilling) (Abimbola et al. 2015). Although there were interesting assessments on the probabilities of failure of several basic events in offshore well construction operations (Abimbola et al. 2014; OREDA 2002), no studies were found in the literature that included the selection of the closure sequence (EDS) of the BOP stack rams, in emergency disconnect events, in case of BOP closing failure. Incorrect selection of the closing sequence can lead to the events of blind rams, which do not have the cutting and well sealing capacity acting on pipes, severely increasing the probability of failure of the blind ram.

The correct selection of EDS will increase the chance of leaving the well closed in the event of an emergency disconnection. The major problem is, as mentioned before, each rig has its own EDS options, and even when they have the same shear and blind shear ram configuration, they do not have the same EDS options. Furthermore, there are dozens of different associated operations that may take place and be analyzed to define the best EDS to be adopted, and this context needs to comply with the limits of the rig. Without the proper tools, this analysis to select the rig EDS should be performed repeatedly for each well design and operation, and depending on the people involved in the discussion, a different EDS may be selected for the same operation and rig.

In order to avoid mistakes and save a great deal of analysis time, Petrobras decided to develop a tool that could analyze the well operations and the rig involved, in order to define the best EDS available, based on pre-defined standard criteria to maximize the chance of leaving the well closed. Therefore, it was possible to concentrate efforts, with the best people available, on defining robust criteria that could be reproduced in all well designs and operations.

3 Automatic generation of operational sequence with EDS

High risks are inherent to any well construction due to the uncertainties and unknowns in geological modeling and in rock and fluid properties. Although risks cannot be eliminated, they can certainly be reduced by using an appropriate safety approach during design and planning phases (Miura et al. 2006). The design of a well can be defined as an interactive process, involving specialists and information to set up a sufficiently detailed plan to drill the well safely and economically. The process is characterized by a set of activities, which present a strong interdependent relationship (Mendes et al. 2003). In order to provide an estimation of exposure time for each EDS during the stages of well construction, Petrobras has developed a system called SEEDS, which compares several BOP settings of the rigs and calculates risk exposure times. Such an approach enables an increase in well design robustness in terms of safety, while also making it possible to supply recommended EDS for each operation in the design phase. This practice encourages discussion on the well construction project, involving both the operations team and company site representatives. The system cost is around 0.01% of the CAPEX (CAPital EXpenditure) of Petrobras well construction. All the development and implementation of SEEDS were performed in house.

The main consequences are an improvement in the quality of the well construction process and also better competence development across the teams involved in important safety issues. This system developed by Petrobras is state of the art in the oil industry. There is no standard description or list making process for EDS, and unfortunately, each rig has its own EDS numbers depending on the BOP model. The EDS list shown in Table 1 is an attempt by the Petrobras team to standardize EDS possibilities. This list considers the four BOP configurations regarding the number of shear rams (and blind shear) available nowadays. These options do not take into consideration the autoshear configuration availability but do provide for the possibility of the rig not having a proper EDS for the operation, or more than one option, based on the criteria developed.

With the solution proposed, it is possible to compare and quantify exposure to EDS 0 (no shear possibilities—see Table 1 above) without riser safety margin (RSM). This condition is critical, as in the event of an emergency disconnection the well would not have the fluid barrier and the BOP would be unable to isolate the well from the outside environment through the blind shear rams. This could represent a catastrophic event such as an oil spill in the ocean. This approach was developed to cover the whole drilling process, including, top hole drilling, bottom hole drilling and temporary abandonment of wells. This program (SEEDS) automates and accelerates the documentation containing recommendations, standards and schedule of well construction operations, contributing to better knowledge management. The approach also allows the use of different software adopted by Petrobras for probabilistic forecasting of well runtime.

4 SEEDS methodological approach

Based on the characteristics of the rigs and the BOPs that equip them, six variables were considered that directly affect the choice of EDS. Then, all possible combinations of these variables (64 scenarios) were analyzed and, for each scenario, the priority order of choice of the EDS was defined empirically, with the premises that the blind ram selected for closure was able to cut the element in front of the BOP and keep the seal, therefore, closing the well safely or, if the blind rams are not capable of cutting, the blind ram selected for closing must close without any material at the front of the BOP, sealing the well securely.

Table 1 EDS modes

EDS	Description
0	No shear[a]
1	UBSR or BSR
2	CSR
3	LBSR
4	CSR + UBSR or CSR + BSR
5	LBSR + UBSR
6	UBSR + LBSR
7	CSR + LBSR
8	BOP does not provide a proper EDS
9	More than one option of EDS available with the same importance
10	No EDS[b]

[a]Disconnect LMRP from BOP stack without activating any blind or casing shear ram

[b]Used for anchored rigs or if the model developed has not found an answer, usually by incorrect input of the rig characteristics, available EDS or material cutting capabilities

4.1 SEEDS description

The application has a data input module where the information for each phase is inserted, such as well depth, well diameter, flow rates, casing diameters, the length of cement left within the casing and cased and open hole tripping rates for each phase (already automatically entered through system integration with the rig values, which can be customized by the user). It is also necessary to define the number of bits for each phase and their drilling rates. The program makes a consistency analysis with databases and displays warning messages in the case of input errors. Every change is automatically saved by the system.

The following information should also be fed into SEEDS: if the stage/phase to be drilled will have RSM and BOP tests, which drills will be performed, if the phase will have enlargement (simultaneously or with dedicated trip), if the phase is going to be cased at the end of drilling, if open hole logging is planned, cementing evaluation logging and if a coring operation will be performed or not. The next step is the generation of the well operation plan, whereby the user can add or delete steps, or edit the text and the calculated duration of a specific step. Following a generated planning sequence (considering a complete well design), after BOP installation, according to the plan, SEEDS will start monitoring the suggested EDS for each step. An example is shown in Fig. 3.

The program presents the EDS in green when the first EDS option selected by the model is available for the rig. If EDS is shown in yellow, the rig selected for that specific well does not have the primary option suggested by EDS. In this case, another scenario option was obtained for the mentioned rig. If it is EDS 8, the selected rig is unable to safely perform this planned stage. If EDS 9 has been selected, it means that there is more than one option available with the same importance. (It is mandatory for the design review to define the appropriate EDS.) Finally, if EDS 10 is occurring, this indicates that it is necessary to rethink this step, because the developed model has not found an answer, usually due to incorrect input of the rig characteristics, available EDS or material cutting capabilities. If EDS 0 is selected in the scenario where the well does not have RSM, the selected EDS will appear in red because of the high risk involved (Fig. 4).

The program also provides a summary of selected EDS, during the BOP connected period, for whole planning, as shown in Fig. 5.

In Fig. 5, the blue section is the total time with RSM, the gray area is the total time without the RSM but with shear and seal capability and the red section is the total time without RSM and EDS 0 (no shear) selected.

4.2 SEEDS development

A new concept of automated generation of the operational sequence in well construction was implemented with SEEDS. In order to develop the sequence, logic was used to split the drilling steps into packages. The packages have equations to estimate the time and well depth at each step, to correlate which material is in front of the BOP and to define if the operation is utilizing the rig movement compensator or not. Besides the operational sequence, an additional routine is used for each BOP test (expected after each casing/liner run and cementing job performed). This procedure inserts an additional BOP test into the operational sequence, depending on whether the period of 21 days (504 h) between BOP tests has been exceeded.

In the EDS selection module, six requirements should be addressed. Table 2 shows an overview of EDS selection. With these six requirements, a model with sixty-four

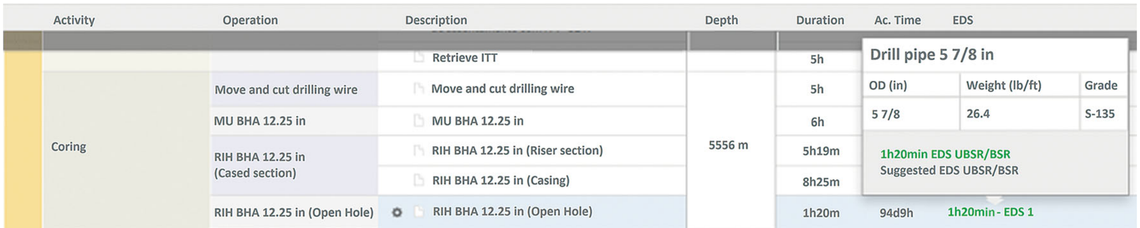

Fig. 3 An example of EDS monitoring in a SEEDS planning sequence

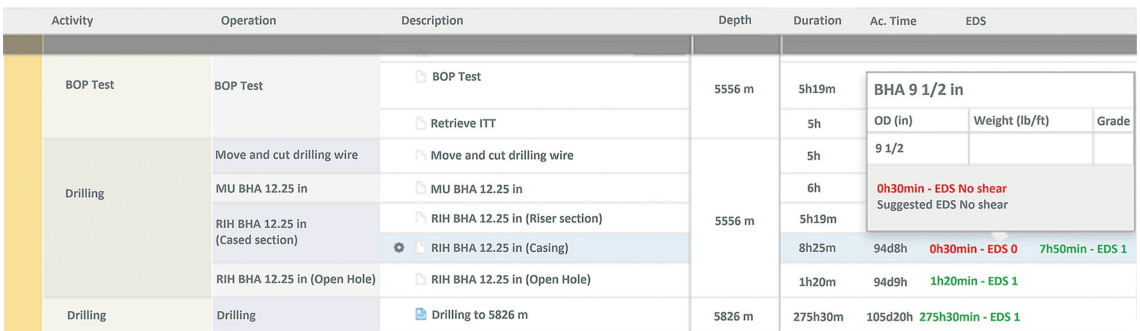

Fig. 4 An example of EDS 0 in SEEDS (in red because the phase is without RSM)

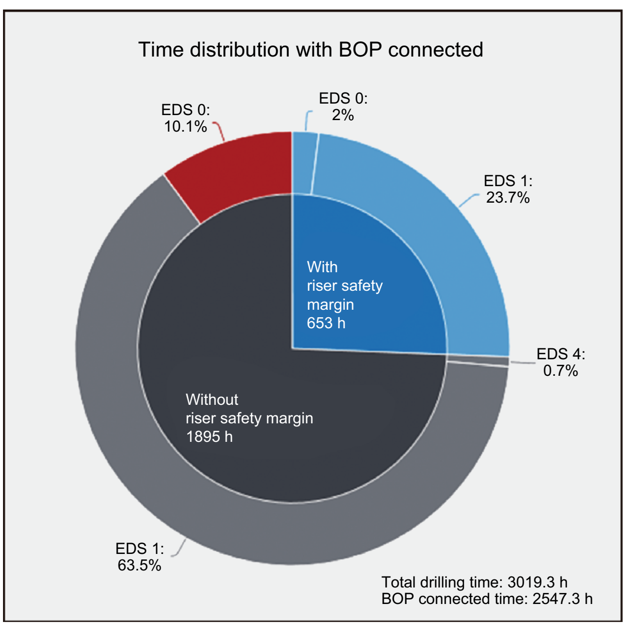

Fig. 5 EDS time distribution with BOP installed (from SEEDS). Reproduced with permission from the authors

possible scenarios and respective EDS priority order was developed. The main drivers defining EDS priority for each scenario were:

- The blind shear ram selected to close must be able to shear the material, maintain the seal capability and consequently close the well.
- If the blind shear rams do not have shear capability, these blind shear rams must close without any material in front.

4.3 Example of EDS selection utilizing the SEEDS approach

An EDS selection example is presented below for a generic operational step "Running casing with the installation string (riser/cased well)," with the casing (14-in., 115 lb/ft, C-110HC) in front of the BOP (the UBSR and CSR rams do not cut such a casing), without the active compensator in the run, for a hypothetical rig (named here as RIG-1, which has 5 rams and an active compensator). Among the 64 mapped scenarios for EDS selection, Table 3 shows the selected Scenario A, which includes the requirements for EDS selection, whereby suggested EDS priority order was EDS 0, EDS 2, EDS 8 and EDS 10.

However, comparing the available EDS options, as an illustrative example RIG-1 will be imagined without EDS 0 capability. The program (SEEDS) will then perform the comparison with the second option (EDS 2) which, in this case, is available, and this is going to be the EDS selected for the step while the material (casing 14″, 115 lb/ft, C-110HC) remains in front of the BOP. For the same operational step, considering that the 13 3/8 in. casing, 72 lb/ft, P-110 is in front of the BOP (CSR cuts, but the UBSR does not cut such a casing), Scenario B (see Table 4) suits the EDS selection requirements.

Table 2 EDS selection requirements

Rig movement compensator type	Answers	
	Passive (0)	Active or passive/active (1)
Number of rams	4 or 5	6
Movement compensator used in the operation step	Yes (1)	No (0)
Shear capacity of the UBSR or BSR ram, considering the material (X)	Yes (1)	No (0)
Shear capacity of the CSR ram, considering the material (X)	Yes (1)	No (0)
Shear capacity of the LBSR ram, considering the material (X)[a]	Yes (1)	No (0)

[a]Applicable for BOP with 6 rams (3 shear rams)

Table 3 Scenario A—used in the EDS selection example

Rig movement compensator type	Number of rams	Use of rig movement compensator in operation step?	UBSR or BSR ram	CSR ram	LBSR ram
Active	5	No	No	No	No
Proposed EDS priority					
Priority 1	Priority 2	Priority 3	Priority 4	Priority 5	Priority 6
0	2	8	10	–	–

Table 4 Scenario B—used in the EDS selection example

Rig movement compensator type	Number of rams	Use of rig movement compensator in operation step?	UBSR or BSR rams	CSR ram	LBSR ram
Active	5	No	No	Yes	No
Proposed EDS priority					
Priority 1	Priority 2	Priority 3	Priority 4	Priority 5	Priority 6
2	0	8	10	–	–

Comparing the EDS options available for RIG-1, considering the EDS proposed in Scenario B, the first option fits very well (EDS 2) and should be selected for this step, while the material (casing 13 3/8″, 72 lb/ft, P-110) remains in front of the BOP. This process of EDS selection is repeated for all steps of the operation in which the BOP is connected to the well.

5 Results and applications

The implementation of SEEDS opened up many possibilities for the performance of risk exposure analysis, enabling the comparison of several BOP configurations of rigs contracted by Petrobras. Figure 6 presents a practical example with results of SEEDS analysis in the same well project, with 5 phases for three different rigs (with distinct configurations of BOP), with diverse levels of risk exposure, as EDS 0 without RSM is selected. Through this analysis, it is possible to observe a reduction in the total time of EDS 0 (no shear), from 20.5% (572 h) to 17.2% (472 h) and finally to 2.4% (68 h).

Another interesting case study for a specific well is shown in Fig. 7, in which it is possible to verify the exposure time varying from 13% to 0.1%. The impact of this reduction is related to the ability of the BOP to cut the casing 10¾″, 85.3 lb/ft and 13 5/8″, 88.2 lb/ft, in addition to the better availability of EDS modes.

Analysis for a group of Brazilian Pre-Salt wells indicated that, for the rigs available for drilling, it is possible to

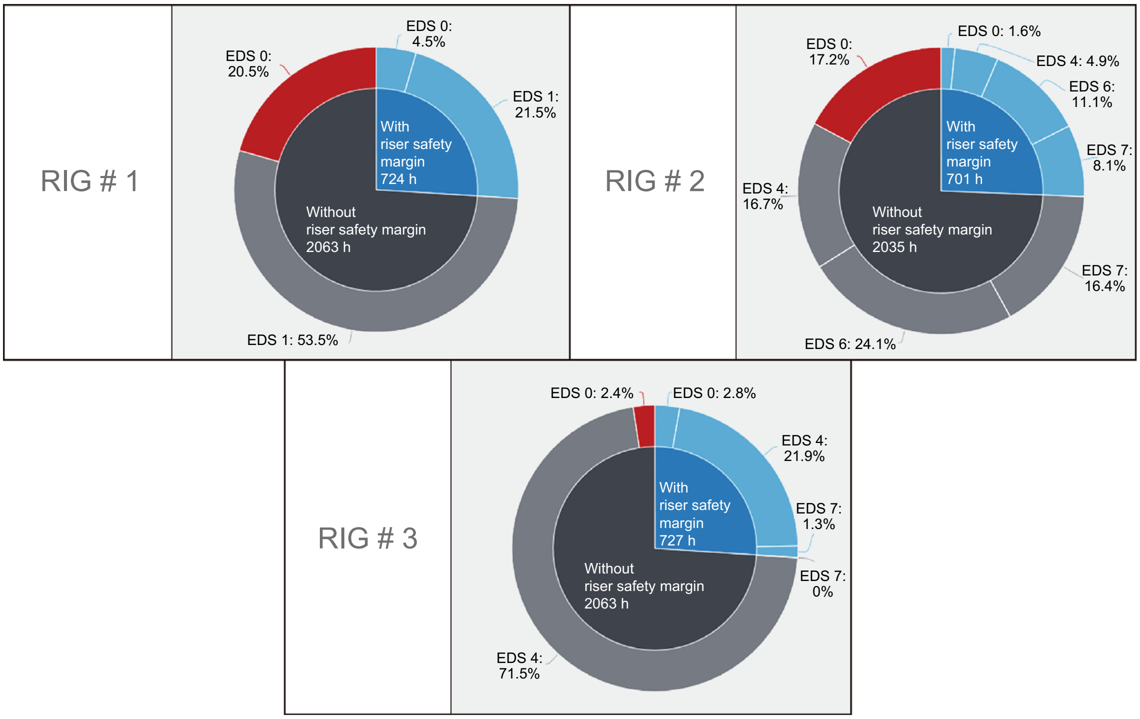

Fig. 6 SEEDS analysis: same well with three different rigs

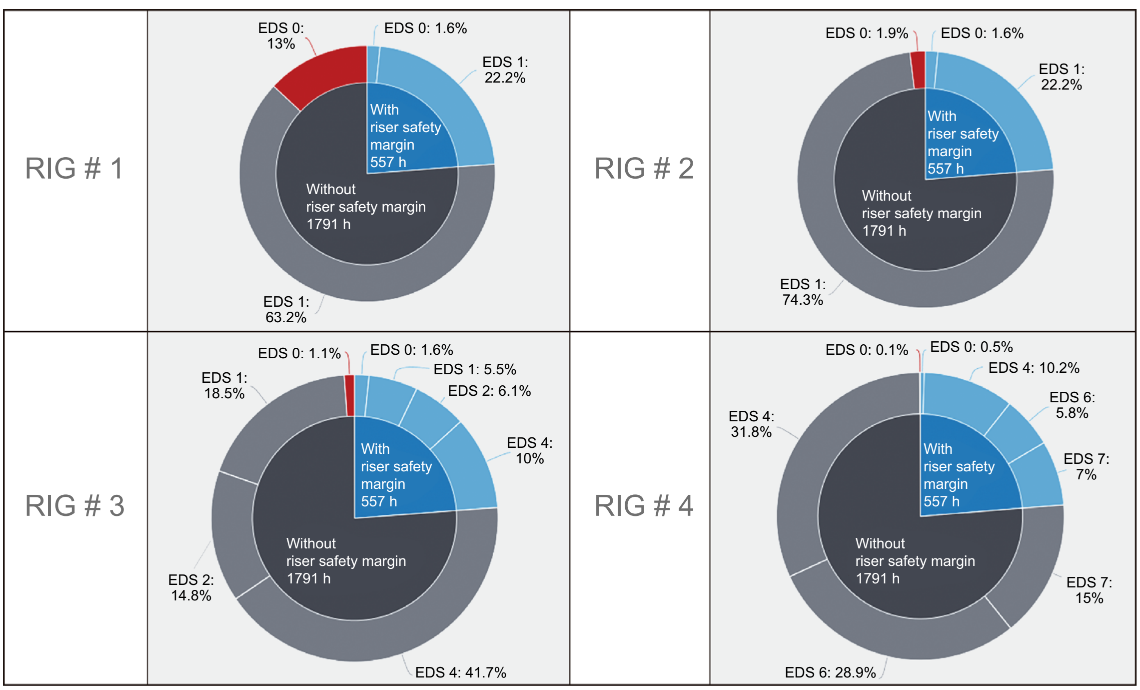

Fig. 7 SEEDS analysis for different scenarios

have a reduction from 13% to 0.1% in the exposure time to EDS 0 without RSM, depending on the definition of rig for the well location.

Over the years, the industry has developed and become more organized, making it clear that increased profit was justified by higher quality production and by the use of faster and more efficient processes. To stay on top, it was necessary to know the competitors and features that made products more attractive to customers and processes at a lower cost (Stapenhurst 2009). Based on this need, benchmarking emerges, with the first studies based on the exchange of information between two companies and the benchmarking clubs. Camp (1995) defined benchmarking as the process of learning and exchange of corporate information, with the purpose of promoting adaptations in an organization based on the observation of the best practices of the market. To develop this analysis, it is necessary to define metrics and evaluation processes to make the comparisons (Boxwell 1994). In the case of this research, no study was found in another company that could be comparable. Due to the current lack of external benchmarking, it would be very welcome to have new research in the future to compare the performance internally in the company studied.

6 Conclusions and future steps

The methodology presented in this paper enables the user to compare the planning of the same well for different rig possibilities, analyzing the EDS times of each step as well as the total exposure times. This tool also makes it possible to export the drilling schedule with the planned time, selected EDS, recommendations and standards of each step to the Petrobras database. This is an important breakthrough in operation planning, enabling the selection of scenarios with lower risk EDS. An important achievement is the possibility of negotiating with the drilling contractors to provide additional EDS modules and/or increase the shear capability of the blind rams, in order to eliminate situations with no possibility of closing the well safely.

The use of this approach allows the effective reduction in exposure time in situations where there is neither shear capability nor RSM. This aspect is relevant when preparing the rig schedules, which have their security increased. In this way, the pool of rigs can be adapted to the portfolio of wells in the planning phase, allowing minimizing exposure to EDS 0 condition without RSM.

The next steps involve the implementation of automated planning for completions and workover operations by selecting EDS. Another possibility is to compare the EDS selected during the operation with the simulation by the system, allowing alarms and avoiding human failure. To better understand the importance of the proposed approach, new research can be carried out in the future to compare the performance in the company studied. These initiatives are mandatory for the safe and efficient development of new Petrobras discoveries.

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References

Abimbola M, Khan F, Khakzad N. Dynamic safety risk analysis of offshore drilling. J Loss Prev Process Ind. 2014;30:74–85. https://doi.org/10.1016/j.jlp.2014.05.002.

Abimbola M, Khan F, Khakzad N, Butt S. Safety and risk analysis of managed pressure drilling operation using Bayesian network. Saf Sci. 2015;76:133–44. https://doi.org/10.1016/j.ssci.2015.01.010.

Ajienka JA, Owolabi OO. Application of mass balance of kick fluid in well control. J Pet Sci Eng. 1991;6(2):161–74. https://doi.org/10.1016/0920-4105(91)90035-L.

Avelar CS, Ribeiro PR, Sepehrnoori K. Deepwater gas kick simulation. J Pet Sci Eng. 2009;67(1–2):13–22. https://doi.org/10.1016/j.petrol.2009.03.001.

Boxwell RJ Jr. Benchmarking for competitive advantage. New York: McGraw-Hill; 1994.

Bhandari J, Abbassi R, Garaniya V, Khan F. Risk analysis of deepwater drilling operations using Bayesian network. J Loss Prev Process Ind. 2015;38:11–23. https://doi.org/10.1016/j.jlp.2015.08.004.

Cai B, Liu Y, Liu Z, Tian X, Zhang Y, Liu J. Performance evaluation of subsea blowout preventer systems with common-cause failures. J Pet Sci Eng. 2012;90:18–25. https://doi.org/10.1016/j.petrol.2012.04.007.

Camp RC. Business process benchmarking: finding and implementing best practices. Milwaukee: ASQ Quality Press; 1995.

Huse, JR, Alme, IA. BOP reliability monitored real time. Paper presented at the SPE European HSE conference and exhibition held in London, UK; 2013. https://doi.org/10.2118/164987-MS.

Januarilham, Y. Analysis of component criticality in the blowout preventer. Master's Thesis presented at the University of Stavanger, Faculty of Science and Technology; 2012. http://hdl.handle.net/11250/182183.

Ji Z, Johnson WR, Wikel GL. Statistics of extremes in oil spill risk analysis. Environ Sci Technol. 2014;48(17):10505–10. https://doi.org/10.1021/es501515j.

Khakzad N, Khan F, Amyotte P. Quantitative risk analysis of offshore drilling operations: a Bayesian approach. Saf Sci. 2013;57:108–17. https://doi.org/10.1016/j.ssci.2013.01.022.

Mendes JRP, Morooka CK, Guilherme IR. Case-based reasoning in offshore well design. J Pet Sci Eng. 2003;40(1–2):47–60. https://doi.org/10.1016/S0920-4105(03)00083-4.

Miura K, Morooka CK, Mendes JRP, Guilherme IR. Characterization of operational safety in offshore oil wells. J Pet Sci Eng. 2006;51(1–2):111–26. https://doi.org/10.1016/j.petrol.2005.11.018.

Nihoul C, Ducrotoy J. Impact of oil on the marine environment: policy of the Paris Commission on operational discharges from the offshore industry. Mar Pollut Bull. 1994;29(6–12):323–9. https://doi.org/10.1016/0025-326X(94)90648-3.

OREDA. Offshore reliability data handbook, 41th ed. SINTEF, Trondheim; 2002.

Østby, P. Improvement of response time and cutting capability of blow out preventer (BOP), Master's Thesis presented at the Norwegian University of Science and Technology, Department

of Energy and Process Engineering; 2008. http://hdl.handle.net/11250/235064.
Paula Jr, RR, Fonseca, DR. Emergency disconnection guidelines. Paper presented at the offshore technology conference Brazil held in Rio de Janeiro, Brazil; 2013. http://dx.doi.org/10.4043/24418-MS.
Sattler, J, Lewis, E. Qualitative risk analysis of emergency BOP control systems to ensure availability. Paper presented at IADC/SPE drilling conference held in, Dallas, Texas; 2004. http://dx.doi.org/10.2118/87157-MS.
Stapenhurst T. The benchmarking book: a how-to-guide to best practice for managers and practitioners. Kidlington: Elsevier; 2009.
Vujasinovic AN. How blowout preventers work. J Pet Technol. 1986;38(09):935–7. https://doi.org/10.2118/15795-PA.