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Quantifying Refinery Reliability and Availability

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Introduction

Over the past ten years, an integrated, international energy company experienced a significant drop in plant-wide availability at one of its larger refineries. Plant leadership identified the hydrocracker unit as one of the primary contributors to the drop in availability and focused efforts on improving that unit. The plan, which had a goal to maximize the availability of the hydrocracker, included a series of asset management improvement initiatives, capital upgrades, and performance improvement plans.

After the initiatives were completed, plant leadership remained uncertain that these activities would actually help them achieve their availability goals. While the plant had implemented a risk-based inspection (RBI) program for its fixed equipment and a reliability centered maintenance (RCM) study for its critical machinery, these efforts seemed subjective and overly conservative, and provided a static view of equipment reliability. As a result, these methodologies were not capable of sufficiently quantifying results that would provide plant leadership with the confidence that the availability improvements they were seeking would be realized.

Plant leadership asked: "Should we be doing more? Are we spending too much? Can we be certain that the actions we are taking are worth the investment? How can we be more confident that the planned maintenance, monitoring and repair, replace, and upgrade activities are worth the investment and will ensure a step change in availability?"

Quantitative Reliability Optimization

The plant needed a solution that would help them better evaluate equipment risk and predict future availability, so plant leadership decided to pilot Quantitative Reliability Optimization (QRO). QRO is a data-driven methodology that combines the best traditional reliability methodologies with data science principles and subject matter expertise (SME), enabling plants to drive and improve complex reliability decision-making. This approach blends the risk assessment of both fixed and non-fixed assets into a single model, removes data silos, and provides plants with insights to reduce unplanned downtime, increase safety, and improve spending performance with statistically supported confidence. Just as the industry evolved its approach to assessing risk with methodologies like RBI and RCM, QRO is the next advancement of reliability modeling.

QRO provides four major benefits to facilities:

1. The ability to predict future availability by leveraging existing data.
2. Accurate forecasting of probability of failure (POF) and consequence of failure (COF) for both fixed and non-fixed assets in the same methodology.
3. Facilities with limited data can use industry analytics and subject matter expertise to build and inform the data models for facilities.
4. The ability to update predictive models in real-time with live data connections including process, monitoring, work order, and task data, which allows risk and mitigation plans to remain evergreened.

QRO Pilot Implementation Process

The QRO pilot implementation occurred in three phases:

Phase 1: **A unit or complex that aligned with plant objectives was identified and leveraged to create a unit model. Baseline risk and availability for the plant's current tasks were calculated.**

Phase 2: **The analysis was updated and modeled with future planned tasks to determine future reliability performance.**

Phase 3: **An optimized inspection, maintenance, and monitoring task and activity plan that met defined criteria for risk, availability, and cost was created.**

Phase 1

During this phase, the plant's hydrocracker unit was evaluated, and a critical depentanizer bottoms system was identified as an area with historical reliability issues. The depentanizer system was selected for in-depth analysis to assist the plant in:

- taking a step toward a quantifying validation of recent repair, replace, and upgrade initiatives,
- identifying additional activities to further improve reliability, and
- removing unnecessary tasks.

Asset Register and Unit Model

Next, an asset register with all critical assets was loaded into a reliability software that facilitates QRO and a unit model was created to identify the asset interdependencies of the fixed and non-fixed assets. This model, which set the foundation for plant-wide reliability analysis, calculated the unit-level baseline availability,

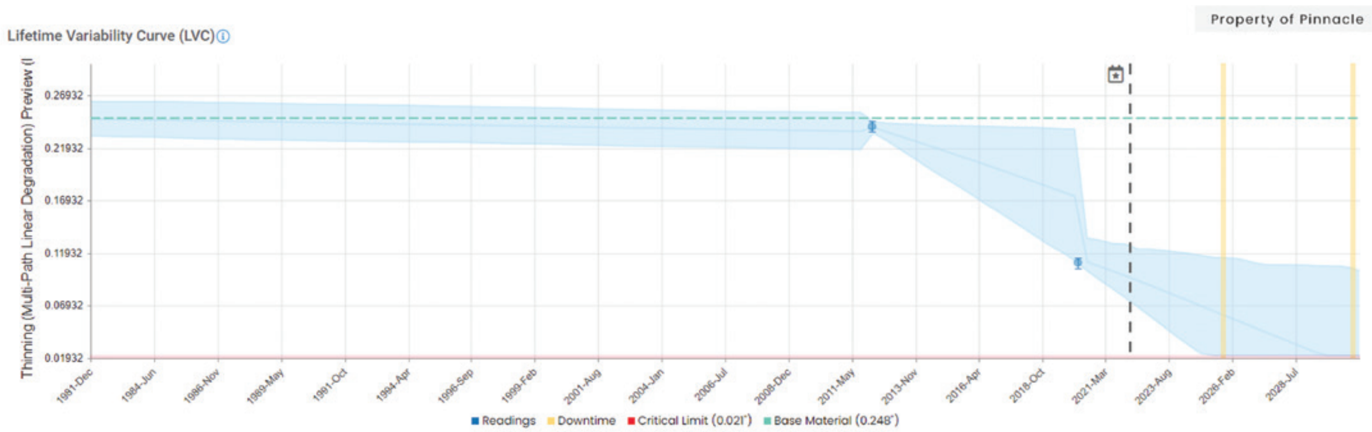

Figure 1. Example of a thinning LVC for one piping CML in the depentanizer bottoms system. This LVC indicated that failure would likely occur between turnarounds (indicated by the vertical yellow bands), however some potential for failure exists before the next turnaround. QRO models can prioritize an inspection activity for this CML to verify the asset's condition and update the uncertainty.

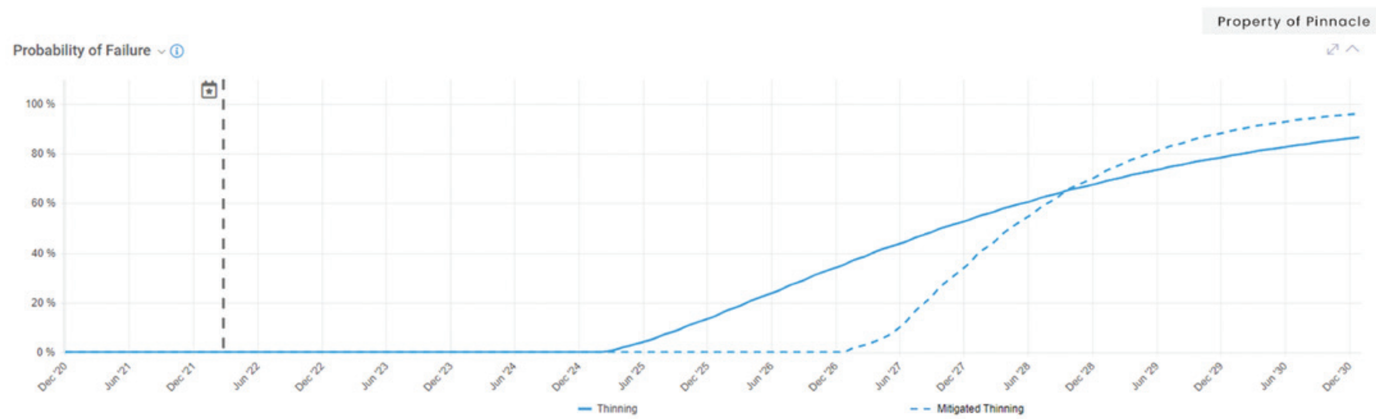

Figure 2. A POF curve for the piping CML in **Figure 1** that identified the CML most likely to fail to represent the piping line number.

risk, and costs by leveraging the assets' current mechanical, operating, design, and historical inspection and task data. While typically performed on a unit level, this modeling can also be performed for a full plant.

Asset Risk Analysis

Following the unit model creation, an asset risk analysis (ARA) was developed using the unit drawings, inspection data, maintenance tasks, monitoring activities, failure experience, and cost/spend data. An ARA integrates first principles engineering analysis and asset data with field execution limitations and operational constraints to create a cause-and-effect link between all assets' functions, failure modes, and failure mechanisms.

For this pilot, the ARA assessed the risk of each asset in the depentanizer bottoms system. The ARA evaluated all available asset data and calculated the probability of failure (POF), consequence of failure (COF), estimated failure dates, risk, and availability over time to properly assess risk. Additionally, the functions, failure modes, and failure mechanisms for each asset were identified or loaded from existing RBI and RCM assessments.

Lifetime Variability Curve

Next, the component's POF was calculated for the assigned failure modes to generate lifetime variability curves (LVCs). An LVC is a dynamic model that predicts POF over time through the application of data science principles, subject matter expertise, and historical plant data.

Using the LVCs, failure was defined by the probability of achieving a specific asset condition, such as the asset reaching a specific thickness in the case of thinning. The LVC models were updated as new inspection and test or monitoring data was provided, which resulted in an improved POF prediction over time. The component's COF was calculated by combining API RP 581 methods with QRO model algorithms, and leveraged health, safety, environment (HSE) data, maintenance costs, and production losses.

Accurate reliability modeling depends on trustworthy sources of historical data. In this pilot, one to two historical thickness readings were available for the majority of the plant's fixed assets. Even with little or no historical inspection data, the LVC models were able to forecast the failure dates of condition monitoring locations (CMLs). In this case, the LVC model applied an increased uncertainty band to the expected thickness and adjusted the uncertainty as additional inspection data was provided. If the additional inspection data agreed with corrosion rates assigned by the plant's SMEs, the uncertainty was reduced. If the inspection data differed (either higher or lower) from corrosion rates assigned by SMEs, the uncertainty was increased. Opportunities for risk reduction or improved reliability through inspection were prioritized and gained by reducing uncertainty in the assets'

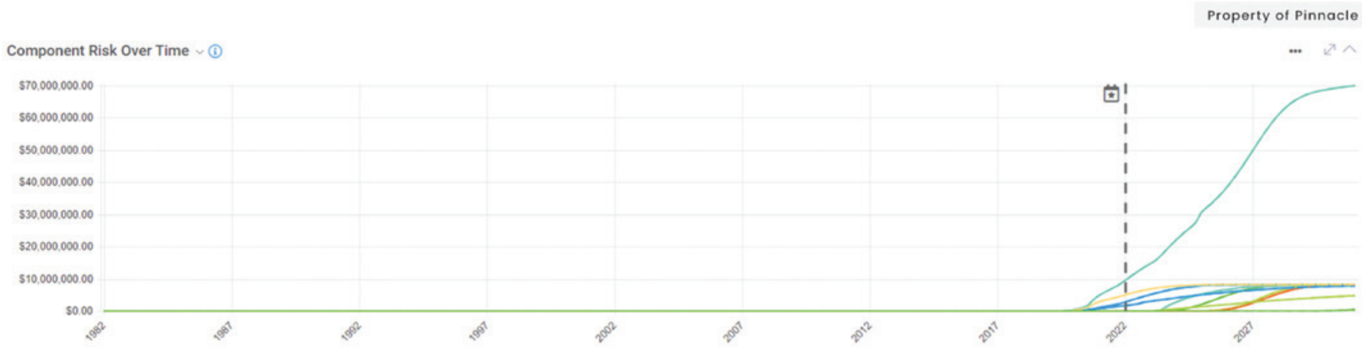

Figure 3. Consolidated failure risk curves for all piping line numbers in the circuit. These curves provided a visual representation of the forecasted risk for each line number in the circuit and highlighted the CMLs and piping line numbers driving risk in the circuit.

condition. **Figures 1-3** are examples of an LVC for thinning.

Phase 2

Phase 2 dove into the details of asset maintenance, inspection, repair, and replacement history and combined the asset interdependencies in the unit model with the individual asset risk from Phase 1. The deeper analysis with historical data established a more accurate baseline risk, availability, and cost forecast for the unit. Additionally, this phase provided recommendations for managing the asset activities that will provide the greatest impact on overall unit risk and availability as opposed to managing risk on an asset-by-asset basis.

During this phase, available historical data (extracted from the plant's IDMS, CMMS, other inspection reports, data historian reports, and design documents) was combined with future planned inspection activities, tasks, and work orders (extracted from the CMMS). The asset interdependencies in the unit model combined with the ARA, POF, and COF for each individual asset established in Phase 1 were rolled up to the depentanizer bottoms level along with the forecasted availability and spend over the next 10-year period. The forecasted availability included the calculated potential impact of failure on the plant's production, as well as repair costs and durations that had been validated by the site. QRO predicted when repairs would need to be completed and also accounted for the impact of the planned activities on the plant's risk and availability.

The analysis in this phase calculated the baseline for an anticipated availability of 98.9% over the next ten years for the depentanizer bottoms system. While the projected baseline availability for the unit was high, several potential loss of containment (LOC) events before the next turnaround were identified—specifically, a potential outlet nozzle failure and associated carbon steel piping. Additionally, the analysis identified a potential reliability exposure of a pump, configured as a shared spare. Despite the high baseline availability forecast, the plant would need to perform certain activities to prevent unplanned failures between scheduled turnarounds. Furthermore, plant leadership wanted to identify any significant, non-value-adding activities to be considered for elimination.

Phase 3

In Phase 3, the QRO model compared the impact of the plant's existing inspection and task plan with an optimized plan to identify opportunities for the plant to achieve similar or improved availability and spending performance. The constraints for risk, availability, and cost were also defined to obtain the recommend plan required to achieve the targeted availability level without increasing risk or cost. For the depentanizer bottoms system, the constraints were defined for the model to produce a plan, or specific set of tasks, that would increase the availability as much as possible without exceeding the plant's spending forecasts.

The optimized plan included a comparison of the impact of unplanned outages by identifying the spending that would be needed to replace the component or asset in the pre-failure planned outage. Replacement-in-kind of the component or asset is recommended if there is a return on investment to perform that action.

Figure 4 shows the comparison of the baseline availability for the depentanizer bottoms system versus the optimized system availability using tasks recommended by QRO.

Results

After piloting the QRO methodology for the depentanizer bottoms system, plant leadership was able to validate recent activities, prioritize existing tasks, and identify new activities and tasks.

Validate recent activities

QRO was able to validate that the recent plant improvement activities created the desired step-change in availability compared to historical availability. While plant leadership expected to see a lower availability than forecasted given the historical poor performance in the depentanizer bottoms system, recent repairs, replacements, and upgrades had significantly improved forecasted availability.

Identify new activities

QRO identified asset or component replacement and upgrade activities that would improve system availability by an additional 0.9% over the next ten years in the depentanizer bottoms system alone. This improvement would result in an increase of $3.29MM profitability. To realize this profitability improvement, predicted failures were first recommended for replacement-in-kind during the upcoming turnaround to either mitigate HSE impact or minimize the economic impact. These in-kind replacement

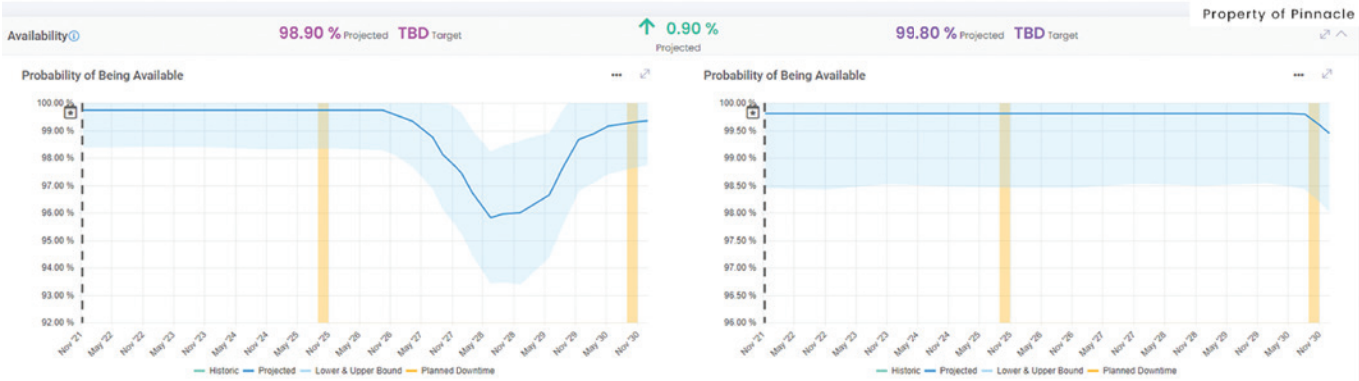

Figure 4. Comparison of forecasted availability for the depentanizer bottoms. While recent activities in the depentanizer bottoms system have significantly improved the forecasted availability, QRO identified additional activities that can be performed for further improvements.

recommendations were reviewed by the pilot team to identify where upgrades would be more beneficial. For example, QRO identified a system nozzle and associated piping that needed to be replaced in kind at the next turnaround that was not previously identified by site personnel. A more detailed investigation revealed that a material of construction upgrade would provide greater value, so the team recommended that the plant implement the upgrade at the next turnaround.

In a second example, the plant had identified a piping section for replacement due to recent accelerated corrosion rates. QRO demonstrated that there was a wide range of uncertainty in the predicted failure date due to an insufficient amount of data that was needed to accurately assess the failure rate reliably. As a result, it was recommended that the replacement plans be postponed, and additional inspections be performed over time to better assess the damage rates and define the process drivers of the corrosion. Once sufficient data becomes available, an informed decision for replacement-in-kind or a material of construction upgrade, as well as the recommended material, is required for improved availability.

Prioritize existing tasks and identify new tasks

With QRO, the plant has the ability to objectively prioritize and plan preventive maintenance, monitoring, and inspection tasks with a higher degree of confidence and value. The recent RBI implementation, combined with a significant lack of historical data, identified a large percentage of fixed equipment and piping in this system circuit as high risk. This resulted in an extensive and costly list of inspections that needed to be performed, which required leadership to consider semi-subjective judgment to set the task priorities. The plant leveraged QRO to better identify and increase the priority of the tasks with the greatest impact on the plant's reliability, reducing the uncertainty of the future availability. As a result, the plant remains compliant with corporate policy and governmental regulations during its transition to RBI while also effectively balancing cost and risk.

QRO identified 100 additional preventive maintenance, monitoring, and inspection tasks for the depentanizer bottoms that would further increase availability while removing unnecessary, non-value adding tasks. The cost savings offset the cost increases associated with the added task recommendations and resulted in lower risk and improved reliability.

Additionally, QRO identified a potential cost savings of $260,000 in maintenance and inspection spending over the next ten years for the depentanizer bottoms system. If extrapolated across the entire hydrocracker, an estimated cost savings of $4MM over ten years could be realized. However, due to regulatory requirements setting maximum internal inspection frequencies, a portion of those cost savings will not be recognized.

Conclusion

By conducting a QRO pilot for the depentanizer bottoms system within the hydrocracker, plant leadership was able to establish a dynamic cause and effect link between every data point in a system of assets, along with the estimated the impact of their decisions. Additionally, the pilot provided the team with a model that calculated the impact of each asset, component, or data point on the unit's long-term availability and performance, and ultimately, demonstrated that the plant has the opportunity to improve its availability and reduce its risk without increasing spend.

The next steps of the pilot include:

1. Conducting the same level of analysis on the entire hydrocracker unit.
2. Calculating the return on investment for prior replacement and upgrade tasks to provide an objective confirmation of recent improvement activities.
3. Creating revised work processes for instances where QRO can be utilized to provide a higher quality, more efficient outcome for processes such as process hazard analyses (PHAs), damage mechanism review (DMR) revalidation and risk review, criticality analyses, and turnaround planning.

QRO's functionality and available quantitative models will continue to be improved to effectively evaluate and analyze the impact of process conditions on damage susceptibility and degradation rates. Additionally, live connectivity with other software databases, including CMMS, IDMS, RBI, vibration monitoring platforms, real-time thickness monitoring, process historian, P&IDs, and PFDs, will allow the model to automatically update as more data becomes available. Live connectivity will also allow the plant to quantify the impact of any inspection or maintenance task on the overall risk, cost, and availability of the unit on a real time basis, providing the plant with the information they need to drive better reliability decisions.

As the plant continues to implement QRO, plant leaders will be able to:

1. Evaluate the impact of fixed and non-fixed assets and components on the plant's risk, availability, and cost within a single platform. This evaluation will allow plant leadership to directly compare the activities for fixed and non-fixed assets instead of having to manage two separate models.
2. Evaluate the impact of the interconnectivity of assets and components, which will allow plant leadership to develop a better understanding of the impact of spared assets, partial operation impacts, and potential upstream or downstream effects of failures.
3. Have access to a single platform that includes the benefits of both RCM and RBI programs, which will allow the data used to develop these programs to be leveraged in QRO for further value.
4. Quantify the impact of an asset's failure on availability, which will provide the calculation of long-term availability with time, risk, and the cost of risk management. Additionally, QRO will help the plant identify the activities required to achieve its availability targets.
5. Quantify uncertainty in models based on available data through LVC models that dynamically update as more data is provided. These LVCs incorporate both an SME-expected degradation and actual inspection and test results to calculate a statistical uncertainty based on data agreement/disagreement.
6. Identify and update inspection and test points that have the greatest impact on risk and availability by prioritizing individual data monitoring locations, such as CMLs, and identifying the CMLs representing the greatest risk of failure for inspection.
7. Provide cost/benefit of various activities where the cost of improvements can be quantified. This will allow the plant to compare various scenarios such as the comparison of the baseline plan against an optimized plan driven by defined risk, availability, and cost constraints.
8. Balance equipment risk, cost, and availability—which will provide a balanced approach to managing risk while achieving high availability targets with optimized costs.
9. Provide long-term value for incremental costs needed to maintain and update a data-driven program. ■

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