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FROM ENERGY MONITORING TO MAINTENANCE DECISIONS: A CONCEPTUAL FRAMEWORK FOR HYDRAULIC BLOWOUT PREVENTER CONTROL UNITS

Research paper

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Abstract: The reliability of hydraulic blowout preventer (BOP) control units is essential for maintaining the functional capability of well-control equipment. This paper aims to develop a conceptual decision-support framework for condition-based maintenance by integrating operational monitoring, energy-performance assessment, and diagnostic evaluation into a structured procedure. The methodology is based on a synthesis of existing maintenance approaches and previously published research on the hydraulic activation of a jaw-type BOP. Five indicators are considered: operating pressure, flow rate, volumetric efficiency, clearance leakage, and required activation power. The proposed framework comprises data acquisition, comparison with documented reference conditions, deviation identification, diagnostic verification, maintenance decision-making, and subsequent monitoring. The results are presented through a decision-support flowchart and an indicator matrix linking potential deviations with diagnostic checks and maintenance-related responses. The framework emphasizes the joint interpretation of operating parameters and distinguishes changes caused by operating conditions from deviations requiring further investigation. The proposed approach provides a structured basis for organizing maintenance-related information but has not been validated using field monitoring or maintenance records. Further research is required to establish diagnostic criteria and evaluate its effectiveness under representative operating conditions.
Key words: blowout preventer, condition-based maintenance, hydraulic control unit, decision-support framework, operational monitoring, energy performance.

INTRODUCTION

Blowout preventers (BOPs) are essential safety systems in the oil and gas industry, designed to control well pressure and prevent uncontrolled fluid release during drilling operations. Their ability to perform the required safety function depends not only on the mechanical integrity of the preventer assembly but also on the reliability of the hydraulic control unit responsible for its activation. Maintaining the functional capability of BOP systems therefore requires particular attention to the condition, performance, testing, and maintenance of their components (Shafiee et al., 2020). Furthermore, the application of integrated Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) has demonstrated the importance of identifying critical failure scenarios and assessing component-level risks in subsea BOP systems (Shafiee et al., 2019).

Conventional maintenance practices, including periodic inspections, functional testing, and corrective interventions, are essential for maintaining BOP functionality. However, periodic activities alone may provide limited information about progressive component degradation between scheduled examinations. Condition-based maintenance (CBM) and prognostic health management (PHM) offer complementary approaches by incorporating equipment condition and operational information into maintenance planning. Brandão Martins et al. (2018) examined the integration of these concepts with reliability-based approaches for BOP systems. The potential of operational monitoring has also been demonstrated through a model-based approach for detecting and identifying leakage in subsea BOP hydraulic control systems using pressure measurements and hydraulic system characteristics (Wassar et al., 2018).

The integration of condition information into reliability assessment has been investigated through several quantitative approaches. Elusakin and Shafiee (2020) developed a reliability analysis method for subsea BOP systems using stochastic Petri nets and incorporating component degradation and condition-based maintenance. In a broader safety-system

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context, Zeng and Zio (2018) proposed a dynamic risk assessment approach that combines statistical failure data with condition-monitoring information to update reliability estimates during operation. Similarly, Cai et al. (2023) developed a data-driven approach for optimizing condition-based maintenance decisions using historical degradation and failure data. Although these studies address different systems and modelling approaches, they demonstrate the importance of incorporating operational and degradation information into reliability assessment and maintenance decision-making.

A previously published investigation of a jaw-type BOP hydraulic activation system examined the influence of operating pressure, flow rate, volumetric efficiency, and clearance leakage on the required activation power. Experimental design, regression analysis, and the Grey Wolf Optimizer (GWO) were combined to identify the influence of these parameters and determine an energy-efficient operating configuration (Marković et al., 2025). The study also introduced a deviation-based operational reliability model and discussed the potential use of operating parameters in predictive maintenance. These findings provide a basis for examining how energy-performance information could support the interpretation of hydraulic system condition.

Building on the previously published research and the identified maintenance approaches, the present paper aims to develop a conceptual decision-support framework for condition-based maintenance of hydraulic BOP control units. The proposed approach integrates operational parameter monitoring, comparison with reference conditions, deviation identification, diagnostic verification, and maintenance decision-making into a structured procedure. Particular attention is given to distinguishing changes associated with operating conditions from deviations that may require additional investigation. The framework is intended to support maintenance planning without replacing mandatory functional testing or established safety procedures. Its effectiveness remains to be evaluated using operational monitoring and maintenance data.

MATERIAL AND METHODS

Research approach

The research was conducted as a conceptual methodology development study aimed at establishing a structured procedure for supporting maintenance decisions in hydraulic blowout preventer (BOP) control units. The methodological approach integrates principles of condition-based maintenance (CBM), operational parameter monitoring, energy-performance assessment, and diagnostic evaluation.

The framework was developed through a synthesis of published research on BOP maintenance and reliability, industrial condition-monitoring practices, and maintenance decision-support methods. Brandão Martins et al. (2018) provided the theoretical basis for integrating CBM and prognostic health management (PHM) concepts into BOP management. The broader context of industrial monitoring practices was considered through the survey conducted by Higgs et al. (2004), while the integration of reliability-centered maintenance and condition monitoring into maintenance decisions was examined using the approach presented by Catelani et al. (2020).

Previously published experimental research on the hydraulic activation system of a jaw-type BOP was used as the technical basis for identifying relevant operating parameters and their relationship with energy consumption (Marković et al., 2025). The present study does not repeat the experimental design, regression modelling, or optimization procedures reported in that publication. Instead, it examines how information derived from these investigations can be organized into a conceptual maintenance decision-support procedure.

Selection of operational indicators

The selection of operational indicators was based on their physical relevance to hydraulic system performance and their potential contribution to identifying changes in operating conditions. Four parameters were considered: operating pressure, flow rate, volumetric

efficiency, and clearance leakage. The power required for BOP activation was included as a complementary energy-performance indicator.
Pressure and flow rate describe the operating conditions and hydraulic power requirements of the system. Volumetric efficiency and clearance leakage provide additional information about hydraulic losses. The relationship between these parameters and the required activation power was previously investigated by Marković et al. (2025).
Leakage was also considered because of its relevance to hydraulic system monitoring. Wassar et al. (2018) investigated a model-based approach for detecting and identifying leakage in subsea BOP control systems using pressure measurements and a hydraulic system model.
For the proposed framework, pressure and flow rate are treated as directly measurable operating variables. Volumetric efficiency, leakage, and required power may be incorporated when they are available from measurements or can be estimated using an appropriate, documented model. Their inclusion does not imply that all five indicators are continuously measured in existing BOP installations.

Deviation assessment

The assessment procedure was formulated around the comparison of available operating information with an established reference condition. Such a reference may be derived from documented functional requirements, approved operating limits, baseline measurements, or previously established operating characteristics, depending on the available information.
Previously published optimized operating parameters may provide an additional reference for evaluating energy performance (Marković et al., 2025). However, an energy-efficient configuration is not considered sufficient evidence of functional integrity or compliance with safety requirements.
The proposed assessment distinguishes changes associated with different operating conditions from deviations that may indicate a need for further investigation. Therefore, operating parameters should be compared under equivalent or appropriately documented conditions whenever possible. Changes in pressure, flow rate, and required power are interpreted jointly rather than independently.
When a deviation is identified, the procedure requires verification of measurement validity and operating conditions before a possible relationship with component degradation is considered. No universal numerical thresholds or experimentally validated fault-classification criteria are introduced in the present study.

Development of the decision-support framework

The decision-support procedure was formulated by linking operational monitoring with diagnostic verification and maintenance planning. The approach follows a sequence consisting of data acquisition, assessment of operating conditions, deviation identification, diagnostic evaluation, maintenance decision-making, and subsequent verification.
The first stage involves collecting available operating information and establishing whether the observed conditions are suitable for comparison with a defined reference. In the second stage, deviations are identified and examined to determine whether they may be explained by changes in operating conditions or measurement-related factors.
Deviations that cannot be adequately explained are directed toward further diagnostic assessment. This stage considers possible hydraulic losses, changes in component performance, and the need for additional functional checks. The resulting information is used to support the selection and prioritization of appropriate maintenance activities.
The conceptual organization of the procedure was informed by the integration of condition monitoring and maintenance decision-making discussed by Catelani et al. (2020). Unlike their application to a wind turbine yaw system, the framework proposed here is specifically directed toward interpreting the operating and energy-performance indicators of hydraulic BOP control units.

The final stage involves recording the diagnostic findings, maintenance actions, and subsequent operating conditions to support future assessments. The framework is intended to complement established maintenance practices and does not replace mandatory testing, prescribed operating limits, or safety-related decisions.
The study does not report a new experimental campaign, field implementation, or validation of maintenance effectiveness. Accordingly, the proposed procedure is presented as a conceptual framework requiring further evaluation using operational monitoring data and documented maintenance records.

RESULTS AND DISCUSSION

The main outcome of this study is a conceptual decision-support framework that organizes information from hydraulic system monitoring into a sequence of maintenance-related assessments. The framework connects five operational and energy - performance indicators — pressure, flow rate, volumetric efficiency, clearance leakage, and required activation power — with reference-condition assessment, diagnostic verification, and maintenance planning. The selection of these indicators is based on the previously published investigation of the jaw-type blowout preventer (BOP) hydraulic activation system (Marković et al., 2025).
The proposed procedure is presented in Fig. 1. Its initial stage involves collecting available operating data and checking their validity and completeness. Operating conditions are then compared with documented reference conditions, taking into account differences in the operating regime. If no relevant deviation is identified, the procedure returns to routine monitoring. Otherwise, the deviation is examined to establish whether it can be explained by measurement errors or changes in operating conditions. Unresolved deviations are subjected to additional diagnostic verification before maintenance actions are considered.

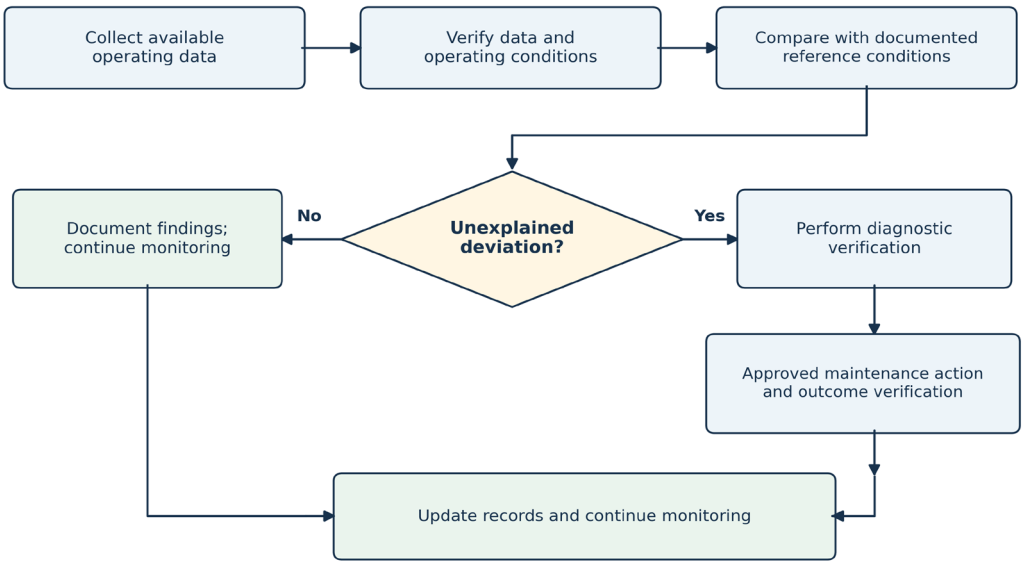


Fig. 1. *Proposed decision-support framework for condition-based maintenance of hydraulic BOP control units.*

An important feature of the framework is the separation of deviation detection from fault identification. An increase in activation power, for example, may reflect a change in operating pressure or flow rate rather than equipment degradation. Consequently, energy-performance indicators should be interpreted under comparable operating conditions and, where possible, together with additional hydraulic measurements. Previously published optimal operating parameters can support energy-performance comparisons, but they must not be treated as substitutes for approved functional requirements or safety limits (Marković et al., 2025).

Operational indicators and diagnostic interpretation

Table 1 presents the proposed relationship between selected operational indicators, possible deviations, diagnostic verification, and maintenance-related actions. The matrix is intended to guide the interpretation of monitoring data rather than provide a validated fault-diagnosis algorithm.

Table 1. *Conceptual interpretation of operational indicators and maintenance-related verification actions.*

Indicator	Deviation requiring assessment	Diagnostic verification	Maintenance-related response
Pressure	Departure from the documented reference range.	Check sensor validity, control settings, and hydraulic circuit conditions.	Investigate confirmed abnormalities and apply approved procedures.
Flow rate	Unexpected change under comparable operating conditions.	Verify flow measurement, pump operation, and possible losses.	Inspect relevant components if the deviation persists.
Volumetric efficiency	Reduction relative to a documented baseline.	Confirm the estimation method and assess possible internal losses.	Consider targeted inspection after verification.
Clearance leakage	Increase relative to the reference condition.	Verify measurement or estimation and investigate possible leakage paths.	Inspect or repair affected components as indicated by diagnosis.
Activation power	Unexpected change at comparable pressure, flow rate, and operating conditions.	Verify power data and jointly assess operating parameters and losses.	Initiate further diagnostics; do not infer a specific fault from power alone.

The matrix emphasizes the need for combined interpretation of the selected parameters. Pressure and flow rate establish the operating context, whereas changes in volumetric efficiency and clearance leakage may provide additional information about hydraulic losses. Required activation power represents an energy-performance indicator that should be assessed in relation to operating conditions. The relevance of hydraulic leakage monitoring to BOP control systems has also been addressed by Wassar et al. (2018).

The proposed framework extends the interpretation of these indicators from energy-performance assessment to maintenance decision support. Its specific contribution is the organization of monitoring, reference comparison, diagnostic verification, and maintenance planning into a single procedure for hydraulic BOP control units. The general integration of condition monitoring and maintenance decision-making is not new; for example, Catelani et al. (2020) investigated this relationship in the maintenance of a wind turbine yaw system. The present framework addresses a different application and focuses specifically on the operational indicators identified in hydraulic BOP activation research.

Applicability and limitations

The framework may provide a basis for structuring operational records and selecting additional diagnostic checks when unexplained deviations are detected. However, the present study does not demonstrate that its implementation reduces failure rates, maintenance costs, or downtime. No field data were used to establish diagnostic thresholds, validate fault identification, or quantify the effectiveness of the proposed maintenance decisions.
Future implementation would require reliable measurement or estimation of the selected indicators, documented reference conditions, maintenance and failure records, and validation under representative operating conditions. The proposed approach is supplementary to mandatory functional testing, approved maintenance procedures, and established safety requirements; any indication of compromised safety functionality must be addressed according to the applicable procedures rather than through energy-performance assessment alone.

CONCLUSION

This paper developed a conceptual decision-support framework for condition-based maintenance of hydraulic blowout preventer (BOP) control units. The proposed approach integrates operational parameter monitoring, energy-performance assessment, deviation identification, diagnostic verification, and maintenance planning into a structured procedure.
The main contribution is the organization of five operational and energy - performance indicators — pressure, flow rate, volumetric efficiency, clearance leakage, and required activation power — into a framework that links deviations from reference conditions with additional diagnostic checks and maintenance-related decisions. The developed flowchart and indicator matrix provide a systematic basis for interpreting available operating information. Particular emphasis is placed on distinguishing changes caused by different operating conditions from unexplained deviations that may require further investigation.
The framework is conceptual and has not been validated using field monitoring or maintenance records. Therefore, no conclusions can be drawn regarding its effectiveness in reducing failure rates, downtime, or maintenance costs. Future research should focus on establishing appropriate reference conditions, validating diagnostic criteria, and assessing the framework using operational and maintenance data. Its application must remain complementary to mandatory functional testing and established safety procedures.

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