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Towards Seamless Interoperability: Verification and Validation of Drilling Automation Features in a Controlled Environment

P. Arévalo, J. Köneke, F. Schuberth, S. Wessling, and D. Dashevskiy, Baker Hughes, Germany; M. Lien and S. Hovda, Equinor, Norway; M. Orevik, NOV, Norway

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Abstract

Drilling automation has emerged as a transformative force in the oil and gas industry, revolutionizing traditional drilling operations to enhance efficiency, safety, and cost-effectiveness. Central to its successful implementation are robust verification and validation (V&V) processes, which ensure the reliability, accuracy, and safety of automated systems. This paper explores the V&V of applications deploying wellbore protection and drilling optimization Advisors integrated with automated drilling control systems (ADCS).

Drilling automation applications performing wellbore protection (e.g., pack-off, hookload, over-torque, among others) and drilling optimization functions (e.g., rate-of-penetration (ROP) optimization) are deployed on an edge device connected to an automated rig control system (ADCS). The Advisors parameterize existing capabilities of the ADCS to carry out protection and optimization tasks. The interplay between Advisors and the ADCS is evaluated using a simulated rig environment at different levels: system integration test (SIT) and hardware-in-the-loop (HIL). A variety of test cases are executed to assess how each Advisor performs in conjunction with the ADCS and how stable the integration is under both normal and contingency conditions.

Each Advisor performs a self-assessment of its readiness to execute its function safely. The ADCS determines how to assign control of rig activities based on the availability of Advisors. The first layer of V&V, using SIT, simulates surface and downhole sensor signals that are ingested by the Advisors to test the interoperable system. The second layer, using HIL, generates sensor signals via actual programmable logic controllers (PLCs) to achieve a more realistic representation of the rig site. A series of tests enables a thorough assessment of whether each interoperable function between Advisor and ADCS meets design requirements (verification). Furthermore, the execution of these tests in the presence of multiple stakeholders (i.e., operators, drilling contractors, service companies) ensures that the systems perform as intended under real-world conditions (validation). Given the high stakes in drilling operations—including financial risks and environmental concerns—a comprehensive V&V framework is essential.

With this approach, potential flaws are detected early in the process and can be resolved during the development phase. This paper presents a summary of the test cases executed for each Advisor across all rounds of testing, along with the corresponding learnings toward achieving seamless interoperability at

the rig site. All tests were witnessed by multiple stakeholders representing operators, drilling contractors, service companies, and even assurance and risk management auditors.

Defining Common Ground: The concept of Levels of Automation

Drilling automation has evolved from a competitive advantage to a critical capability in modern well construction operations. Automation is applied across various levels and domains—from rig floor operations to subsurface environments. This diversity in application and deployment scenarios presents challenges in objectively analyzing, comparing, categorizing, and verifying each solution. To address this, a taxonomy based on Levels of Automation (LOA) provides a standardized framework for analysis and subsequent verification and validation (V&V). In well construction, the most recent work on levels of automation taxonomy (LOAT) by (De Wardt, et al. 2024) offers a valuable reference. LOAT also delineates the boundary between automation and autonomy, clarifying the distinction between these often-interchanged concepts. Fig 1 presents an adaption of LOAT.

	LOA	Human to System Interface	Information Acquisition	Information Analysis	Decision and Action Selection	Action Implementation
Humans	0	Whole task done by human except for actual operation by machine	Manual	Memory Analysis	Human Decision	Manual Action & Control
	1		Non-Software Artefact Supported	Non-Software Artefact Supported	Non-Software Artefact Supported	Non-Software Artefact Supported
Automation	2	Human ask computer to suggest options and selects...	Low-Level Automation	Low-Level Automation	Automated Decision Support	Step-by-Step Action Support
	3	System proposes options to human who selects option	Medium-Level Automation	Medium-Level Automation	Rigid Automated Decision Support	Low-Level Action Execution Support
	4	System generates and selects options and informs human	High-Level Automation	High-Level Automation	Low-Level Automation	High-Level Action Execution Support
	5		Full Automation	Full Automation	High-Level Automation	Low-Level Action Sequence
Autonomy	6	System chooses action and executes with human supervision	Full Automatic Information Acquisition	Fully Automatic Information Analysis	Full Automatic Decision Making Generation of options and decision selection	Low-Level Autonomous
	7	Computer exhibits autonomous traits (managing uncertainty, perceiving its environment, making decisions)				Medium-Level Autonomous
	8	It acts alone or in cooperation with other computers and humans				Full Autonomous

Figure 1—Levels of automation taxonomy (LOAT). Adapted from (De Wardt, et al. 2024)

Assigning LOA to Drilling Automation Applications

Using LOAT, drilling applications can be assigned a specific LOA to simplify understanding, comparison, and V&V requirements:

- Rig Floor Automation (LOA 2–3): Applications such as automated drill pipe handling (Whatley, et al. 2022) execute predefined sequences and manage interruptions within simple decision workflows. These systems operate with limited environmental awareness and decision-making complexity.

- Auto-Drillers (LOA 3–4): Widely deployed by drilling contractors and ADCS, auto-drillers control on-bottom drilling via stable weight on bit (WOB) or rate of penetration (ROP). Though they operate automatically, their environmental awareness is limited, constraining their decision-making scope. Nevertheless, auto-drillers operate automatically in the sense of controlling surface equipment, such as top-drive and draw-works to apply corrections based on feedback coming from the process. Literature by (Barajas, et al. 2023), (Chhantyal and Padir 2025) among others explores their setup and performance benefits.
- Passive Well Protection (LOA 3-4): Applications such as trip speed and flow rate limiters (Arevalo, Becker, et al. 2023) dynamically calculate limits to maintain wellbore and equipment integrity. These limits are applied to the rig equipment by the ADCS, which applies them to rig equipment to ensure safe operations—such as controlling the drill pipe tripping speed to remain within a defined safe operating envelope (SOE).
- Slide Drilling & Tool-Face Orientation Control (LOA 4–5): These applications estimate build-up rates and tool orientation using downhole data (e.g., inclination, azimuth, gravity, magnetic tool-face). Once activated by a human, they generate and select options for execution, informing the driller without requiring approval (Boone, Papouras, et al. 2021).
- ROP Optimization (LOA 5): Operating outside the ADCS, this surface-deployed application uses surface and downhole data to suggest optimal WOB and RPM parameters to auto-drillers. It interfaces with the ADCS to control drilling with the objective of mitigating downhole vibration and optimizing on-bottom drilling, elevating the driller to a supervisory role. Its independent decision-making and process awareness justify a LOA 5 classification.
- Fault Detection, Isolation, and Recovery (FDIR) Applications (LOA 4): Safety-focused applications such as stick-slip, overpull, and pack-off mitigation detect hazards and execute predefined mitigation steps. While they require activation by a user, they operate automatically within static or dynamically calculated boundaries. Taking overpull mitigation as example, a static limit is a fixed boundary part of the drilling program, while a dynamic limit is calculated based on equipment and process integrity. The estimation of dynamic limits requires more information about the environment at surface and downhole. In either case, when an overpull limit is reached, the application indicates the hazard to the driller and monitoring specialists and then engages into pre-defined mitigation actions to counteract the overpull situation. FDIR applications (Cayeaux, et al. 2023) can involve complex decision-making and execution that do not require the involvement of the user other than to activate such features. Nevertheless, the execution steps are pre-defined and not dynamically generated. Hence the LOA of 4.

Transitioning Toward Autonomy

Two notable applications illustrate the upper bounds of automation:

- Automated Directional Drilling (ADD) – LOA 5: ADD (Hansen, et al. 2020) uses a well plan as reference to follow and continuously predicts the distance between current wellbore and planned wellbore in terms of direction and inclination. It calculates steering parameters for rotary steerable systems (RSS) to stay close to the plan and sends them automatically as downlinks (DLK). It operates at LOA 5 but remains within the automation domain, as it does not factor in reservoir data.
- Autonomous Reservoir Navigation (Auto-RNS) – LOA 6: Auto-RNS (Wessling, Hummes, et al. 2023) represents a breakthrough in autonomous drilling. It uses deep resistivity measurements and real-time inversion to identify the oil-water contact (OWR), calculates a new trajectory, and directs ADD to follow it. This closed-loop system continuously adapts to reservoir boundaries, maximizing exposure and exemplifying true autonomy.

A summary of multiple drilling automation applications is presented in Table 1.

Table 1—Applying the reference of level of automation to known drilling automation technologies

Application	Brief description	LOA
Automatic roughneck	Application controls roughneck to connect/disconnect drill pipe on demand	2
Handling drill pipe at rig floor	Handle drill pipe automatically during the complete connection procedure	3
Automatic reaming	Parameterize reaming procedure and execute automatically	3
Drill of tests	Automatic execution of parameterized friction tests	3
Friction tests	Automatic execution of parameterized friction tests	3
Swab/Surge protection	Estimate and enforce dynamic limits for the block movement to avoid swabbing/surging the wellbore	3/4
Flow rate protection	Automatic estimation and application of maximum flow rate limit to ensure integrity of the wellbore and equipment	3/4
Auto-Driller	Automate on bottom-drilling by controlling surface parameters	4
Tool-face orientation and correction	Adjust tool-face for slide-drilling by applying rotation at surface	4
Hookload protection (overpull, set-down)	Estimate hookload limits to define overpull and set-down and mitigate such dysfunctions when triggered using a pre-defined set of steps	4
Over-torque protection	Estimate surface torque limits dynamically, and mitigate over-torque when triggered using a pre-defined set of steps	4
Over-pressure protection	Estimate pressure limits dynamically and mitigate over-torque when triggered using a pre-defined set of steps	4
Automatic slide drilling	Automate drilling of a slide-segment	5
Automated directional drilling	Automate drilling of a section of the wellbore using a well plan as reference	5
ROP optimization	Automate parameter setting to mitigate vibration and improve ROP performance	5
Automated reservoir navigation	Automate navigation along the reservoir to stay close to the reservoir's wall	6

The rise in drilling automation features is driven by the broader adoption of machine learning (ML) and artificial intelligence (AI) algorithms that analyze both surface and downhole data. Drilling contractors and service companies have invested heavily in infrastructure to harness and curate this data, enabling them to process it through proprietary ML/AI engines. This approach has yielded deeper insights into optimizing operations and unlocking new sources of value.

Verification and Validation of Drilling Automation Applications

The pace of developing new drilling automation applications often outstrips the effort dedicated to their verification and validation (V&V). Depending on the level of automation (LOA), V&V may involve verifying sequence execution within a defined time frame. However, more advanced features, such as fault detection, isolation and recovery (FDIR), rate of penetration (ROP) optimization, automated directional drilling (ADD), or auto-RNS, require more sophisticated setups to conduct meaningful V&V, especially in multi-vendor or multi-component environments (Mihai, et al. 2024).

For example, applications that rely on drilling engineering simulations necessitate V&V of the digital twins involved (VanDerHorn, et al. 2025). Given that these applications often operate in multi-vendor contexts, the V&V process must also address interoperability. Each vendor is responsible for validating its own components through functional testing before integrating into the broader system. Subsequently, the interconnected system is validated using simulators that closely replicate surface and downhole conditions.

In the context of this paper, the V&V process was structured into three key stages prior to field deployment:

- Self-validation

- System integration test (SIT) using primarily software-in-the-loop (SIL) setup
- Hardware-in-the-loop (HIL)

This methodology draws from the V-Model framework for system verification and validation defined by the Association of German Engineers (VDI 2021), widely adopted in the automotive, aerospace, and oil & gas industries for developing algorithms in electronic control units (ECUs). Fig 2 provides a general overview of the V-Model.

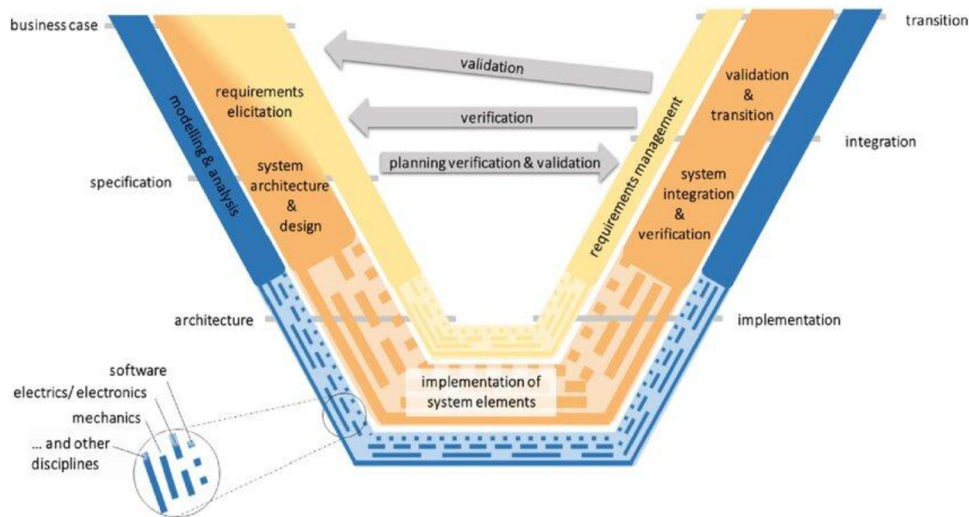


Figure 2—V-Model used in algorithm development, verification and validation (VDI 2021)

In the oil and gas industry, this approach is widely adopted for developing and testing algorithms deployed on downhole tools and edge devices that support drilling automation at the surface. It enables the simulation of complex downhole environments, allowing algorithms to be rigorously tested under conditions that are difficult to replicate through field trials or conventional laboratory tests. For instance, specific vibration scenarios can be simulated to validate the performance of downhole dynamics tools (Arevalo, Oueslati, et al. 2017), as illustrated in Fig 3.

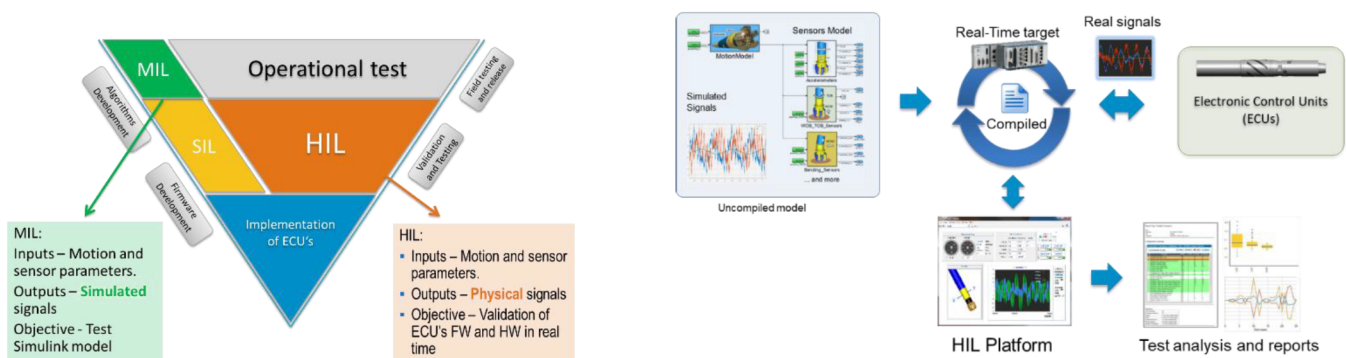


Figure 3—Example of MIL and HIL testing as part of V-Model for V&V of electronic control units in drilling dynamics tools (Arevalo, Oueslati, et al. 2017): (a) Schema of V-Model used; (b) HIL setup used

The applications discussed in this paper operate within a multi-vendor environment, necessitating a specialized setup to ensure successful V&V. A critical component of the V&V process was the active involvement of stakeholders, including operators, drilling contractors, service companies, and independent

auditors. This diverse input enabled the categorization of test results and helped prioritize follow-up actions based on collective feedback.

This paper provides an overview of the tested applications, which include rate of penetration (ROP) optimization, overpull mitigation, over-torque mitigation, and over-pressure mitigation—each accompanied by its respective V&V methodology. A case study is presented to highlight the V&V outcomes and the immediate corrective actions taken to enhance the robustness and usability of the interoperable system ahead of field deployment.

Drilling Automation Applications

Drilling automation applications—also referred to as *advisors*—are built through the integration of multiple components, including pre-job and real-time drilling engineering engines, signal processing modules, visualization tools, and more. These components communicate via a unified aggregation layer based on the industrial protocol OPC UA, as illustrated in Fig 4.

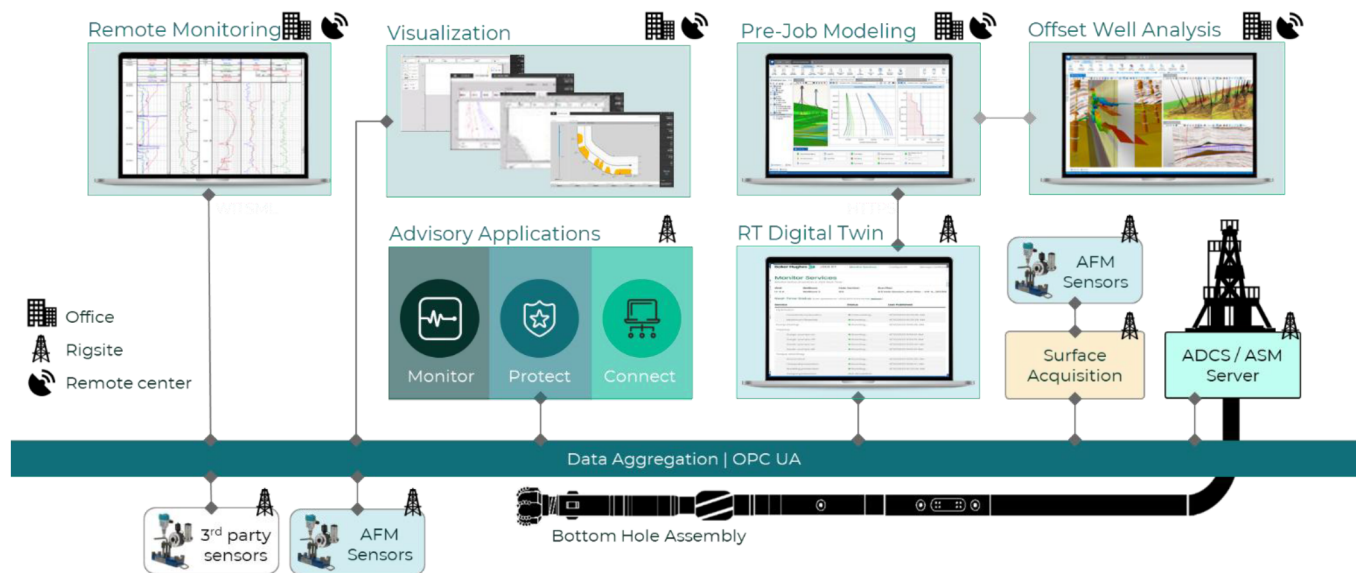


Figure 4—System overview of drilling automation applications

Applications that execute processes in real time are deployed at the edge to leverage low-latency access to sensor data and reduce dependency on cloud connectivity. This edge deployment is critical for advisors that influence mitigation routines executed by the Automated Drilling Control System (ADCS).

Beyond the core applications discussed in this paper—namely ROP optimization, overpull mitigation, over-torque mitigation, over-pressure mitigation, trip speed protection, flow rate protection—additional drilling automation services are deployed on the same edge device. These include automated torque and drag (T&D), transient hole cleaning, and automated directional drilling (ADD), among others. Each application can operate in either advisory mode or automatic mode. The automatic mode requires integration with an ADCS to configure and execute activities, facilitated through an intermediate component known as the Drilling Control Management System (DCMS).

The following section provides further details on the specific applications featured in the case study presented later in this paper.

Trip Speed and Flow Rate Limits: Passive Protection for the Wellbore and Equipment

Trip speed and flow rate protection are applications that operate on similar principles. Both utilize transient, physics-based models of the wellbore and equipment to estimate dynamic limits for specific processes—

for example, constraints on hoisting and lowering the string in and out of the wellbore. These limits are transmitted to the ADCS, which applies them to the rig equipment. These applications implement *passive protection* by defining Safe Operating Envelopes (SOEs) for specific processes, but they do not initiate mitigation actions if the rig equipment operates outside those limits.

Tripping Protection. As detailed by (Arevalo, Becker, et al. 2023), the tripping protection application estimates speed and acceleration limits for hoisting and lowering the string, taking into account factors such as downhole formation characteristics, drilling fluid properties, wellbore geometry, high-temperature/high-pressure environments, and heave compensation, among others. These limits are combined with the mechanical constraints of the equipment to derive an optimal operational threshold. Fig 5 presents a simplified example of a Pulling Out of Hole (POOH) scenario, where the tripping protection application was deployed in automatic mode to write hoisting and lowering limits to the ADCS. The green dots represent the system's bit velocity, while the bold continuous lines indicate the SOE at various depths. The string's motion is constrained within the limits defined by the tripping protection application.

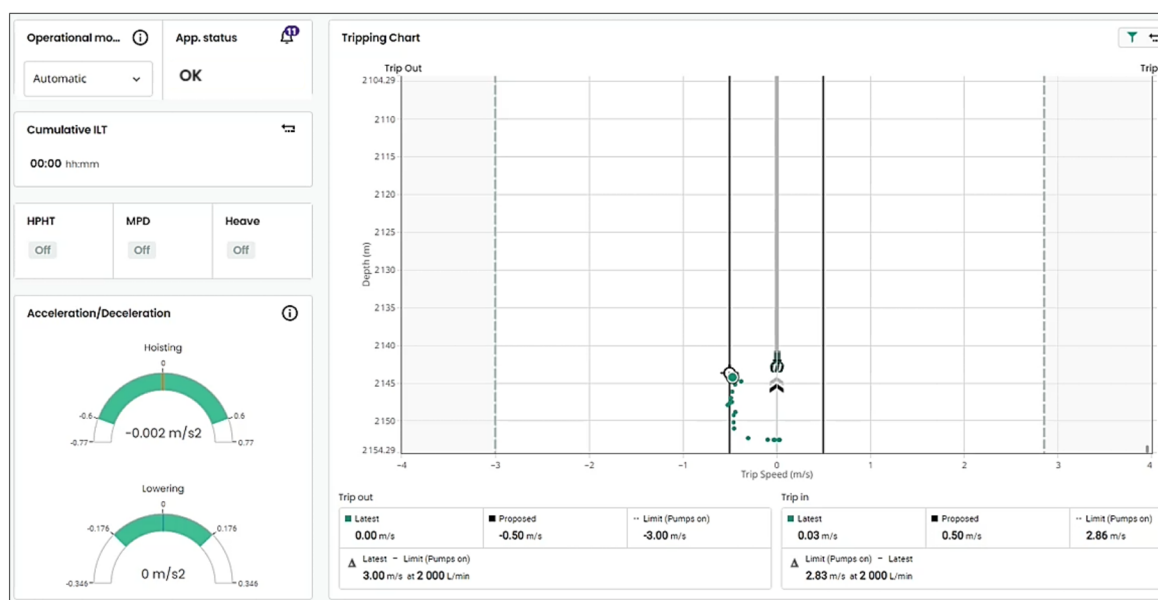


Figure 5—Automated tripping protection application

Flow Rate Protection. The flow rate protection application is a core component of the hydraulics optimization service, which includes borehole pressure monitoring, automatic pump management (Arevalo, Schuberth, et al. 2024), and hydraulic protection—specifically flow rate and pressure limits. The flow rate limit is calculated based on constraints from the drillstring, rig pumps, and the pressure envelope defined by downhole formation fracture gradients and surface pump pressure. This limit is then used by the ADCS as a circulation constraint to safeguard wellbore and equipment integrity. Fig 6 illustrates the hydraulics optimization application.

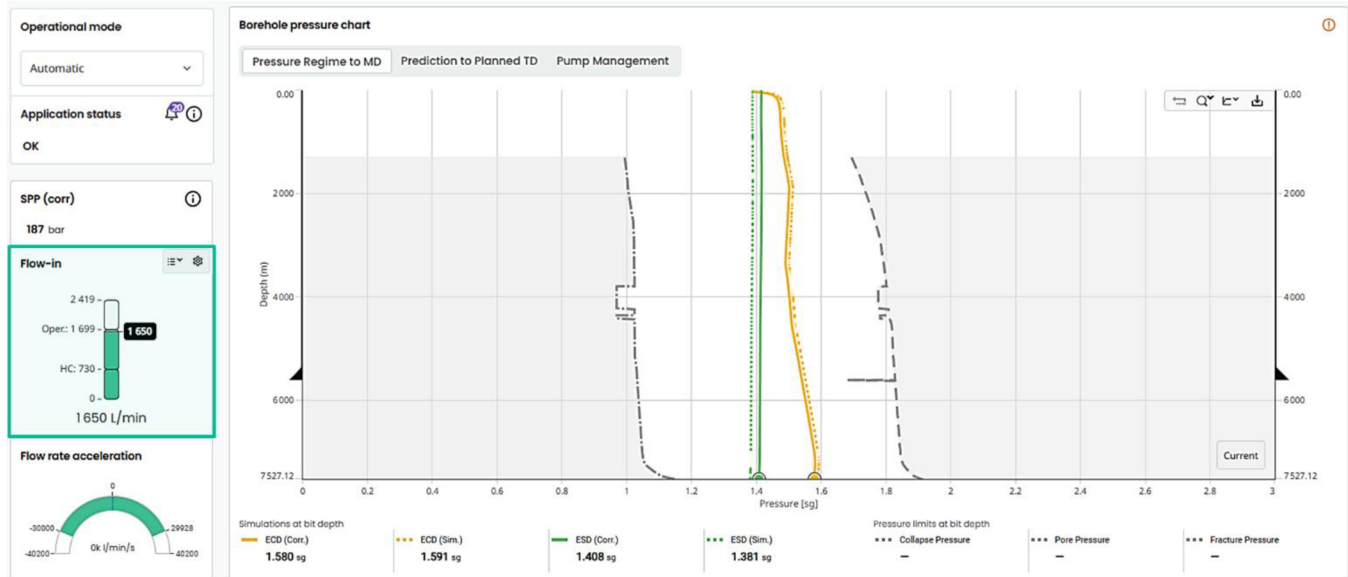


Figure 6—Flow rate protection application

In Fig 6, on the left, the vertical flow rate display shows the computed flow rate limit, considering the Bottom Hole Assembly (BHA), rig pump specifications, and operational conditions—formation pressure gradients and pump pressure limit. The flow rate gauge also highlights the minimum flow rate required to ensure effective cuttings transport under current drilling parameters.

Additionally, the visualization includes profiles for Equivalent Circulating Density (ECD) in yellow and Equivalent Static Density (ESD) in green. Dotted lines represent simulated values, while solid lines indicate calibrated results derived from Pressure While Drilling (PWD) data.

Over-Torque Protection and Hookload Protection: Ensuring Process Integrity and Mechanical Integrity

Both over-torque protection and hookload protection are integral components of the automated torque and drag (T&D) application. This system leverages real-time, physics-based models to generate predictive roadmaps for surface torque and hookload along the wellbore, as well as to define surface operating limits that help prevent hazardous conditions threatening the mechanical integrity of the drillstring—specifically over-torque, overpull, and buckling.

These roadmaps and integrity limits serve as a canvas for plotting T&D samples automatically captured by the application. Sample types include pick-up (PU), slack-off (SO), rotating off-bottom (ROB), and break-over (BO) indicators. The integration of roadmaps, mechanical limits, and sample data forms the foundation for advanced monitoring capabilities, enabling trend prediction, detection of increasing friction factors within the wellbore, and identification of potential issues such as inadequate hole cleaning. Fig 7 presents the user interface of the T&D monitoring application. A more detailed description of this application is presented in (Ait Ali, et al. 2023). Likewise, more in-depth information about T&D modeling is presented in (Arevalo, May, et al. 2025).

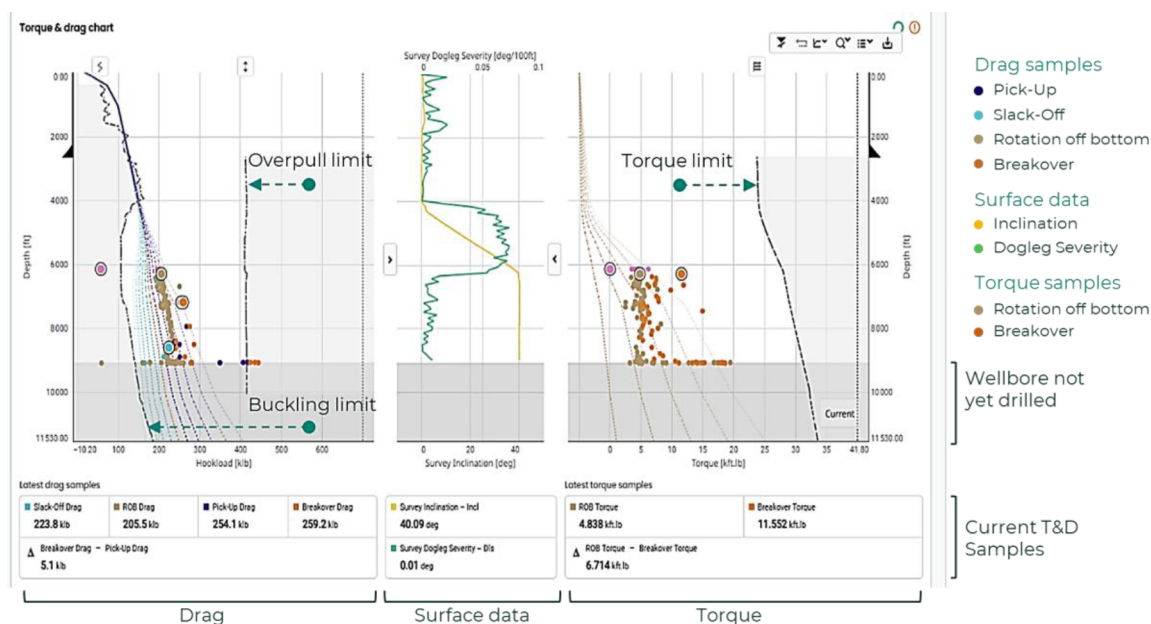


Figure 7—Automated T&D application

Over-Torque Protection. The over-torque protection application estimates a dynamic limit for surface torque using a real-time, physics-based Torque and Drag (T&D) model. This limit is continuously updated and transmitted to the ADCS, which then configures and initiates over-torque mitigation actions. As such, over-torque protection is classified as an *active* protection system because it automatically executes mitigation strategies when thresholds are exceeded.

Fig 8 illustrates an example of over-torque mitigation. The T&D monitoring application detects that surface torque has exceeded the calculated limit sent to the ADCS. In response, the ADCS activates the appropriate mitigation steps to reduce torque and restore safe operating conditions. Throughout this process, the driller is kept informed via the ADCS user interface, which includes dedicated visual elements for each type of well protection application.

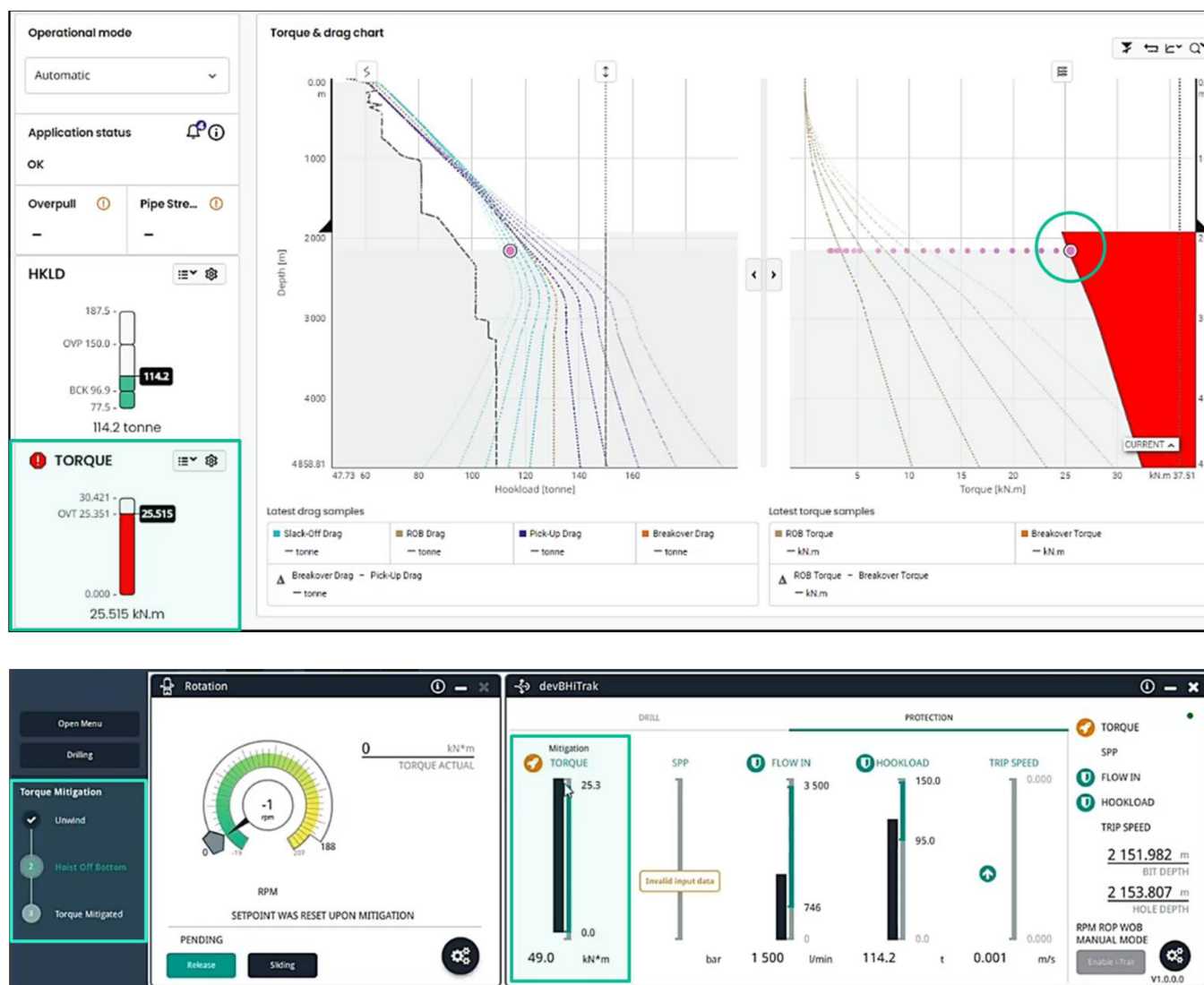


Figure 8—Example of torque protection. (a) Over-torque event indicated on the automated T&D monitoring application. (b) Mitigation initiated by ADCS and communicated to the driller via the user interface

Hookload Protection. The automated Torque and Drag (T&D) application calculates surface hookload limits to prevent mechanical integrity issues such as excessive overpull and buckling. However, even when operating within these limits, the string can still become stuck in the wellbore. To address this, a data-driven layer is applied on top of the mechanical integrity limits to define a narrower Safe Operating Envelope (SOE). This SOE incorporates two data sources: predicted pickup (PU) and slack-off (SO) samples, and the real-time surface hookload signal.

The SOE establishes a corridor around the surface hookload and overlays it with expected PU and SO values to define suitable limits for the Automated Drilling Control System (ADCS). Overall, hookload protection is classified as an active protection system, as it automatically initiates mitigation strategies when thresholds are exceeded.

Fig 9 and Fig 10 illustrate examples of hookload mitigation. In Fig 9, the T&D monitoring application detects that the surface hookload has exceeded the overpull limit communicated to the ADCS. In response, the ADCS activates mitigation steps—halting the hoisting operation and lowering the string—to reduce overpull and restore the hookload to safe operating conditions. Throughout this process, the driller is kept informed via the ADCS user interface, which features dedicated visual elements for each type of well

protection application. Fig 10 presents a similar scenario, this time involving set-down—the lower boundary for surface hookload.

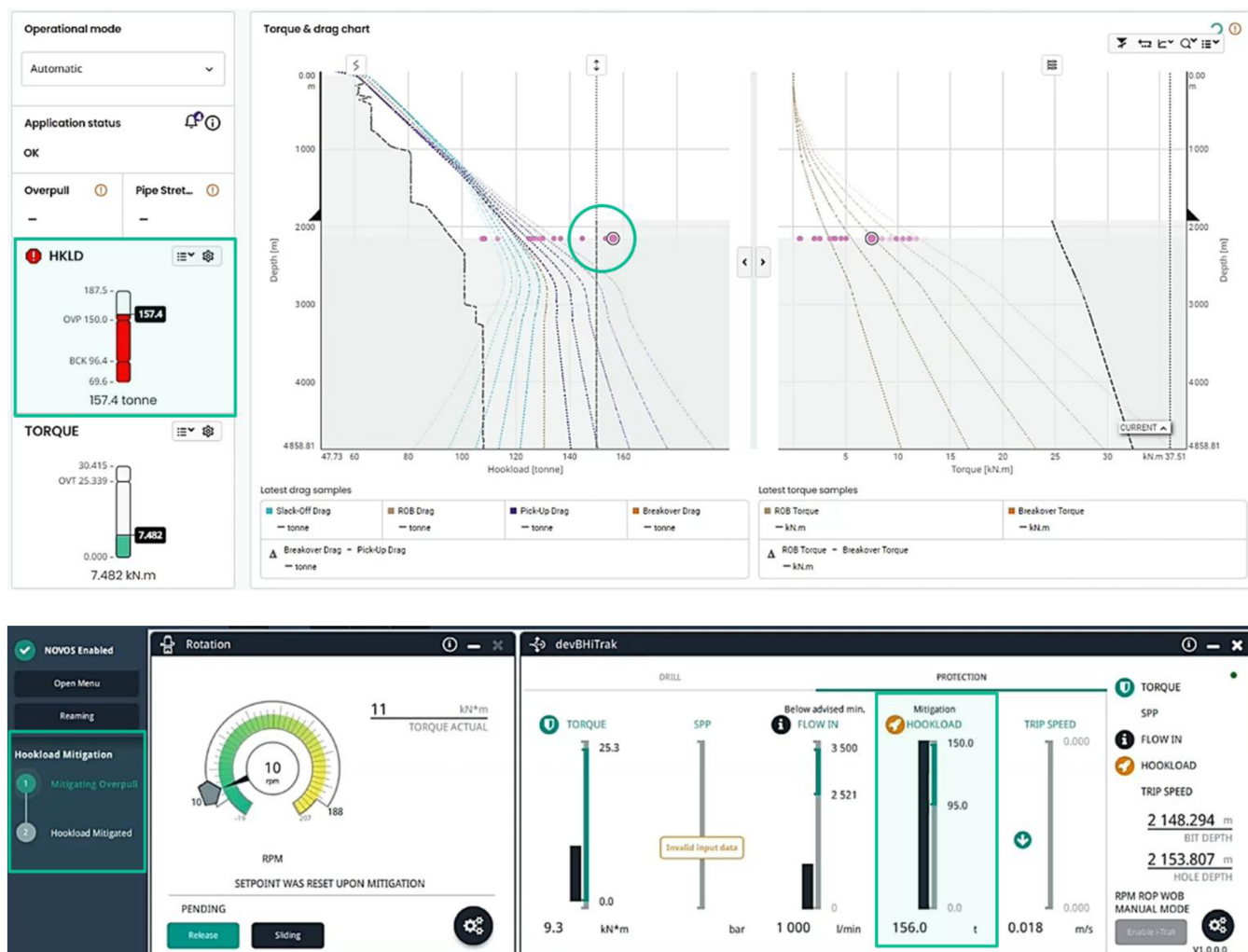


Figure 9—Example of overpull protection. (a) Overpull event indicated on the automated T&D monitoring application. (b) Mitigation initiated by ADCS and communicated to the driller via the user interface

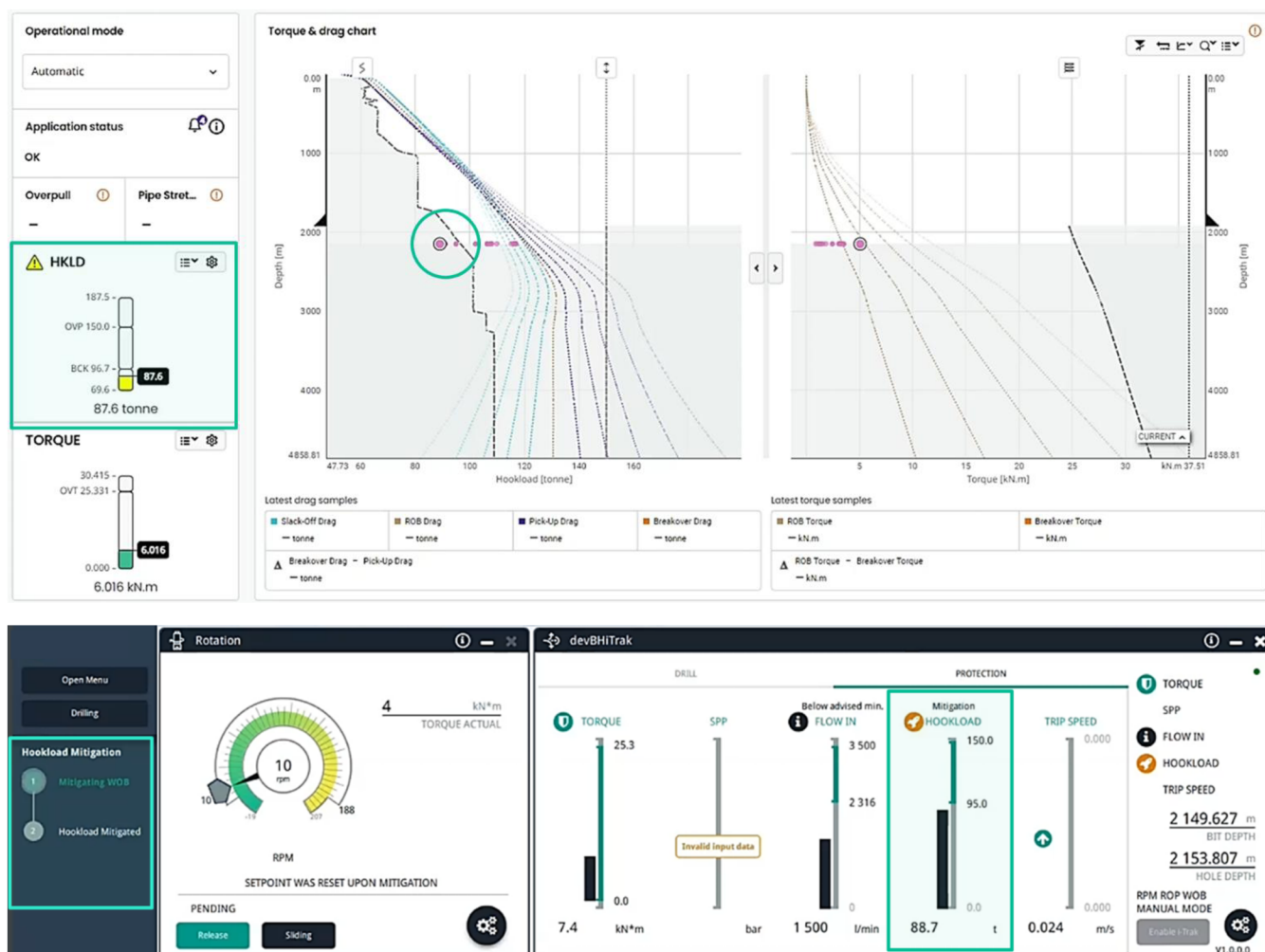


Figure 10—Example of set-down protection. (a) Set-down event indicated on the automated T&D monitoring application. (b) Mitigation initiated by ADCS and communicated to the driller via the user interface

Pack-off Protection: Protecting Formation and Equipment from Sudden Over-Pressure

The pack-off protection application is a core component of the hydraulics optimization service. It employs a combination of physics-based and data-driven models to estimate limits for standpipe pressure (SPP), focusing on its dynamic behavior—oscillation, slope, and overall expected maximum. These limits are sent to the ADCS to configure trigger points for pack-off mitigation.

The ADCS continuously monitors SPP against the defined limits—maximum, slope, and oscillation. If any of these thresholds are reached while the flow rate remains steady, the ADCS initiates a pack-off mitigation sequence. To execute this mitigation, the ADCS receives configuration parameters from the pack-off protection application, including:

- An indicator of when the flow rate is steady, enabling SPP monitoring against the limits
- The initial flow rate to apply in response to a pack-off event
- Subsequent flow rate adjustments following the initial response
- A threshold for SPP to be considered safe, allowing the ADCS to conclude the mitigation

Fig 11 and Fig 12 illustrate an example of pack-off mitigation. In this scenario, the pack-off protection application calculates SPP limits and provides mitigation parameters for the ADCS. The ADCS then compares the real-time SPP against these limits and initiates mitigation accordingly. First, the flow rate is

reduced as an initial response to counteract the pressure increase. Simultaneously, the pack-off protection application estimates the expected SPP for the current flow rate. The ADCS compares the actual SPP to this expected value and assesses its stability to determine whether the mitigation has been successful, as demonstrated in the example.

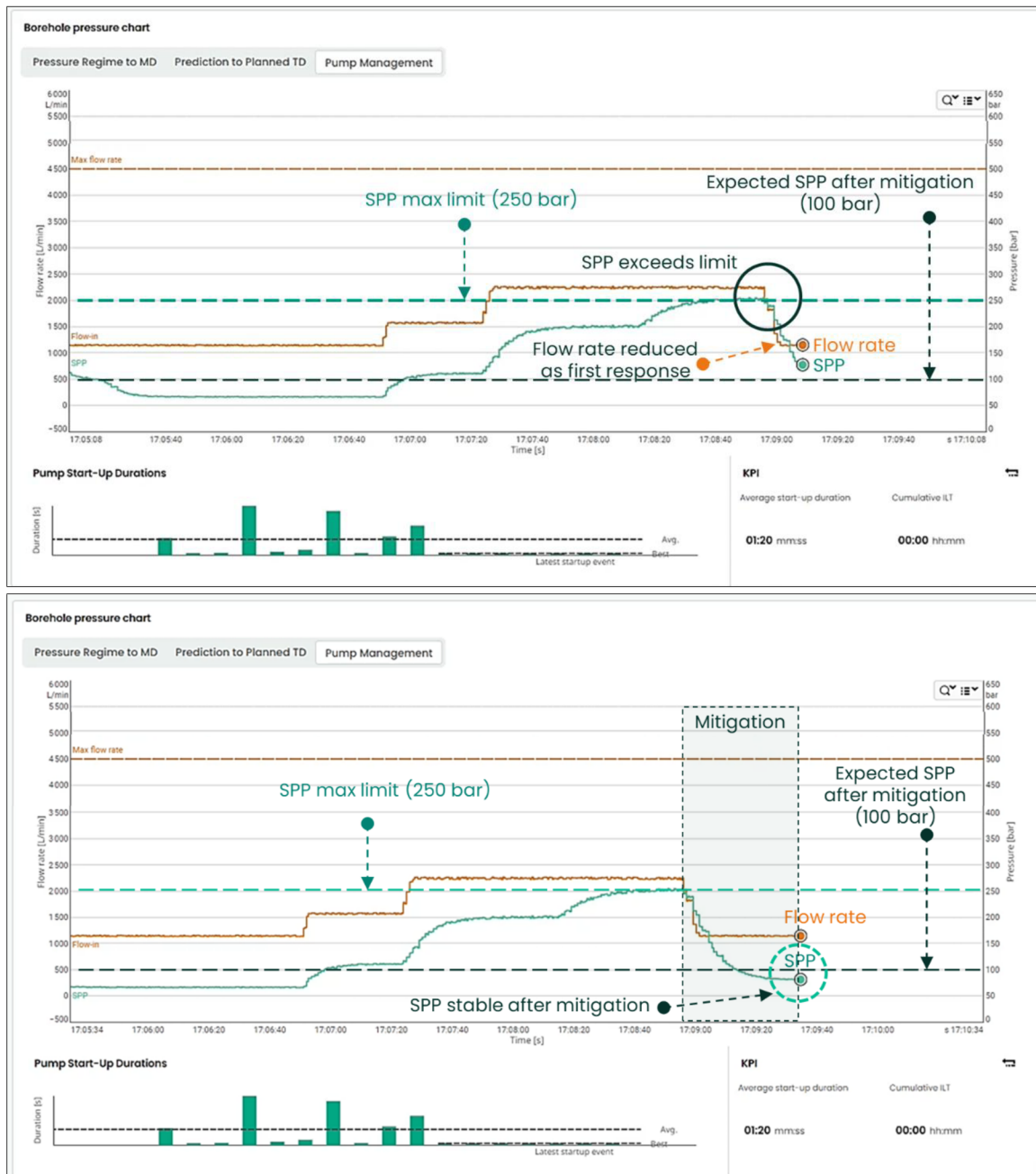


Figure 11—Example of pack-off protection. (a) Over-pressure event indicated on the hydraulics optimization application. The ADCS initiates mitigation by reducing the flow rate as first response; (b) Over-pressure event is mitigated successfully

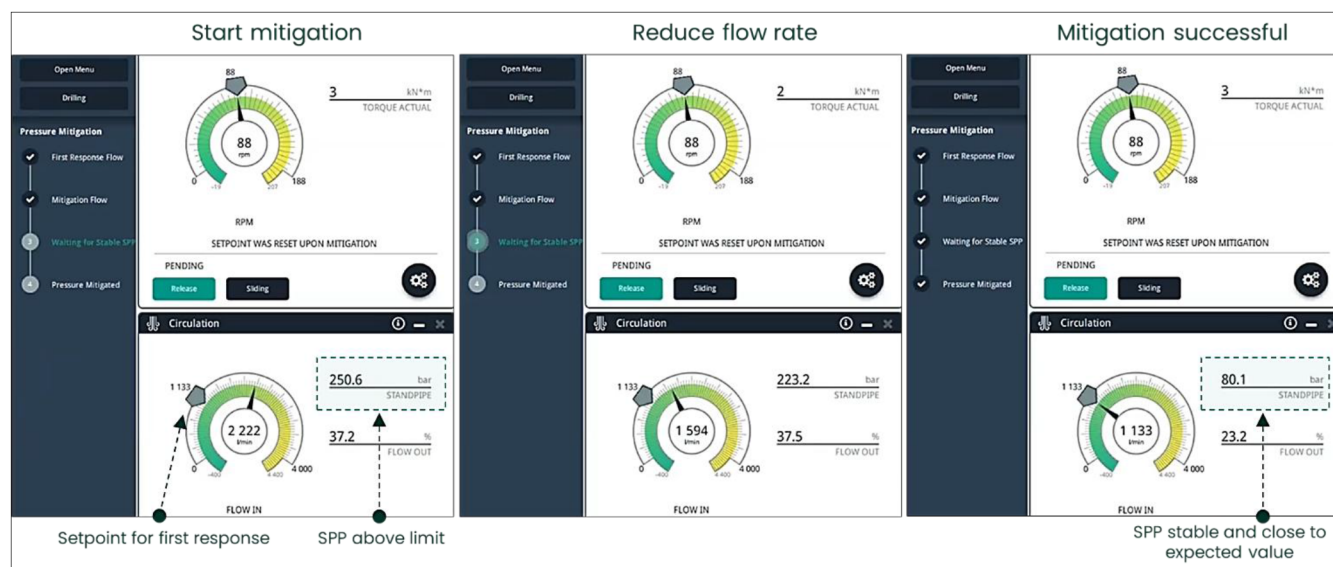


Figure 12—Example of pack-off protection. (a) Over-pressure event detected by ADCS and start of mitigation by changing flow rate setpoint to first response value; (b) Flow rate being reduced and SPP dropping; accordingly; (c) Mitigation successful. The SPP is stable and around expected value.

If the SPP does not stabilize after the initial flow rate reduction, the pack-off protection application may attempt to reduce the flow in stages while continuously evaluating the stability of the SPP signal. If the SPP still fails to settle or continues oscillating above the calculated limits, the ADCS will shut down the pumps as a last resort. In such cases, the mitigation is considered unsuccessful.

Mitigating Vibration Downhole and Improving Performance: ROP Optimization

Drilling in challenging formations often demands considerable time and leads to increased operational costs. To improve the rate of penetration (ROP), aggressive drilling parameters such as higher weight on bit (WOB) and rotary speed are commonly applied. However, these aggressive settings can induce harmful drill string vibrations, resulting in tool failures and costly round trips. On the other hand, conservative drilling parameters reduce ROP and prolong drilling time. Achieving an optimal balance between maximizing ROP and minimizing drill string vibrations requires deep expertise in drilling optimization and constant attention from the drilling crew.

The Automated ROP Optimization service assists drilling personnel in maximizing ROP while keeping vibrations within tolerable limits. It does so by interpreting downhole vibration measurements, tracking vibration severity and remaining tool life, and analyzing the relationship between ROP, vibrations, and drilling parameters such as WOB and rotary speed. Based on this analysis, the service iteratively proposes optimized drilling parameters. The interpretation of vibration data and tool life estimation relies on inputs from the Measurement While Drilling (MWD) tool and a configuration that defines vibration severity levels. The system is designed to require minimal user input and can be adapted to meet the specific needs of different regions and customers.

To support decision-making, the service generates drilling parameter stability maps that illustrate how various vibration types respond to changes in WOB and rotary speed. These maps use traffic light colors to help users easily identify problematic zones. In addition, an ROP heat map visualizes the measured ROP for different combinations of WOB and rotary speed. By combining these maps, users gain a comprehensive overview of the most severe vibration types and the corresponding ROP values in regions where all vibration types remain within acceptable limits. Historical data from previous drilling runs can also be incorporated by importing offset well stability maps as a starting point for new operations.

The optimization process is driven by the stability maps, an expert system for vibration mitigation based on internal drilling guidelines, and a gradient-based algorithm that iteratively maximizes ROP. Users can further refine the optimization space by narrowing operational limits to avoid complications such as poor hole cleaning. Fig. 13 shows an example of the user interface for the Automated ROP Optimization service.

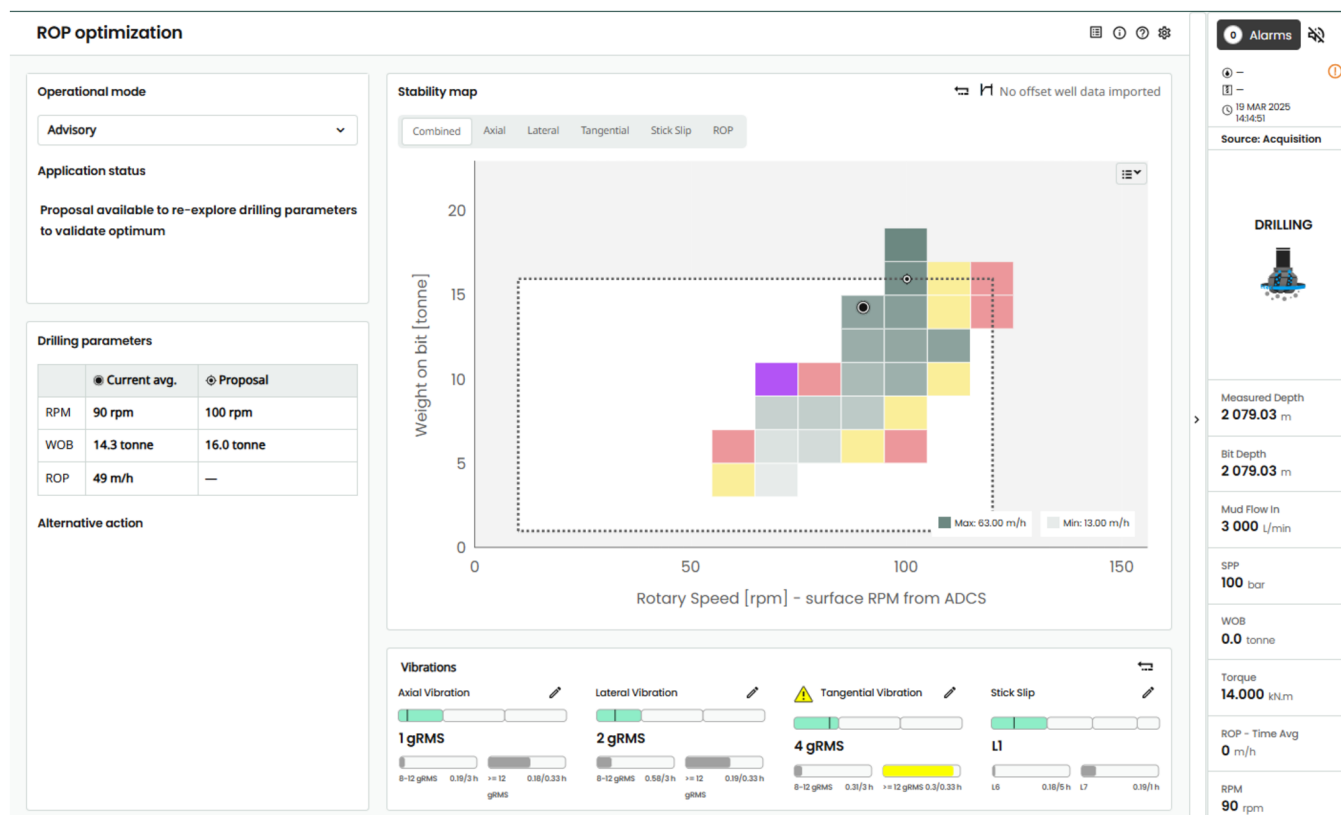


Figure 13—Example of Automated ROP Optimization Service

The service can be deployed in two operational modes. In the default advisory mode, the system proposes optimized drilling parameters that are communicated to the driller for manual implementation. When integrated with an Automated Drilling Control System (ADCS), the service also supports automatic mode. In this configuration, the system reads parameter limits directly from the ADCS to refine the optimization space and transmits proposed setpoints for automatic application. This continuous optimization loop updates setpoints every 2 to 4 minutes, enabling rapid convergence to the optimal operating point. By using the Automated ROP Optimization service, drillers are elevated to a supervisory role and can focus on executing the drilling program, as the burden of process optimization is effectively managed by the system.

A lightweight application deployed on the ADCS enables the driller to manage the control delegated to ROP optimization and to monitor its operation. Fig. 14 illustrates an example of the user interface of the application running on the ADCS, which facilitates interaction with the ROP optimization system.

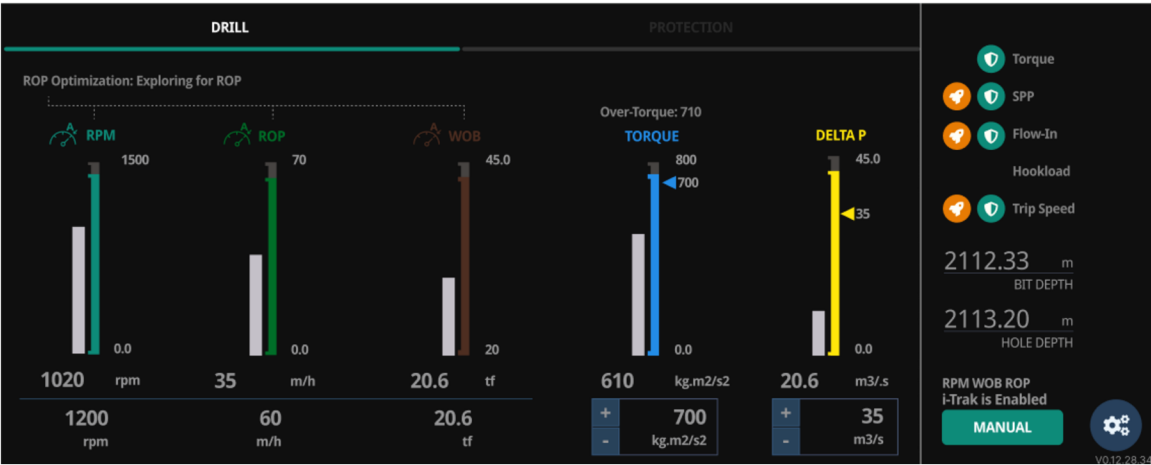


Figure 14—User interface embedded in the ADCS to control ROP Optimization service

Drilling Control Management System: Fostering Interoperability in a Multi-Vendor Context

Interoperability is the ability to share information. There are different levels of interoperability depending on how much the applications can understand from the shared data (D-WIS 2025). Several publications discuss the topic of interoperability, its importance, the challenges ahead, and practical examples (Cayeux, et al. 2023) (Daireaux, et al. 2023) (Arevalo, Schuberth, et al. 2024). The approach presented in this paper uses semantic interoperability (D-WIS 2025), where both the Advisor and the ADCS define the meaning of the exchanged data and use a defined data model to share this information via the industrial protocol OPC UA. The data exchange is routed through a central application deployed on an edge device, referred to as the Drilling Control Management System (DCMS), which interfaces with both the Advisors and the ADCS. Fig. 15 illustrates the concept of the DCMS from a logical perspective. From a network connectivity perspective, all applications, including DCMS and the ADCS, are connected to the same aggregation layer on the edge device where they can exchange information.

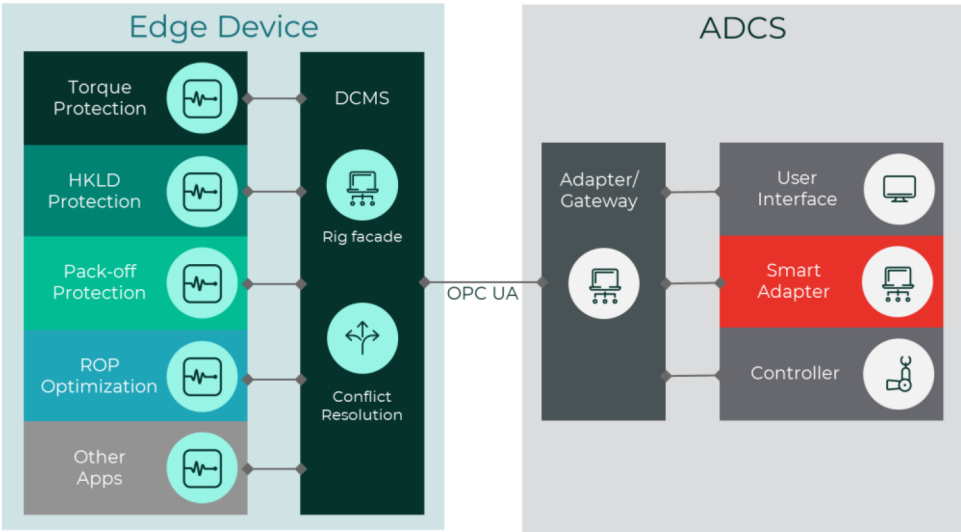


Figure 15—Logical data exchange between advisors and ADCS via DCMS using OPC UA

The DCMS serves multiple purposes in enabling collaboration between the Advisors and the ADCS. It provides a defined data interface to the Advisors, allowing extensibility of the automation suite, where all Advisors can connect via the same interface to the DCMS and, consequently, to the rig ADCS. The DCMS creates a façade of the rig ADCS data model and translates it into an internal neutral data model. This means

ADCS-specific logic is encapsulated in the Rig Façade, making the Advisors independent and therefore reusable across different ADCS types. Additionally, the DCMS ensures that proposals for setpoints and limits provided by the Advisors are written to the rig ADCS, and that messages and notifications from either the Advisors or the DCMS itself are communicated to the ADCS. These are defined as integers so they can be translated using a mapping table into rig ADCS-specific terminology, further ensuring decoupling between Advisor and rig ADCS logic.

One of the most important roles of the DCMS application is resolving conflicts that may arise when multiple Advisors connected to the ADCS attempt to write to the same setpoints and/or limits. In such cases, the DCMS resolves the conflict by prioritizing control requests based on their criticality. Advisors related to protective features are ranked higher on the priority list than those focused on performance improvements. This prioritization also takes place within the ADCS itself.

For example, if both the ROP optimization application and the over-torque protection application are deployed in automatic mode, both the DCMS and the ADCS will grant control to ROP optimization—provided that over-torque mitigation is not required. If over-torque mitigation is initiated, the setpoints from ROP optimization are discarded in favor of those defined by the over-torque mitigation strategy.

Regarding control handover, the DCMS ensures transparency to both the ADCS and the operator when any Advisor requests control to write setpoints to the ADCS. This includes notifying the driller when a control request is available or when an Advisor wants to revoke control. The transparency is bi-directional: in cases where the operator intervenes and takes back control, or when there is a loss of connection due to network instability, the DCMS informs the Advisors whether their specific control requests are active or not. Fig. 16 presents an example of the control state of each Advisor considering the three parties involved: the Advisor itself, ADCS and the driller. All three need to give consent to deploy an Advisor in automatic mode.

Automation Overview Connected ⓘ ⓧ ⚙

Well Protections				
	Service	Constraints & Mitigations	Automation	
▼	Tripping	Hoisting Constraints	ⓘ Waiting for I-Trak	ⓘ Waiting for Driller
▼	Hydraulics Optimization	Flow Rate Circulate Constraints	Ⓢ Activated by I-Trak	Ⓢ Activated by Driller Automatic
▼	Hydraulics Optimization	Pack Off Mitigation	Ⓢ Activated by I-Trak	ⓘ Waiting for Driller
▼	Torque & Drag	Hookload Mitigation	⚠ Waiting for driller to revoke control in ADCS	ⓘ Waiting for ADCS
▼	Torque & Drag	Torque Rotate Constraints	⚠ Waiting for driller to revoke control in ADCS	ⓘ Waiting for ADCS
Optimization				
	Service	Activities	Automation	
▼	ROP Optimization	Drill & Rotation	⚠ Waiting for driller to revoke control in ADCS	ⓘ Waiting for ADCS

Figure 16—Overview of control state of different advisors managed by DCMS

Case Study: Verification & Validation of Advisors in a Controlled Environment

The verification and validation (V&V) of drilling automation applications—referred to as advisors—and their interplay with automated drilling control systems (ADCS) are of great significance as a preliminary step before introducing the advisors to the rig site. This section describes the setup, execution, and results of the tests performed to evaluate the interoperable system, which includes field operators, drilling contractors, service companies, and external auditors as stakeholders. The V&V is part of a broader effort to prepare the interoperable system for rig-site deployment, as discussed by (Wessling, Forshaw, et al. 2025).

Building Technology for the Actual Users

From a technical standpoint, the objective of the test series was to verify and validate multiple drilling automation applications operating concurrently and connected to the same Automated Drilling Control System (ADCS). However, even when automation functions correctly, the human factor plays a critical role in deployment. User perception significantly influences the adoption and effectiveness of drilling automation features. Therefore, involving users throughout the design, implementation, and verification and validation (V&V) processes is essential to ensure that solutions are not overfitted, address all relevant scenarios, and offer a clear value proposition.

The V&V process included a diverse group of stakeholders—operators, drilling contractors, service companies, and independent auditors. Yet, the most insightful feedback came from the end users: the drillers. Many drillers were interviewed and trained on how to use the interoperable system, which comprises advisors and the ADCS, prior to the System Integration Test (SIT) and Hardware-in-the-Loop (HIL) tests. Moreover, drillers actively participated in the SIT and HIL tests to evaluate whether the automation features were relevant, user-friendly, and added value to their daily tasks.

Initially, some drillers expressed skepticism about using automated features, citing concerns such as fear of job displacement and the burden of learning yet another system to monitor during routine operations. Over time, these concerns were alleviated through close collaboration, which helped clarify doubts and improve the usability of the interoperable system.

The Control Dilemma

Drilling automation applications—referred to as advisors—work in tandem with the ADCS to enhance performance and maintain wellbore and equipment integrity. To achieve this, they must control rig equipment, requiring the driller to relinquish direct control to the interoperable system. This raises a fundamental question: with multiple components involved, who is truly in control? Shouldn't the driller always retain control of the rig?

These questions warrant careful consideration, as their answers reflect the architecture and philosophy of the interoperable system. The first principle is that the driller is always in control. Even when a function is executing automatically, the driller can override it at any time. Additionally, the driller can enable or disable each advisor as needed. The goal of automation is to elevate drillers to a supervisory role—not to bypass them.

The second principle is that the driller interacts exclusively with the ADCS, not directly with the advisors. The ADCS serves as the interface for managing advisor execution, configuring parameters, and delegating or revoking control. A deliberate abstraction exists between advisors and the ADCS to maintain a separation of concerns: the ADCS controls rig equipment, while advisors configure activities within the ADCS. Thus, neither the ADCS nor the advisors independently control the rig. Control is delegated to the interoperable system by the driller.

To execute any automated feature, the following conditions must be met:

- The ADCS is enabled by the driller
- The advisor is deployed in automatic mode
- The advisor is enabled via the ADCS interface
- The advisor successfully validates its ability to execute automation

The last point introduces the concept of revoking control. Advisors perform self-validation to determine whether they can operate effectively in automatic mode. For example, advisors relying on real-time drilling engineering models will fail validation if the digital twin of the wellbore and equipment stops producing results for an extended period. In such cases, the advisor cannot determine whether outdated results remain

valid and will revoke control to avoid misconfiguring the ADCS. Despite the importance of this capability, handling revoke control requests and informing the driller remains a challenge for the interoperable system.

Test Setup

The applications selected for testing exhibit distinct Levels of Automation (LOA):

- LOA 3 for passive protection features
- LOA 4 for Fault Detection, Isolation, and Recovery (FDIR) mechanisms
- LOA 5 for ROP optimization

Validating technologies at these automation levels requires a carefully designed test setup. It is crucial to evaluate not only the individual applications but also the interactions and dependencies across the entire system. To achieve this, the testing framework goes beyond basic self-validation and functional testing. Two additional layers were introduced to ensure robust assessment of system interoperability:

- System Integration Testing (SIT), to verify cohesive operation across components
- Hardware-in-the-Loop (HIL) Testing, to simulate real-world conditions and hardware interactions

The SIT and HIL setups differ primarily in how sensor data is generated. Other components—rig simulator, ADCS, edge device, and a local PC running real-time drilling engineering models—remain consistent. All components were connected to the rig network, and data exchange occurred via aggregation within the edge device using OPC UA as the communication protocol.

- SIT: The rig simulator generated surface data simulating various operations such as drilling, tripping, and circulating off-bottom.
- HIL: Programmable Logic Controllers (PLCs) produced physical signals emulating sensors and equipment at the rig site.

In both setups, surface data was streamed by the ADCS into the data aggregation layer via OPC UA. The ADCS also served as the interface between equipment controllers, the driller, and the automation applications.

The edge device hosted all advisors and the Drilling Control Management Service (DCMS). While advisors ran concurrently, DCMS orchestrated their access to the ADCS to resolve potential conflicts. The local PC executed real-time drilling engineering software, deploying digital twins of the wellbore and equipment.

In addition to surface data, the test required downhole data simulating responses to vibration and formation changes. This data stream was recreated by an Automated Electronic Procedure (AEP) running on the edge device and aggregated into the shared data layer. From the advisors' perspective, all necessary data was centrally available. [Fig. 17](#) presents an overview of the test setup and the data exchange.

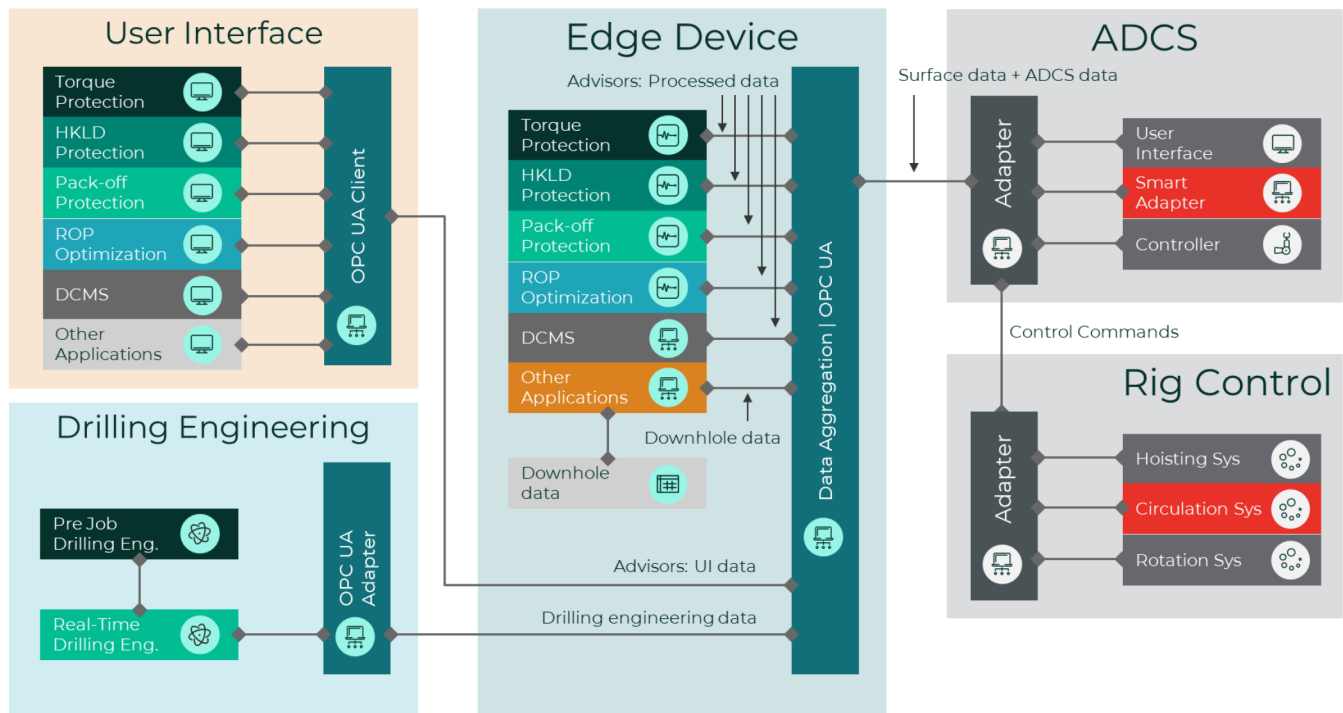


Figure 17—System overview and data exchange during the test

Furthermore, the downhole environment related to drilling engineering models was configured as a drilling run of an offshore well located in the North Sea. The overall test was executed as a continuation of a drilling run in the 16" section starting with running in hole and then continue drilling for 4 stands. Fig. 18 presents a snapshot of the test environment used.

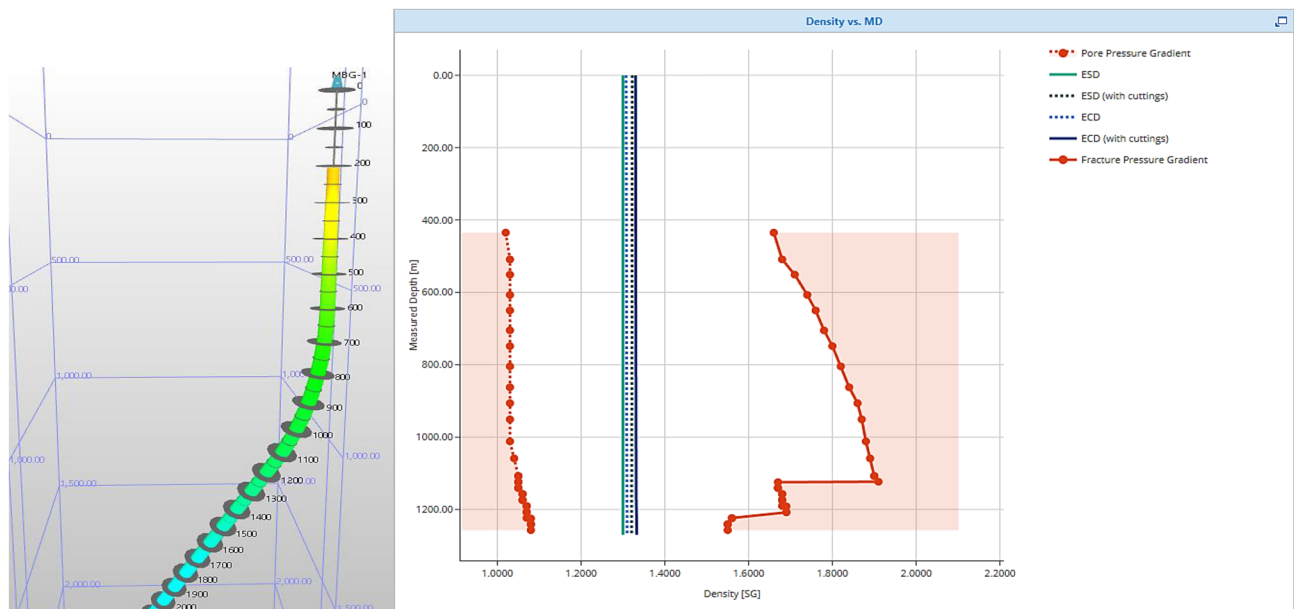


Figure 18—Snapshot of scenario used during the test. (a) – Snapshot of wellbore trajectory covering the 16 in section with MD marks in meters; (b) Downhole pressure regime

System Integration Test (SIT)

The SIT had a duration of 2 days, where a total of 26 test cases were executed to assess how the interoperable system (Advisors + ADCS) performs. Table 2 presents an overview of the test cases executed and Fig. 19 presents a breakdown of the test cases by type.

Table 2—Overview of test cases executed during the system integration test (SIT). Light green indicates successful tests w/o comments and dark green indicates successful test with action items.

Test	Operation	Advisor	Test Scenario	Results
1	Trip in & Connection	Tripping protection	Operator is able to enable tripping protection advisor in the ADCS	OK
2	Trip in & Connection	Tripping protection	Operator is not able to trip faster than the calculated trip speed limits	OK
	Start up the pumps			
3	Circulate off-bottom	Flow rate protection	Operator is able to enable flow-rate protection advisor in the ADCS	OK
4	Circulate off-bottom	Flow rate protection	Operator is not able to increase the flow rate beyond the calculated limit	OK
5	Drilling	ROP Optimization	ROP optimization uses operational limits defined in the ADCS	OK
6	Drilling	ROP Optimization	Optimizing with ROP limit	OK
7	Drilling	ROP Optimization	Optimizing w/o ROP limit	OK
8	Off-Bottom . Reaming	Hookload Protection	Operator is able to enable hookload protection advisor in the ADCS	OK
9	Off-Bottom . Reaming	Hookload Protection	Overpull mitigation	OK
10	Off-Bottom . Reaming	Hookload Protection	Set-down mitigation	OK
11	Off-Bottom . Reaming	Hookload Protection	Revoke control	OK
	Circulate off-bottom			
	Connection			
	Start up the pumps			
12	Drilling	ROP Optimization	Change ROP and torque limits while optimizing	OK
13	Drilling	ROP Optimization	Revoke control from application running on the ADCS	OK
14	Drilling	ROP Optimization	Revoke control from the Advisor	OK
15	Drilling	ROP Optimization	The driller takes over control from the advisor using the ADCS	OK
16	Drilling	Over-torque protection	Operator is able to enable over-torque protection in the ADCS	OK
17	Drilling	Over-torque protection	Over-torque mitigation in response to excessive torque caused by wrong selection of surface parameters	OK
18	Drilling	Over-torque protection	Over-torque mitigation in response to stuck-pipe event	OK
19	Drilling	Over-torque protection	Revoke control	OK
	Circulate off-bottom			
	Connection			
	Start up the pumps			
20	Circulate off-bottom	Pack-off protection	Operator is able to enable pack-off protection in the ADCS	OK
21	Circulate off-bottom	Pack-off protection	Pack-off mitigation in response to over-pressure	OK
22	Circulate off-bottom	Pack-off protection	ADCS shuts down the pumps in case of failed pack-off mitigation	OK
23	Circulate off-bottom	Pack-off protection	Revoke control	OK
24	Drilling	ROP Optimization & Over-torque protection	Over-torque mitigation started while ROP optimization is optimizing parameters to drill	OK
25	Drilling	ROP Optimization & Pack-off protection	Pack-off mitigation started while ROP optimization is optimizing parameters to drill	OK
26	Drilling	DCMS	Contingency: connection recovery after connection loss between DCMS and ADCS	OK
27	Drilling	DCMS	Contingency: connection recovery after connection loss between advisors and DCMS	OK

Overview of test cases per service / objective

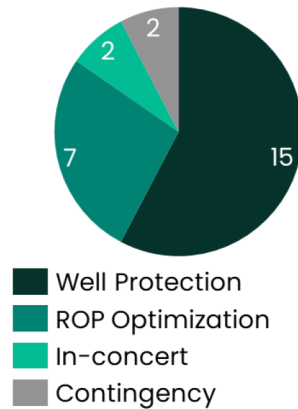


Figure 19—Break down of test cases by type. Adapted from (Wessling, Forshaw, et al. 2025)

The objectives behind the SIT test can be grouped in three categories:

- Functional validation of advisors and ADCS
- Verification of interoperability
- Verification of in-concert scenarios where two advisors request control of the same interface to the ADCS

Overall, the test was successful and well received by end users, who provided valuable feedback to enhance the usability and robustness of the interoperable system. The role of the DCMS as an abstraction layer between the advisors and the ADCS was verified: each advisor was able to write limits or target setpoints to the ADCS. Furthermore, the operator could select or deselect specific advisors (or all), modify configuration settings, and regain control when necessary. This highlights the evolving role of the operator when advisors are deployed in conjunction with an ADCS—the driller is elevated to a supervisory position, focusing on execution rather than monitoring. Fig. 20 presents a snapshot of the SIT execution, where the two screens at the top left represent the ADCS and a dedicated visualization of drilling automation applications.

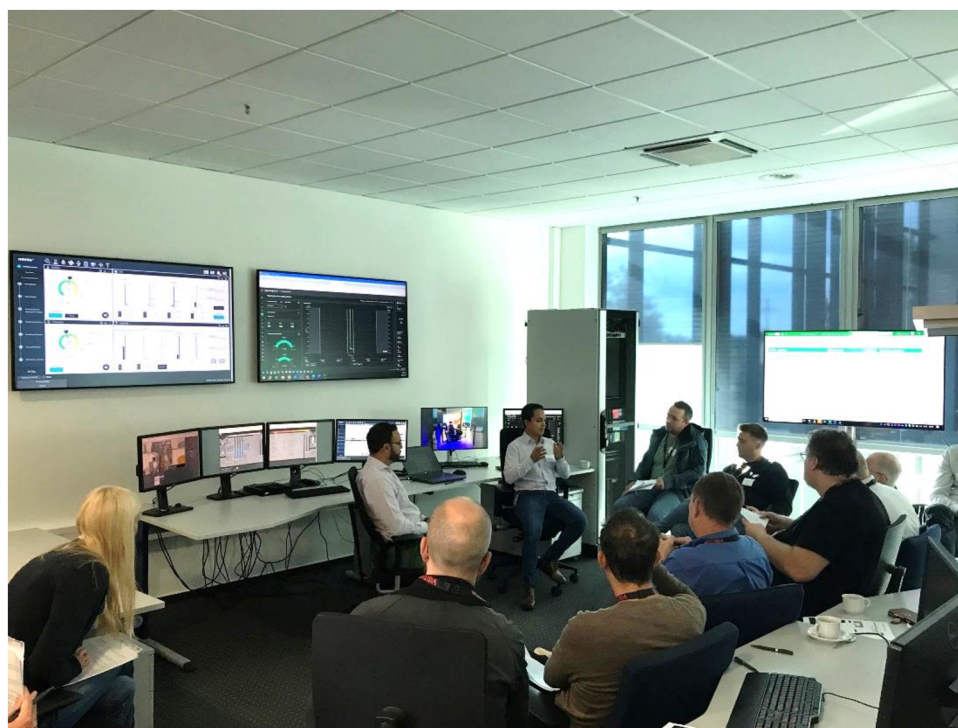


Figure 20—Stakeholders representing field operators, service companies, drilling contractors and external auditors taking part in the System Integration Test (SIT) to evaluate the interoperable system of Advisors + ADCS

The areas most actively discussed by stakeholders included revoking control, system transparency, and in-concert operations—where the ADCS orchestrates control assignments among advisors.

Revoking Control. When an advisor requests to revoke control, the ADCS processes the request to determine whether control should return to the driller and whether the latest values written by the advisor prior to revocation should be retained. End-user expectations varied depending on the type of advisor. For instance, when ROP Optimization requests to revoke control, control returns to the driller and the previous setpoints for WOB and RPM are removed. However, for well protection functions, handling revocation requests is more complex. Take the case of tripping protection: if the advisor requests to revoke control, the ADCS cannot simply return control to the driller and remove the last setpoint limits, as this might cause the driller to move the pipe too quickly. The consensus among stakeholders was that the ADCS should retain the last valid setpoints and notify the driller about the advisor's unavailability, allowing the driller to manually take over control. As a result of the SIT and follow-up discussions, the concept of control revocation remains open to interpretation and presents opportunities to further streamline the operational framework.

System Transparency. System transparency can be improved by increasing the driller's awareness of operational changes triggered by the automated system. While the interoperable system does communicate events to the driller via the ADCS screen, drillers typically rely on the rig control system (RCS) screen as their primary interface. The RCS screen displays real-time surface data and settings for surface equipment. To enhance awareness, both systems—RCS and ADCS—could share more information bidirectionally.

Another source of confusion is the presence of multiple limits for the same surface parameter and their interplay. Take flow rate, for example: there are rig pump limits, formation limits, BHA limits, operational limits defined by field operators, and drill plan limits. Although the interoperable system manages all these limits, the way it does so may not be transparent to the driller. This presents a tangible opportunity for service providers to improve clarity by implementing a structured taxonomy for different types of limits and presenting the driller with the most restrictive limit in effect—along with the rationale behind it. This issue was specifically addressed in preparation for the next validation step: the HIL test.

Operation In-Concert. When multiple advisors request control of an interface, the ADCS must orchestrate control delegation based on context. For example, control of WOB and RPM is delegated to ROP Optimization during drilling. However, if pack-off mitigation is triggered, the hoisting system must reduce WOB to pick up from bottom, and control is delegated to the pack-off protection advisor. This handover of control between advisors is already implemented in the interoperable system. Once a mitigation process concludes, control is returned to the driller to determine the next steps. Nevertheless, broader adoption of this functionality requires increased exposure and familiarity among end users.

Hardware in the Loop (HIL) Test

The main advantage of Hardware-in-the-Loop (HIL) testing is the use of actual hardware during the test. Programmable Logic Controllers (PLCs), responsible for controlling the rig equipment, are integrated into the setup to make the test environment closely resemble real-world conditions. The HIL test was conducted by an external auditor as part of a broader process of validation and preparation for commissioning the interoperable system.

The HIL test was carried out over five days, with participation from representatives of the rig operator, the field operator, engineers from both the system development organization, and the external qualification body. An extensive test program comprising 80 test cases across 14 categories was executed to evaluate the behavior of the interoperable system in relation to:

- Functional validation of advisors and ADCS
- Handling of failure scenarios
- Usability of the interoperable system

Table 3 presents a summary of the areas covered in the test.

Table 3—Overview of test cases executed during the hardware in the loop test (HIL)

Test Area	Test Cases	Overview
Enabling & disabling the ADCS	5	Enable individual constraints, enable/disable ADCS while advisors are in control
Drilling using ROP optimization	7	Control of parameters while drilling, transition to manual control, mitigation takes place while drilling
Hookload protection	11	Overpull and set-down protection, dynamic update of limits, overlay machine limits with dynamic limits, abort mitigation
Torque protection	6	Torque mitigation, limit dynamically updated, abort mitigation
Tripping (surge & swab) protection	7	Tripping protection limits trip speed, tripping limits dynamically updated, overlay with machine limits
Maximum flow rate protection	5	Flow rate protection limits flow increase, flow rate limit dynamically updated
Pack-off Protection	8	Pack-off mitigation off-bottom, pack-off mitigation while drilling, pack-off detection, SPP limits dynamically updated, abort pack-off mitigation
Simultaneous protections triggered	2	Pack-off triggered while flow rate protection limit is reached, pack-off and torque protection are triggered simultaneously
Power loss	5	ADCS loses power, Advisors lose power, network equipment loses power
Communication failures	7	Communication failure inside ADCS components, between ADCS and Advisors
Sensor failures	6	Simulate wrong sensor readings for SPP, block position, flow rate, hookload, surface rotation
Signal failures	1	
Operator panels	5	Test function of operators panel
Exploratory tests	5	
Total	80	

The results of the HIL test comprised a comprehensive list of findings, which were classified according to the structure presented in [Table 4](#).

Table 4—Categories used to organize test findings

Category	Description
A-finding	Non-conformity with rules and regulations and/or undesirable risk for damage or injury to human, machine or environment
B-finding	Non-conformity with requirements - Not in compliance with specifications, industry guidelines and standards, documentation (such as functional design specifications and user manuals) or intended use.
TBD	An observation may require further discussion before it is categorized. These test results are marked TBD (To Be Decided).
Observation	Valid and relevant observations that are not considered findings but give additional information to the vendor, the vessel's crew or the ship owner remain categorized as observations. These are not followed up in the project.
Void	Observations that are irrelevant or invalid due to e.g. misunderstandings or interface problems are categorized as VOID and not followed up in the project."
Documentation	Findings related to missing documentation.

The findings ranged from simple observations (e.g., the color of widgets) to more complex issues related to system operation. Each finding was documented along with comments from all stakeholders. Overall, the HIL test was considered a success, with a reasonable number of findings. It covered a broad spectrum of test cases aimed at verifying and validating the interoperable system. An overview of the findings is presented in [Fig. 21](#).

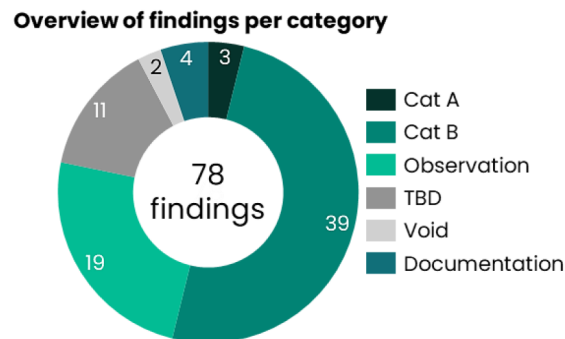


Figure 21—Overview of findings. Adapted from (Wessling, Forshaw, et al. 2025)

Category A findings. These findings were observed during in-concert test cases, where the ADCS interrupts a drilling sequence to initiate a mitigation and then hands back control to the driller once the mitigation is complete. These findings are specifically related to the handover process from the ADCS back to the driller. This situation affects both the ADCS and the Advisors, and must be resolved before deploying such services on an actual rig.

Category B findings. These are minor non-conformities, mostly related to system transparency and usability. However, due to the volume of findings, it was necessary to significantly reduce Category B issues prior to deployment on actual rigs to avoid user frustration, which could negatively impact system adoption.

Resolution of Findings. Following the HIL test, both the ADCS and the Advisors collaborated closely to address the open issues and retest the system. In parallel, features without Category A findings and with

minimal or no Category B findings continue to be introduced to the field. As a result, well protection and ROP optimization features are scheduled for deployment on a rig in the North Sea, under close monitoring by operations and engineering teams. This deployment aims to evaluate live system performance, verify issue resolution, and foster broader adoption of automated features at the rig site.

Conclusions

The oil and gas (O&G) industry is moving toward more efficient well construction operations by investing in digital technologies that maximize asset value. One such technology driving higher efficiency is drilling automation. The number of drilling automation applications is rapidly increasing, and the pace of development often outstrips the effort dedicated to their verification and validation (V&V). Additionally, the complexity of V&V varies depending on the application's level of automation (LOA) and the number of stakeholders involved in building the service.

The applications presented in this paper exemplify interoperability achieved through collaboration between Advisors and the ADCS. In interoperable systems, each component performs the task it is best suited for. For example, the ADCS interfaces with the user, controls the state of rig equipment, and manages control delegation. Advisors execute complex drilling engineering and data-driven models in real time to configure activities available in the ADCS. Together, the interoperable system delivers performance improvements in well construction operations (e.g., ROP optimization) while maintaining wellbore and equipment integrity (e.g., pack-off protection, hookload protection, torque protection, tripping protection, flow rate protection).

Verification and validation of interoperable systems require test setups capable of simulating environments similar to those expected at the rig site, accounting for user interaction and interactions among hardware and software components. The System Integration Test (SIT) and Hardware-in-the-Loop (HIL) test provided valuable opportunities to evaluate the interoperable system before field deployment. These tests helped identify system and component shortcomings early, simplifying issue resolution prior to introducing the applications in the field.

Overall, both SIT and HIL were successful, demonstrating that drilling automation applications can be deployed using interoperable systems. Furthermore, the tests revealed opportunities for improvement in both the ADCS and Advisors, enhancing the robustness of individual components and the overall system. This, in turn, increases the impact of field deployments and accelerates adoption by end users—namely, the drillers.

Continued efforts to advance drilling automation will focus on enhancing system awareness of its environment and improving decision-making capabilities. These developments aim to elevate the level of automation across applications and move closer to full autonomy.

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Nomenclature

ADCS	Automated drilling control system
AEP	Automated electronic procedure
ADD	Automated directional drilling
BHA	Bottom hole assembly
DCMS	Drilling control management service
DLK	Downlink

D-WIS	Drilling and Wells Interoperability Standards
ECD	Equivalent circulating density
ESD	Equivalent static density
FDIR	Fault detection, isolation and recovery
HIL	hardware in the loop
LOA	Level of automation
LOAT	Level of automation taxonomy
MD	Measured Depth
ML	Machine Learning
MWD	Measurements while drilling
NPT	Non-productive time
OPC	Open platform communications
OPC UA	OPC unified architecture
OWR	Oil-water contact
PC	Personal computer
RCS	Rig control system
RNS	Reservoir navigation system
ROP	Rate of penetration
RPM	Revolution per minute
RT	Real-time
SIT	System integration test
SOE	Safe Operating Envelope
SPP	Standpipe pressure
UI	User interface
V&V	Verification and validation
WOB	Weight in bit

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