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A Reliability Model Repository for Real-Time Well Integrity Management in Oil and Gas Operations

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Quantitative Risk Analysis (QRA) is essential for well integrity management, providing data-driven insights into current and future well conditions. This paper presents the Reliability Model Repository, a framework integrating multiple reliability data sources with real-time well monitoring to enhance operational safety and optimize performance. The repository employs statistical distributions, accelerated life-test models, structural reliability models, and machine learning to assess failure rates, track component degradation, and incorporate well characteristics, environmental conditions, and operational parameters. It also accounts for failure dependencies, such as cascading effects and common-cause failures (CCF), while supporting incomplete testing scenarios.
Additionally, two tools are introduced: ReliaWell and WellRAMS. ReliaWell optimizes well design by balancing reliability, production potential, and cost. WellRAMS focuses on the production phase, enabling real-time reliability monitoring, failure tracking, and predictive maintenance planning. Together, these tools help minimize unplanned downtime, reduce operational risks, and optimize maintenance strategies.
A case study demonstrates the framework's application by analyzing the impact of real-time well conditions on the failure rates of critical components: the Downhole Safety Valve (DHV), Production Tubing, and Production Casing. Results show how the Reliability Model Repository and its tools improve well integrity predictions, ensure compliance with Brazil's ANP-SGIP regulations, and enhance operational safety. The study further explores advanced modeling techniques, such as estimating Remaining Useful Life (RUL) and analyzing degradation effects, offering a data-driven approach to well integrity management across the entire well lifecycle.

Keywords: Reliability Model, Condition-Based, Well Integrity, Real-time Monitoring.

1. Introduction

Well Integrity Management Systems (WIMS) are essential for ensuring the safe and efficient operation of oil and gas wells, directly impacting operational safety, production continuity, and cost management. According to ISO 16530-1:2017, well integrity is maintained by controlling fluid movement through the application of well barriers, preventing unintended migration between formations or environmental discharge. To uphold well integrity, operators must implement a structured management system that aligns with corporate policies on health, safety, environment, and asset protection. Failures in well components compromise these safeguards, increasing operational risks, causing production losses due to unplanned downtime, and leading to significant maintenance costs associated with specialized interventions and high-value resources, such as intervention rigs.

Quantitative Risk Analysis (QRA) is a key methodology for evaluating well integrity risks, enabling the assessment of both the probability and consequences of failure events. To enhance decision-making, QRA utilizes reliability data to quantify potential well integrity failures, supporting proactive risk management. The risk assessment follows a structured framework, with risk analysis being a critical sub-process within the broader risk management cycle (Figure 1). This process involves system definition, threat identification, and risk estimation, followed by failure frequency and consequence estimation. Given the complexity of contemporary oil and gas operations, the integration of real-time monitoring and predictive failure modeling is indispensable for accurate risk evaluation. Further details on risk management can be found in ISO:3100 (2018). Additionally, the application of the ALARP (As Low As Reasonably Practicable) principle ensures that risk-reduction measures are implemented to a level where additional mitigation would result in disproportionately high costs, as outlined in ISO:16530-1 (2017) and Health and Safety Executive (HSE) (nd). By incorporating structured risk assessment frameworks, QRA strengthens well integrity management, minimizing risks to health, safety, the environment, and operational continuity.

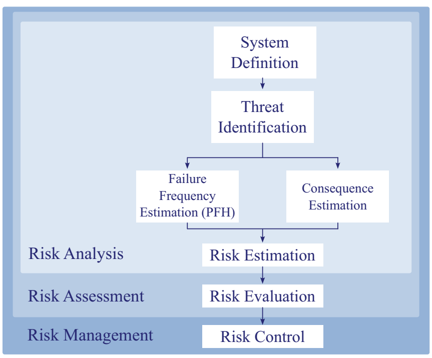

Fig. 1.: Structured Framework for Risk Assessment and Management. Adapted from Stephens et al. (2020)

Expanding on these concepts, this paper presents the development of a **Reliability Model Repository**, an integrated system designed to enhance well integrity management through data-driven risk evaluation. By combining reliability data sources with real-time condition monitoring, the repository applies diverse reliability models to dynamically assess and predict well integrity risks, as illustrated in Figure 2. Statistical distributions, accelerated life-test models, structural reliability models, and machine learning algorithms are employed to provide a comprehensive evaluation of well component reliability and failure rates, supporting proactive decision-making.

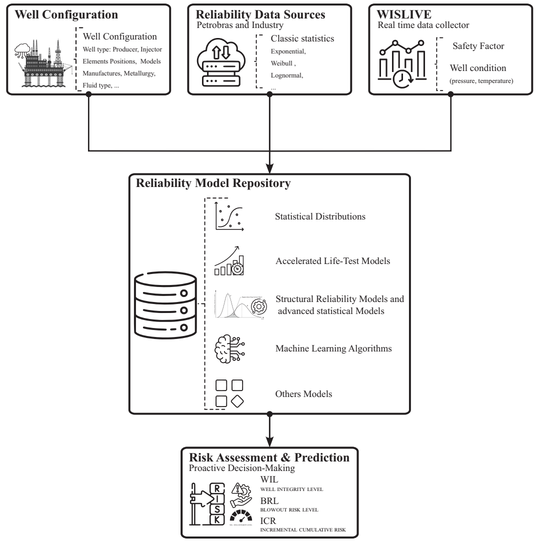

Fig. 2.: Schematic representation of Reliability Model Repository.

To further improve well integrity assessment throughout the well lifecycle, this study introduces two complementary tools — ReliaWell and WellRAMS.

- ReliaWell supports the design phase by optimizing well configurations based on reliability and operational cost considerations, while
- WellRAMS focuses on the production phase, monitoring component failures and optimizing maintenance planning.

A detailed case study will be presented in the Case Study Section (4), showcasing the practical application of these tools. It demonstrates their effectiveness in assessing well conditions, predicting failure risks, and enhancing operational safety. Furthermore, the study aligns with Brazil's Resolution No. 46/2016 - SGIP regulations Agência Nacional do Petróleo (2016), highlighting the critical role of structured reliability analysis in ensuring regulatory compliance and strengthening risk mitigation strategies.

2. Fundamental Theory

Reliability analysis has become essential in the oil and gas industry for enhancing operational safety and efficiency. Traditional reliability models, which often rely on historical failure data and statistical distributions, may struggle to capture the complexities of modern well operations. These complexities include the effects of degradation, interdependencies among system components, and the presence of non-binary failure modes, which are not always captured by standard models.

To address these challenges, Quantitative Risk Analysis (QRA) provides a systematic approach for evaluating risks related to well integrity. By assessing both the current and future states of components, QRA allows for a deeper understanding of potential failure scenarios. Advanced reliability models, such as those based on Remaining Useful Life (RUL) predictions, offer valuable insights into the degradation of components over time. These models are particularly instrumental in optimizing the operational life of wells and repurposing existing assets, thereby ensuring efficient resource management.

Furthermore, well integrity management in the oil and gas sector requires a comprehensive understanding of the well life cycle, which spans planning, drilling, production, and abandonment. Each of these phases presents unique challenges that must be addressed to maintain well integrity, ISO:16530-1 (2017). However, underlying these phases are common methodologies and principles of reliability and risk management that ensure a cohesive approach. Figure 3 provides a visual representation of this elements which are common among phases, and the relation between the phases (adapted from ISO:16530-1 (2017)).

A critical aspect of reliability modeling is the ability to capture dependencies between failures, such as cascading failures, common-mode failures, or the increased likelihood of failure in one component due to degradation in another. For example, the structural integrity of casing may be compromised if there is annular communication with the production tubing, leading to a significant

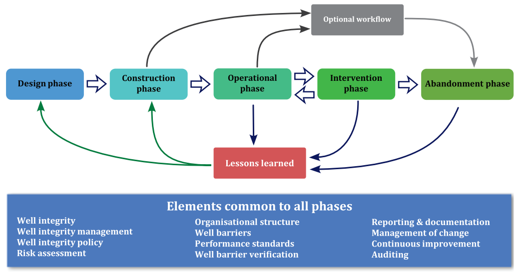

Fig. 3.: Well Integrity life cycle phases, adapted from ISO:16530-1 (2017).

impact on overall well reliability. This interconnected approach ensures that all potential risks are effectively managed across the well's life cycle.

3. Methodology of the Applications

3.1. *Reliability Model Repository*

The proposed Reliability Model Repository is designed to centralize and integrate various reliability models with real-time well monitoring data and historical reliability information. It supports dynamic evaluations of well integrity by combining:

- Classical probability distribution: simple models to determining the failure probability distribution based on historical data (ex. Weibull, exponential, Lognormal...)
- Accelerated Life Test Models: Models developed for considering the presence of covariates (ex. Pressure, Temperature, Flowrate, etc.), i.e., models able to adress component failure rate under different operational and environmental conditions. Besides that, it takes into consideration differente characteristics of the component (model, manufacturer, metalurgy, dimension...) and the well (injector/producer, type, etc.)
- Machine Learning Models: A especial class of models capable of modeling the failure rates considering different covariates and modeling complex relations that classical probabilistic models are not capable of handling (ex. ANN, SVR,

DeepLearning, RSF)
- Dependency models: can be coupled with the previous models but considers the dependancy of failures between components. Ex. Cascading failure models, Common cause failure models

The repository not only addresses scenarios where failure data is incomplete by incorporating partial testing methodologies but also serves as a model database designed to integrate with existing reliability analysis tools, such as the WellRisk suite, with MyBarrier, ReliaWell, WellRAMS, with future compatibility planned for other developments. As illustrated in Figure 4, the repository provides these tools with an array of time-dependent failure rates upon request. The applications querying the repository will specify parameters such as the time period, a particular equipment/failure mode, and relevant characteristics or scenarios. In response, the model database will return a corresponding failure rate vector.

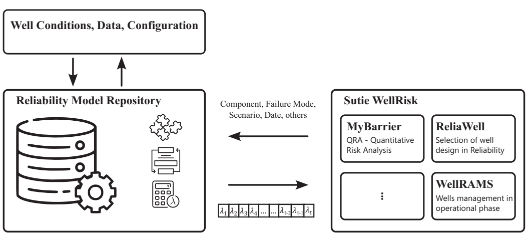

Fig. 4.: Model Repository Integration with Reliability Analysis Tools.

3.2. *ReliaWell and WellRAMS*

To complement the Reliability Model Repository, two tools — ReliaWell and WellRAMS — are being developed, each address to specific stages of the well lifecycle. Both tools share the same computational engine, with ReliaWell being the more advanced in terms of development. Their key characteristics are described below:

- **ReliaWell:** Designed for the well design phase, this tool assists engineers in evaluating and selecting configurations that maximize performance and reliability. It calculates key integrity and production indicators, including maintenance costs (rig, services, equipment), operational expenditures (OPEX), production losses, production efficiency (losses and outages), Riskex, and Well Integrity Level (WIL). By employing Monte Carlo simulations to model failure and maintenance dynamics, ReliaWell supports data-driven decision-making on well structure, material selection, and intervention strategies, ensuring an optimal balance between cost, risk, and operational efficiency before field implementation.
- **WellRAMS:** Applied during the operational phase, WellRAMS assesses reliability, maintenance, and risk indicators based on the well's operational history. Unlike ReliaWell, where configurations are being defined, WellRAMS works with an already selected well design, analyzing real-world performance by tracking equipment failures, replacements, and component aging. This tool combines RAMS (Reliability, Availability, Maintainability, Safety) analysis with LCCA (Life Cycle Cost Analysis) to provide insights into performance, maintenance costs, and safety. Additionally, WellRAMS enables platform-level management by aggregating data from all wells connected to the same infrastructure, allowing for drill-up analyses that consolidate performance indicators at the platform level while maintaining integration with reservoir simulations.

Figure 5 illustrates the distinction between the applications of ReliaWell and WellRAMS. ReliaWell is applied during the well design phase, where the figure depicts the possible life paths of a given well configuration under different failure and maintenance events throughout its simulated lifespan across multiple Monte Carlo realizations. These varied scenarios enable the extraction of key performance indicators related to well configuration, integrity, and production. Conversely, WellRAMS is used in the operational phase, where the figure highlights the actual path taken by a well based on historical data. This historical information, including equipment failures, workovers, and component aging, is crucial for RAMS simulations projecting future performance from the current operational state (t = today) onwards. By incorporating these parameters, WellRAMS allows for the assessment of performance indicators, average maintenance costs, safety metrics, and overall reliability. Additionally, it supports platform-level management by aggregating well-specific indicators, ensuring seamless integration with reservoir simulations for a comprehensive operational analysis.

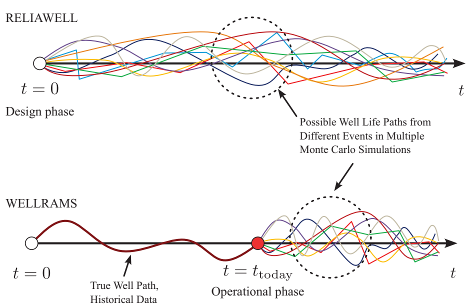

Fig. 5.: Comparison of ReliaWell and WellRAMS Applications in Well Design and Operation.

Both tools incorporate the company's existing maintenance policies, with the flexibility to adopt a risk-based approach. This includes the Well Integrity Level (WIL) framework and Incremental Risk Cumulative (IRC), which accounts for accumulated risk following a failure. By integrating failure profiles, testing and maintenance strategies, and real-time monitoring data, these tools ensure a comprehensive and data-driven approach to well integrity management.

4. Case Studys

4.1. *ReliaWell Case*

The first case study applies reliability modeling to assess the performance of Downhole Safety Valves (DHSVs) from three manufacturers. A machine learning-based framework was employed to analyze failure and censored data, incorporating covariate dependencies. Initially, a regression model estimated the effect of covariates on failure time distribution while accounting for censored data through a custom loss function. The adjusted failure times were then used in a non-parametric reliability estimator (Kaplan-Meier). A second regression model was applied to obtain a smoothed reliability curve, as illustrated in Figure 6.

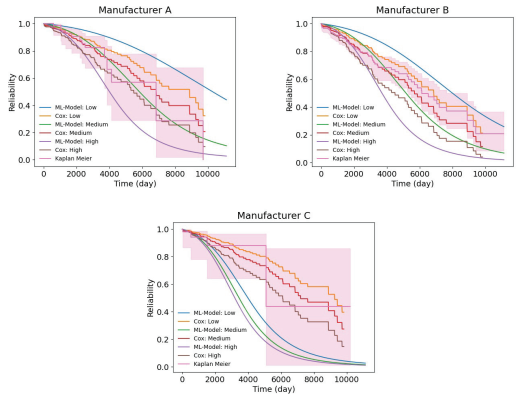

Fig. 6.: Reliability Estimation of Downhole Safety Valves Using Machine Learning-Based Failure Modeling.

Once the reliability functions were determined, they were integrated into ReliaWell, a risk evaluation and analysis tool within the model repository framework. ReliaWell directly utilizes time-dependent reliability data of well components to assess key indicators—such as Well Integrity Level (WIL), Blowout Risk Level (BRL), and the probabilities of integrity loss and blowout—further analyzed in Figures 7 to 11. In addition to integrity-related indicators, the model also incorporates metrics associated with production losses, as illustrated in Figure 10, which depicts the probability of production loss. These reliability-driven insights can be linked to maintenance costs, operational expenditures, production efficiency, Riskex, and other performance metrics. Table 1 specifically presents the impact on downtime, demonstrating the influence of reliability modeling on operational availability.

This approach enables a data-driven assessment of well reliability and its implications for strategic decision-making.

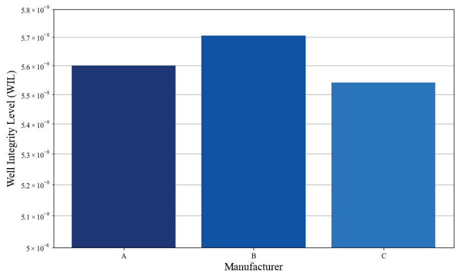

Fig. 7.: Well Integrity Level by Manufacturer.

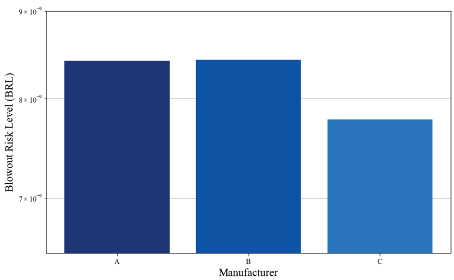

Fig. 8.: Blowout Risk Level by Manufacturer.

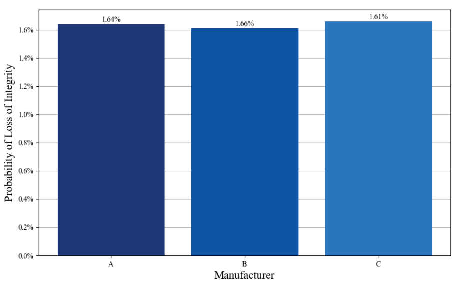

Fig. 9.: Probability of Loss of Integrity by Manufacturer.

The analysis indicates that despite the differences in survival curves among manufacturers, Figure 7), the Well Integrity Level (WIL) and Blowout Risk Level (BRL) remain within the same order of magnitude. Data fitting modeling confirms that the failure rate follows the relationship Manufacturer $C < A < B$, which is reflected in the reliability indicators, such as WIL and the probability of integrity loss (Figures 8-to–11). This result highlights the tool's capability to convert different system configurations (component variations) into quantifiable performance indicators, making them valuable for decision-making.

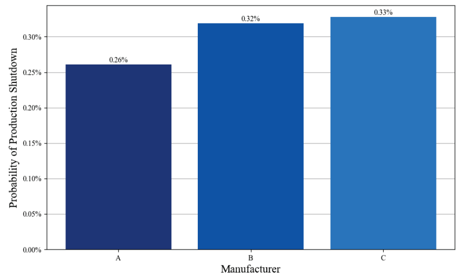

Fig. 10.: Probability of Production Shutdown by Manufacturer.

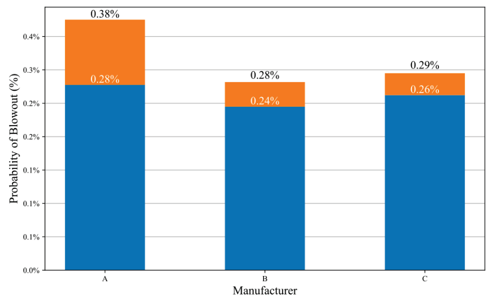

Fig. 11.: Probability Blowout by Manufacturer.

Table 1.: Expected Downtime Throughout the Productive Lifecycle (days).

	Manufacturer		
Downtime Trigger	A	B	C
Integrity Repair	419.3	154	138
Production Repair	2.7	3.0	3.1
Production and Integrity Repair	12.6	8.7	8.2
Production Failure	31.2	39.2	37.3
Total	465.5 ± 2.8	204.9 ± 2.8	186.6 ± 2.6

Additionally, the downtime values presented in Table 1 represent the median values for different downtime triggers, while only the total downtime includes the confidence interval. These results indicate that, for the selected well configuration, the average downtime values and their associated uncertainty ranges remain consistent across manufacturers, providing a reliable basis for operational planning and management. This further demonstrates the tool's ability to deliver data-driven insights for optimizing well design and maintenance strategies.

4.2. *Reliability Model Repository Case*

The second case study represents a proof of concept (PoC) for applying the Reliability Model Repository to assess the integrity of a production well. The analysis focuses on three critical components: the Downhole Safety Valve (DHSV), Production Tubing, and Production Casing. Using simulated condition data, the repository employs advanced reliability models to evaluate key aspects of well integrity, particularly in estimating failure rates based on monitored parameters and component degradation trends. The PoC utilizes a structured approach to determine failure probability distributions, incorporating the following models:

- **Penalty Rule Tables:** A rule-based framework that assigns penalty factors to components operating outside their designed conditions, adjusting failure probabilities accordingly.
- **Multivariate Statistical Models:** Advanced statistical techniques that establish correlations between multiple operational parameters and failure likelihood, improving predictive accuracy.
- **Classical Probability Distributions:** Fundamental probabilistic models that estimate failure distributions based on historical data, including Weibull, exponential, and lognormal distributions.

To illustrate the repository's structure and functionality, Figure 12 presents the main interface developed in PoC. In this interface, users can create a project and associate its components with pre-registered models linked to specific equipment. As structured in this PoC, the DHSV is associated with both multivariate statistical models and classical probability distributions, while Production Tubing and Casing are linked to Penalty Rule Tables and classical models, as described above. It is important to note that, in this PoC, failure rate vectors were not consumed by client applications, such as risk analysis tools (ReliaWell, or MyBarrier).

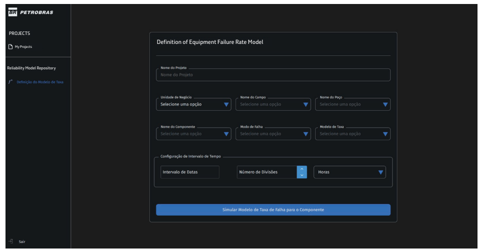

Fig. 12.: Main Interface of the Reliability Model Repository PoC.

Furthermore, Figure 13 provides examples of model outputs, showcasing results from Penalty Rule Tables applied to casing (b), multivariate statistical models for the DHSV (a). These results demonstrate how the failure rate, represented by the hazard function $\lambda(t)$, dynamically varies based on well conditions. This adaptability highlights the model's capability to refine reliability predictions in response to operational parameters, reinforcing the repository's potential as a decision-support tool for well integrity management.

The results demonstrate that this proof of concept provides a structured framework for predicting failure rates, optimizing maintenance planning, and reducing unplanned downtime. While not yet deployed in a real-world scenario, the methodology highlights the potential of the Model Repository to enhance operational safety, regulatory compliance, and cost efficiency. This study reinforces the repository's capability as a decision-support tool for well integrity management.

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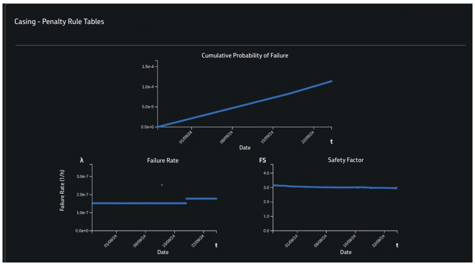
(a) Failure rate variation for the DHSV model.



(b) Failure rate variation for the casing model.

Fig. 13.: Example Outputs of Reliability Models Applied to Well Components.

mitment to advancing reliability modeling and well integrity analysis.

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References

Agência Nacional do Petróleo, G. N. e. B. (2016, December). Resolução anp n° 46/2016. National Regulatory Resolution. Available at: https://www.gov.br/anp/pt-br/.

Health and Safety Executive (HSE) (n.d.). Risk management: Alarp explained. Acessado: 2025-02-01.

ISO:16530-1 (2017). Petroleum and natural gas industries – well integrity – part 1: Life cycle governance. ISO Standard. Accessed: 2025-02-23.

ISO:3100 (2018). Risk management — guidelines. Acessado: 2025-02-01.

Stephens, M., S. Koduru, J. Vani, T. Paxman, and C. Wright (2020, September). Final report: Risk assessment and treatment of wells. Prepared for Pipeline and Hazardous Materials Safety Administration. Prepared by C-FER Technologies. Reviewed by Maher Nessim, PhD, PEng, FCAE. Copyright © 2020.