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Digital Twin Implementation on Current Development Drilling, Benefits and Way Forward

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Abstract

In the recurring need to optimize drilling operations and reduce costs, a full RTOC (Real Time Operations Center) solution was deployed as part of the organization structure. To bring accurate, automatic and relatable data capture from surface sensors, the RTOC introduced a digital twin approach to improve field to town collaboration. The paper will demonstrate the benefits brought to operations by the solution in terms of risk identification and lessons learnt.

RTOC digital twin solution integrates standard physical models' workflows for hydraulics, torque and drag with advanced solutions using machine-learning algorithms. Capitalizing on operations recognition algorithm, the solution identifies thresholds and calibrates parameters to automatically classify operations into "Rig States" and "Drill States". The algorithm is trained to identify operational sequences and can derive complex measurements like downhole weight-on-bit and torque that are in turn fed into different workflows. This holistic event-based torque and drag baseline determination is used to define hole cleaning roadmap with minimum manual inputs.

RTOC receives, processes and publishes the real time data on through its platform for all drilling and completion operations. This continuous process has enabled drilling operations team to assess and intervene on a need basis thanks to the clear event identification it offers. Amongst the digital workflows, the hole cleaning roadmap, combines modelled and automatically identified torque and drag data points rendered and shared with the stakeholders to ensure the capture of deviations and framing of potential risks to acceptable levels through a common decision platform. The clear output of single identifiable drilling event (such as pick up, slack off and free rotating weight) provides constant fact-based data for an adequate protocol to run casings and liners and refine engineering designs. In turn it has enabled to break casing and liner run records in their different operating fields. The drilling efficiency roadmap rely on quantitative algorithm and reliable output of downhole weight-on-bit, downhole torque and mechanical specific energy with automatic calibration, without user intervention nor bottom-hole-assembly modelling, allowing to substitute actual downhole measurements. This has been a performance enhancer in the improvement of rate of penetration regardless of the availability of downhole sensors.

This new approach based on modern data science and digital twin based on a robust method, provides with a consistent and clear outcome regardless of service providers involved in the direct operations. It was trained, tested and validated prior to deployment, on more than 80 wells. This has also made possible the introduction of other algorithmic developments for Realtime dynamic modelling.

Introduction

The well construction planning process requires several engineering simulations and plans to define the work sequence and required material selection weeks if not month in advance to spudding. One of the challenges during the execution of the well is to bring together the drilling engineers and site operation team to work on a common "blue print" consisting not only of raw data feeds but also through a more complete and oriented monitoring solution that allows to verify the observed results against the plans and models. This approach allows detection of deviations and abnormal conditions that may potentially compromise the overall well objectives including delivery times and budget constraints, while reducing reporting load, and providing easier decision making.

The digital twin solution using live data delivers foresight through real-time software that dynamically models physical drilling enviroments, accommodating small changes in the operating process while providing reliable drilling roadmap. This process allows correction at early stages to avoid undesired consequences, considering that this collaborative platform is properly implemented and sustained. Among many challenges of a Digital Twin workflow are the solutions level of automation, the real time measurement data availability and quality since different sources are involved during the different stages of the execution and may offer diverse sensor coverage, data sampling rate and quality level.

Another paramount aspect is the clear framing of the solution within the organizational structure and day-to-day activities to ensure efficient and effective flow of information. The overall workflow of the implementation as per Figure 1, extends through the planning, execution and review stages of the well construction, and involves stakeholders from different departments, on one side, the Operations Team, and on the other the RT Drilling and RT Monitoring, which conform the RTOC.

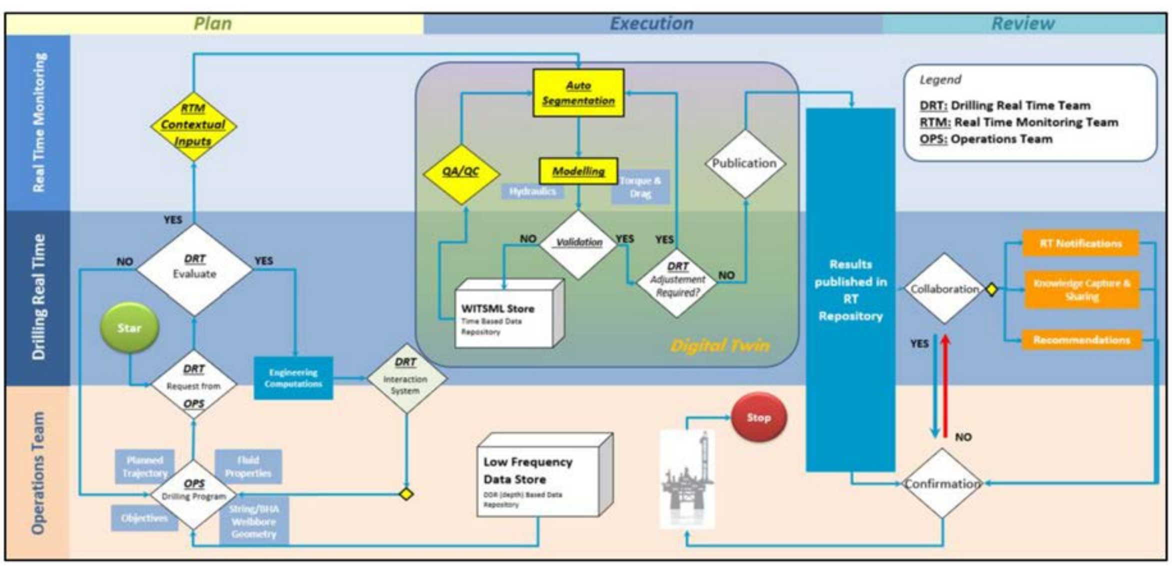

Figure 1—Digital Twin RTOC Workflow

Description and Application of Processes

Considering the mentioned challenges and factors involved on the workflow, the RTOC decided to implement a platform with high level of automation, capable of handling data quality issues through machine learning techniques to improve the processing of data with reduced human intervention to produce systematic results and digital models like hydraulic, drilling performance, torque and loads in real time.

Overall, the steps within the solution platform can be summarized as follows:

- Data Aggregation & QA/QC
- Contextual Information Ingestion
- Automation of Algorithms for Activity Segmentation
- Data Modelling with Computation & Engineering module

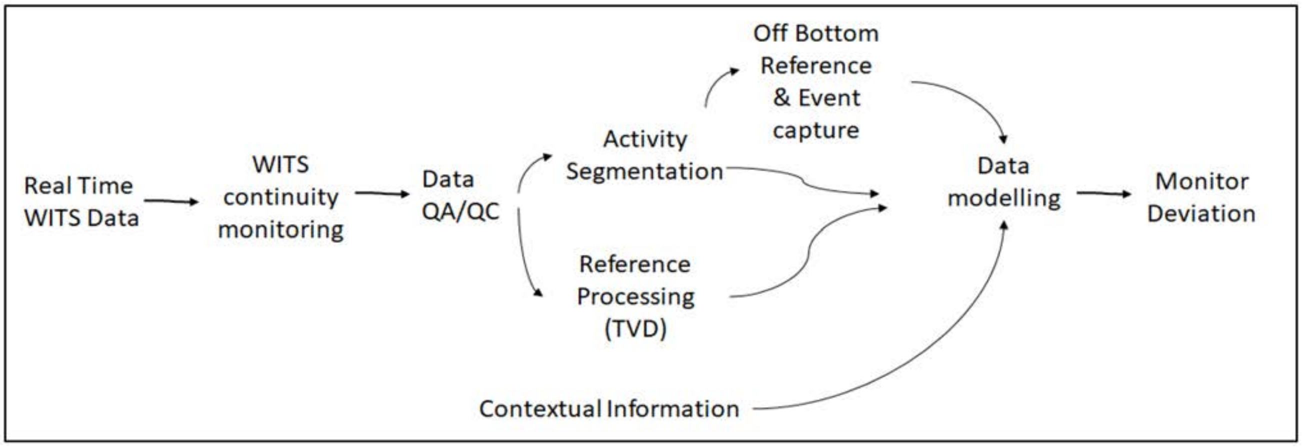

Figure 2—Data flow within the RTOC's platform

Digital Twin Solution – Data aggregation and QA/QC

Overall, the solution is vendor agnostic and interfaces through WITSML protocol with the various providers that deliver their services at the Rig Site. The WITSML store data feed is continuously monitored to detect interruptions on the data flow for a selection of channels, and alerts when human intervention is required from the RT Monitoring Team. These interruptions are dealt through the hardware deployed on the rig site that continuously buffer the data streams from the vendors to then re transmits once the link is reestablished. Such mechanism provides with the first line of defense in terms of QA/QC, as to secure the availability of data.

The advanced computations and data processing (workflow engine) are performed in dedicated servers distinct from the WITSML store which pull and push data in WITSML format to also enable end users to consume the information through web viewers. The solution manages depth and time data sets with average sampling rate of 1hz, which represents relatively large amounts of data to be handled and modelled.

The second critical challenge is the inherent quality of the data streaming to the WITSML store prior to modelling. While the data provided by each vendor (i.e. Mud Logging, MWD, MPD, etc) are rarely subject to major QA/QC issues, the rig data acquisition system is often not supervised and subject to frequent issues that constitute 47% of the support interventions, being the most common:

- Alteration or jump in bit depth & hole depth due to corrections;
- Sensor calibration issues like negative values for weight-on-bit and block position; and
- Inconsistent data frequency

While a couple of those challenges can be addressed directly by the solution engine (carry on data point, cancelling process if not all input are presents), a dedicated method was integrated in the workflow engine to automatically flag QA/QC issues on the main data channels to assist the RTOC technical team and report to the Rig for correction. The most relevant channels aggregated from the Rig Instrumentation can be listed as follows:

- bit depth
- total or hole depth
- flow rate
- standpipe pressure
- topdrive torque
- topdrive RPM
- hook load
- weight-on-bit

Data Quality Check

The Quality Check method provides a quick data sanity on these parameters. The principle consists of eliminating negative values in the stream, filling in absent values, and sanitation of the hole and bit depth channels.

The hole depth is the first parameter to be assessed and dynamically corrected. The algorithm assumes that if the same value is observed at 2 non-consecutive instances, then the latest and shallowest one is correct and therefore no depth can be deeper before this point in time (Figure 3, ensuring that the values are strictly increasing.

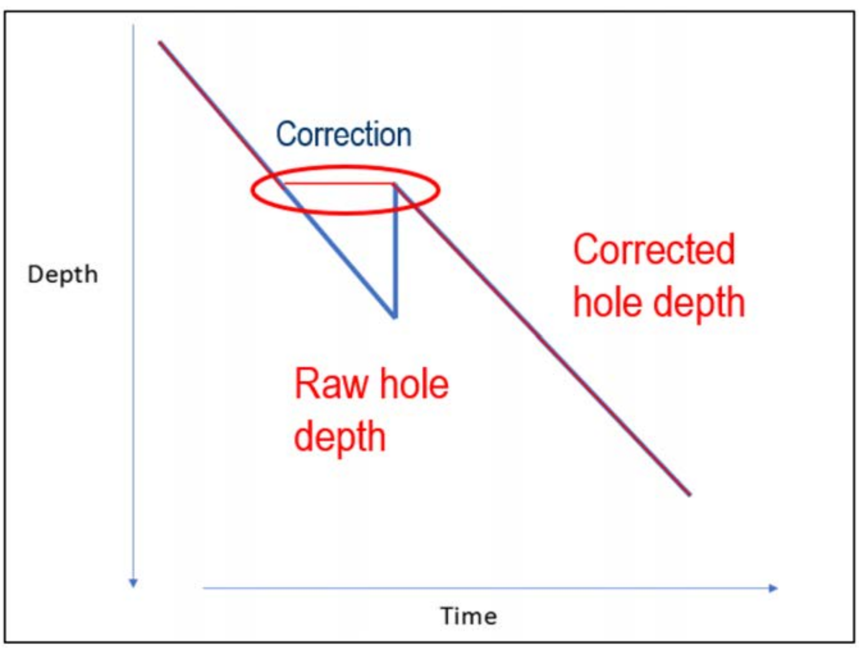

Figure 3—Example of Hole Depth Correction

Subsequently, the bit depth correction is applied once the hole depth is corrected. Correction on the bit depth has for objective to remove the distortions in the drill string between the neutral point and the top drive. It assumes that the bit is staying on the bottom even if the top drive moves of few centimeters (Bit cut off) as indicated in Figure 4.

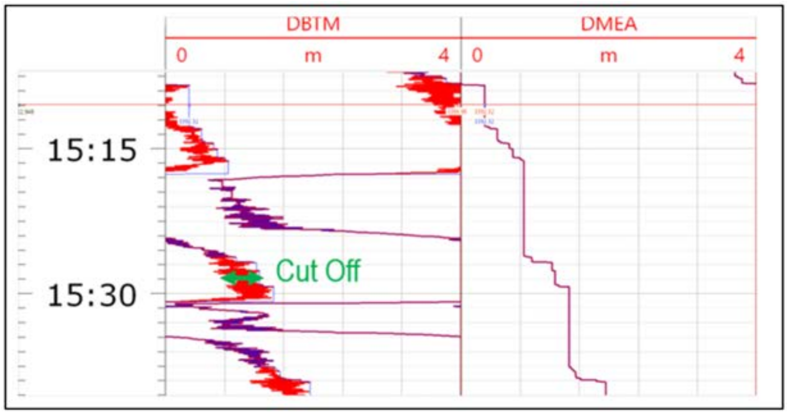

Figure 4—Cut-Off management

In case of major inconsistencies like frequent depth jumps, the automatic recalculations are excluded, and the issues are escalated to the data provider to intervene and correct at its origin on the rig.

An important point to note, is that despite any automatic corrections being implemented by the system, both the corrected and raw channels are stored and segregated to keep record of the changes and to allow for proper auditing on the data.

Data Quality Assessment

On the other hand, the Quality Assessment method, which the user defines as the expected measurement range and behavior for the parameter, allows assignment of following classifications:

- Healthy (good to be used for other workflows)
- Out of Range
- Spikes in data (abrupt variation of the values beyond physical possibilities)
- Gap (absence of values when these are expected)

The workflow generates output flags for each parameter (if there is gap in one parameter only, it will display alarm for that parameter). An example is provided in Figure 5, where such flags (black ticks) are displayed on the first track to the left. The blue curve on the track represents the block position and the flags are signaling "out of range" instances.

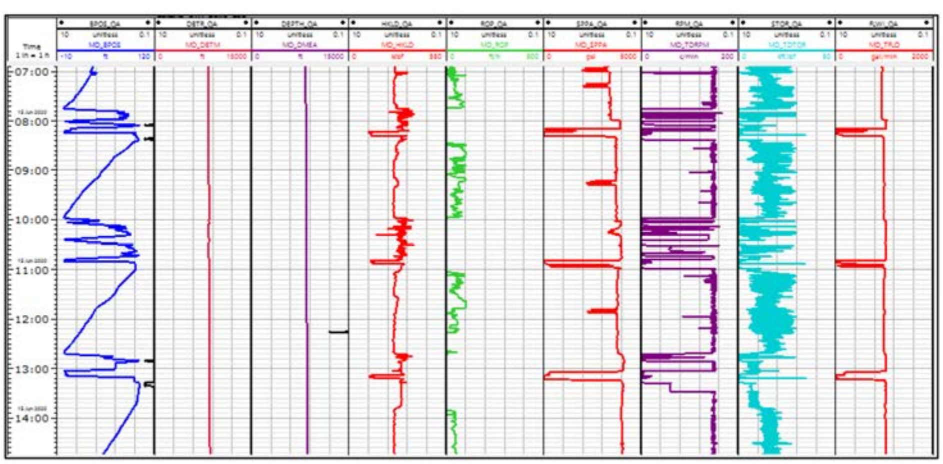

Figure 5—Time display

Digital Twin Solution – Contextual Information Input

Besides the ingestion of continuous and accurate real time data, the solution also requires complementing the information needed to describe in physical terms, the characteristics of the system that will be digitally replicated and modelled. In this sense, the engine has the capacity to integrate and save contextual information which is not commonly stored in WITSML format. This information includes the wellbore geometry details, bottom-hole-assembly (BHA) configuration and properties as well as the fluid related data. This information is needed to provide accurate context for the hydraulic engine and for the torque and drag simulation (BHA, wellbore deviation). In the case of projections ahead of actual conditions during the execution phases, the modelling is performed based on the inputted expected well profile, that is then converted and incorporated as a WITSML stored log to allow for important forward estimations such as TVD that is also the pivot to perform multi wellbore analysis and correlations.

Digital Twin Solution – Automation of Algorithms

AutoStates and RigStates

At the core of all the digital twin models lies the ability to perform activity segmentation. This method used in the RTOC platform and called AutoStates and is a fully automated algorithmic method with no manual intervention/input required while ensuring automated and reliable results.

This method was developed using machine learning technique and tested over a hundred wells data prior deployment and delivers two levels of operation analysis: 1) RigStates (micro event) and 2) DrillStates (macro event) with different degrees of granularity. The previous engine, "Rig State" required user to manually alter settings or create time range of application for thresholds according to changes in sensor calibration, equipment or fluid density/BHA ratio in order to trigger the onslip detection. The algorithm self-calibrates and adapt to the changes in conditions over the well duration, identifying the hookload value for "on slips" condition for each stand or joint added to the string.

One common case of change in threshold, illustrated in Figure 6, is the change during drillstring tripping, from elevators only to top drive connections on those rigs with the capacity to alternate between the two options. In these cases, the hookload weight values moved from ~20 klbf. while on elevator, to ~80 klbf when the top drive was added. AutoStates automatically calibrates "in slips" threshold to overcome these kinds of issues and avoid the need for manual intervention and potential error.

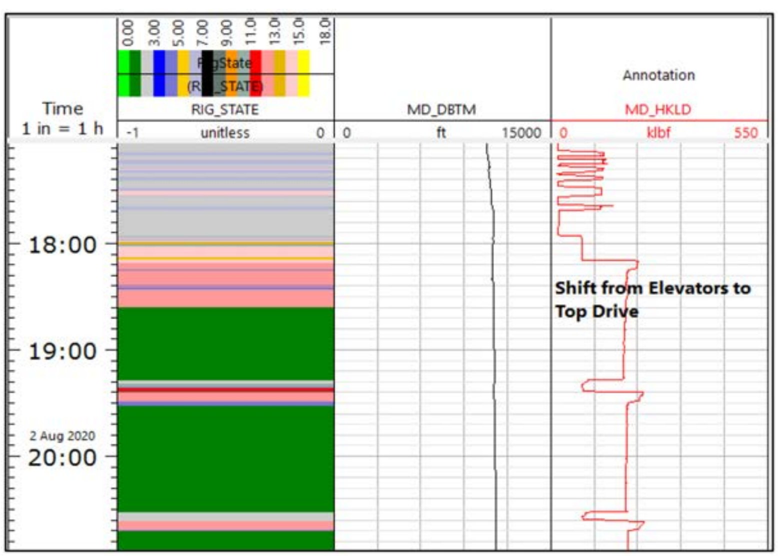

Figure 6—"InSlips" Threshold change. Elevators versus Top Drive

The algorithm performance was finally assessed against two wells outside of the training dataset with activity manually mapped. One comparison criteria was the matching of the onslip and connection period detected by both methods of Rig State and Drill State, as these are defined in slightly different terms (Rig State Onslip event is based on a hookload trigger to identify the disconnection of the string, while the Drill State connection event is determined by a combination of hookload trigger and block position value).

Table 1—Benchmark of "OnSlips" and "Connection time"

Well	Rig State	Drill State	Total rows
Well 1	99.72%	99.73%	300313
Well 2	98.39%	99.92%	1645452

Table 1 demonstrates more than 98% accuracy in detecting the On Slips and Connection Times for both methods alike. Moreover, unlike the previous Rig State method, the AutoStates requires no supervision, which enhances the automation of the workflow, without compromising the accuracy.

Reference Connection

Surface measurements are an important source of information during the connection of new pipes to the string, and so is the consistency on the selection of the exact moment when to capture these values. It is common knowledge that the consistency in capturing the pick up and slack off load events can introduce systematic errors, or even deviations that are too commonly observed on the field. To overcome this, the system incorporates a smart data processing to extract these points. This smart solution is the backbone for the Torque and Drag monitoring, and constitutes the basis for torque losses, downhole torque and weight on bit estimations.

The solution applies machine-learning algorithms to identify these references in an accurate and consistent manner, that are then used to define smart filters for the hookload and surface torque, effectively removing the need for manual inputs. This provides a systematic data processing with comparable results among different users, string runs and wells.

The algorithm requires besides the measurements of the hookload and torque, an accurate "rig activity" detection which is provided by the previous automated algorithm of AutoStates and DrillStates. The torque and drag (T&D) model, and downhole mechanical specific energy (DMSE) computations use the output provided by this algorithm to fill in a torque and drag roadmap which supports the assessment of wellbore conditions and allows the modelling needed for the DMSE estimation, which represents an important resource implemented by the RTOC.

For the torque and drag roadmap, the drag losses represent frictional forces generated by the contact between the drillstring and the borehole. This is measured during each drill pipe connection period and its variation against the modelled value (detailed in next chapter) will help the user to quantify the variation in hole condition status (hole cleaning or wellbore stability related) and act upon to perform mitigation actions to avert significant issues.

During drilling, it is necessary to monitor the effective transmission of the drill string weight and rotation to the bit as these are the driving elements of the rock destruction process. The torque is the rotational component of the contact force between the drillstring and bit against the wellbore, and a part of it is used for the drilling of the rock by the bit (downhole torque) The torque losses, due to friction generated by contact between the drillstring and the borehole, is the remaining component of the overall Torque supplied to the system from the surface after a part of it is been used to destroy the rock.

Unlike the drag forces, that can be monitored during any connection, the torque losses can only be recorded if the string is being rotated freely while the bit is not in direct contact with the bottom of the borehole i.e. while drilling.

On this regard, Figure 7 shows the "detections" carried by the algorithm to capture the discussed reference values during the operations. On the 3rd track from top to bottom, the pick-up (red triangles), slack-off (blue triangles) and the free-rotation values (green dots). These points are plotted superimposed over the Hookload values curve, indicating the exact moment where the algorithm has identified as meeting the criteria of a Reference Connection. Worth noting, in some instances it is observed that these points do not necessarily abide to the common precepts that for example, a pick-up is the maximum value observed, or the minimum is the slack-off respectively.

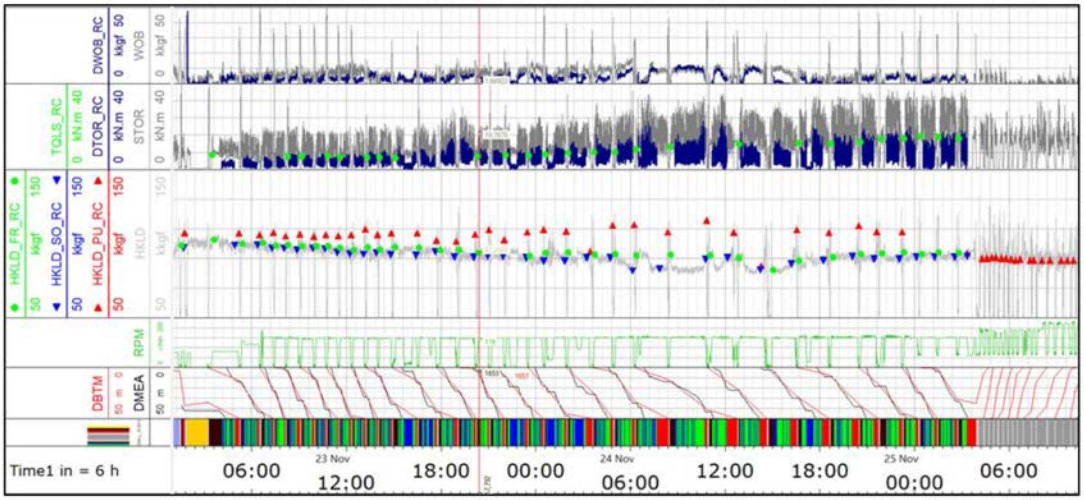

Figure 7—Output of Reference Connection Algorithm

The Reference Connection logic warrants an unsupervised way of capturing these points during similar and consistent actions throughout the operations, to ensure that meaningful tendencies are identified and acted upon.

Similarly, the second track from the top, displays the captured torque losses (green dots) during each Reference Connection. On the first and second track, the surface weight on bit and surface torque are plotted along with the respective downhole (at bit) estimations which form the basis of the DMSE computation.

Digital Twin Solution – Data Modelling

The current solution contains both, predefined modules for engineering (hydraulics, torque and drag, MSE modules) and the capacity to implement ad hoc solutions through python base script that allows to perform further advanced computations and modelling in both, in real time and offline modes. These common engineering modules will be discussed in the following parts:

Hydraulics model

This module provides modelled values for standpipe pressure, ECD at bit and at casing level with cutting load effect taken in account. This is performed to identify abnormal conditions within the equipment (drillstring and BHA) and to identify poor wellbore conditions that might affect the return of the drilling fluid through the annular space up to the surface.

The engine also computes swab and surge pressures generated by the string/BHA movement along the borehole to aid in estimating safe tripping speeds within the constraints of formation pore pressure and fracture gradient. The pressure distributions, dependent of the string action for pulling and running in hole, is estimated for both drillstring and casing strings. Only dynamic models are used adequately to study the effects of pipe acceleration and provide accurate swab and surge pressures estimations that consider transient conditions (time-dependent) flow, fluid compressibility and inertia, and drillstring/casing elasticity.

The contextual inputs required for the computation include:

- wellbore trajectory
- BHA and drillstring design including diameters and weights
- wellbore geometry including hole size and inner casing diameters
- mud weight, type and rheological properties
- drilling parameters like depths, block velocity, standpipe pressure and flow rate

The platform proposes the selection of two different rheological models in the fluid editor. The Bingham plastic and Power Law models approximate the pseudoplastic behavior of drilling fluids. A Bingham plastic requires a minimum of shear stress called the yield point (YP). Once reached, the shear stress is then proportional to changes in the shear rate, this is the plastic viscosity (PV). The thixotropy is not modelled as is acceptable for most drilling conditions unless the fluid remains in static conditions for a long period of time. The Power Law rheological model also requires two parameters to define the relationship between the shear rate and the shear stress: a consistency factor to represent the apparent viscosity and a flow behavior index describing the fluid property from a Newtonian model, to a fluid highly dilatant in its behavior. The model does not have a yield stress and is inaccurate at very low shear rates like Bingham. Usually drilling fluids exhibit between a Power Law and a Bingham fluid behavior.

The Herschel-Bulkley model is a more complete alternative, allowing modeling both yield behavior of a non-Newtonian fluid and allowing for shear-thinning effect to be considered. The Yield Point and Plastic Viscosity can be directly set or alternatively derived from the FANN readings at 300rpm and 600rpm.

The hydraulic model used by the platform divides the string and the annulus into several elements to compute and store the respective pressure drop as well as the overall pressure across the system.

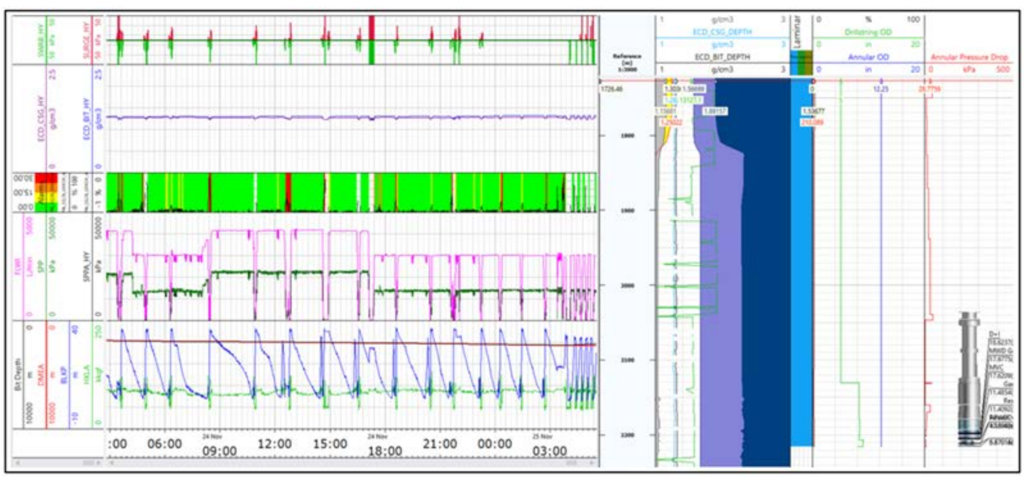

Figure 8—Hydraulic engine output

Figure 8 displays the different output channels from the hydraulic engine. The 1st track from top to bottom displays the swab (green) and surge (red) pressures. The 2nd track represents respectively the Equivalent Circulating Densities at the bit (blue curve) and at the Casing Shoe (purple) at any given instant during operations.

In the same order, the 4th track displays the mud flow rate (pink), the actual standpipe pressure (green) and the modelled standpipe pressure (black, overlaying across the actual values). These modelled values provide the basis for a comparison with the observed parameters, including the elaboration of alarms as displayed on the 3rd track, where the difference between actual and modelled pressures are plotted (black) and assigned a traffic light shading based on the magnitude of the difference. In similar fashion, these outputs are used to display and activate sound alarms at the rig site.

On the other hand, the right side of the figure, displays in depth basis, the distribution of pressures along the string and within the borehole, including the ECD displayed within the context of the Pore and Fracture pressure gradients window.

Torque and Drag Model

The torque and drag workflow enables real time analysis of different friction models against measured points for pick-up and slack-off events. The friction is the result of the contact between the string or casing and the wellbore walls during lateral and axial movement, and it is defined as the ratio of the force required to move an object, divided by the side force between the string and the wellbore. The platform allows modeling six friction factors (FF) discretely along the cased-hole and open-hole intervals of the well. These resulting models are plotted superimposed over the observed pick up or slack off points to determine the current friction factor. Such representation, commonly known as broomstick plot, is generally visualized to identify the downhole conditions. Examples of these plot as well as the measurements used for computation are depicted in several case studies in this paper (see Figure 10 and 11)

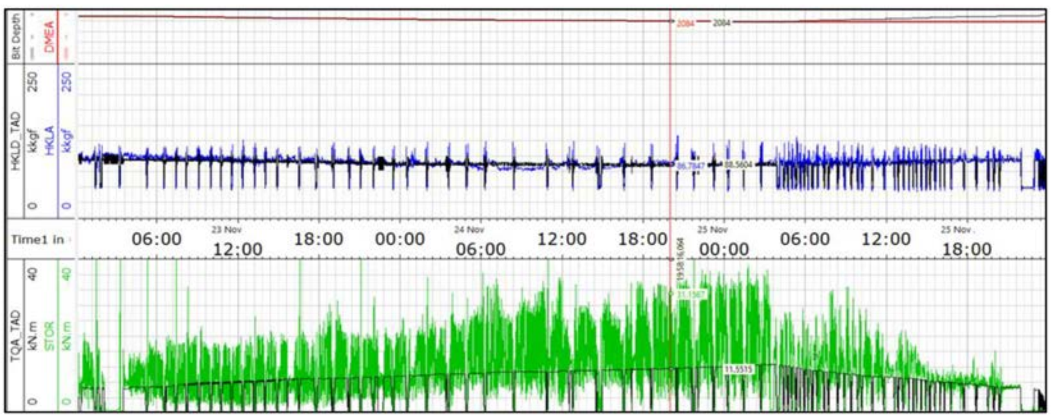

Figure 9—Torque and Drag model output

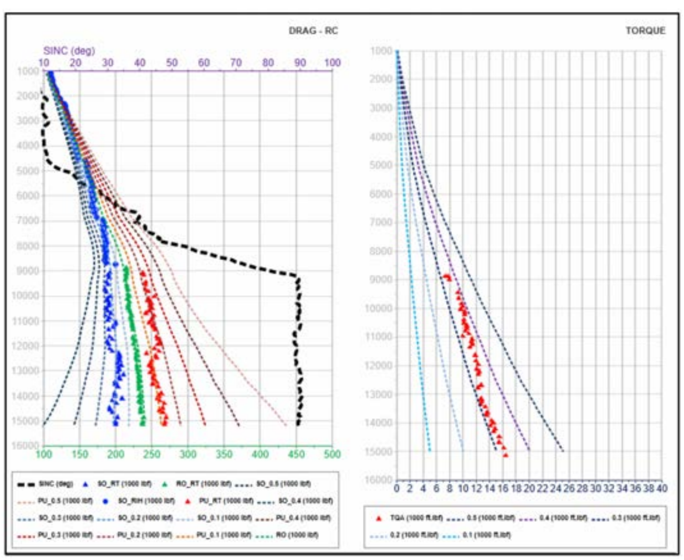

Figure 10—Torque and Drag Modelling and Monitoring

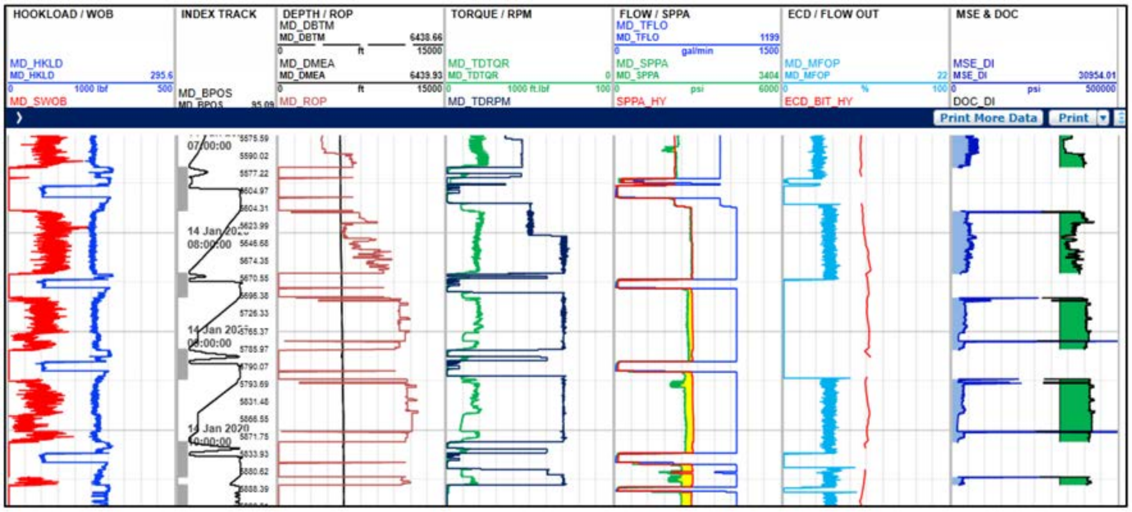

Figure 11—Modelled versus Real Standpipe pressure: Washout indication

The required inputs to generate the models are:

- Wellbore trajectory
- BHA and drillstring design including diameters and weights
- Wellbore geometry including hole size and inner casing diameters
- Friction factors for cased hole and open hole
- Mud weight and type
- Drilling parameters like actual hook load, torque, RPM and flow rate

The model available with the platform is a soft-string model that assumes that axial forces and moments are supported by the string and lateral forces by the wellbore. With this model, it is assumed that the string curvature is always equal to the wellbore curvature, meaning that the string is in contact with the wellbore throughout. With an increase of the inclination, the side force increases giving the spreading or "broomstick" effect to the modelled curves.

The platform allows to produce not only depth based results, but also time domain ones, in both, real time and offline modes as displayed in Figure 10, where also the computed hook load (black curve on the 2nd track) and the computed torque given predefined friction factor for sliding, translation and rotation (black curve on the 3rd track).

The possibility to handle the results in time, provides with the basis to generate alarms and flags by directly comparing the modelled against the actual values at any given time during the operations. Figure 9 provides with such visual comparison, where on the 2nd and 3th tracks, the difference between the modelled and actual torque and hookload becomes evident when plotted superimposed on each other.

Presentation of Data and Results

Below are series of case studies for well construction operations performed and followed through the RTOC platform, that showcases the main aspects covered through the solution. These illustrate the different applications and results obtained by utilizing the features of the solution that have been described through the previous sections.

Drilling

During drilling a 6" section in one of the several fields covered by the RTOC. The left portion of Figure 10 displays the "broomstick" plot where the detected hookload values for Slack off (blue triangles), free rotation (green) and Pick up (red triangles) are plotted along the different friction factor models. The black curve represents the borehole inclination. Both, the Slack off and pick Up values can be seen tracking the 0.2 FF model curves till a depth of around 12000 ft. Upon comparing with an offset well with the same BHA, drillstring and geological configuration, it was noticed that FF should be around 0.1 and not the observed 0.2, so it was decided to circulate for 2 hours and add lubricants into the drilling fluid. After circulation, there was an observed drop in the FF to 0.1 and the rig was able to drill to the intended total depth and later land the Liner Casing as per plan. Also is worth noting that the same behavior was observed with the torque, as displayed to the right of the figure, where the values can be seen also decreasing into a lower FF after the circulation and conditioning.

Anomaly detection during drilling

In this case study, a drillstring or BHA washout was detected during the drilling of a 12 1/4" section using RSS BHA. On the 5th track from the left side of Figure 11, the measured (green curve) and the modelled SPPA (red) matched till 8:30 am when these two values started to diverge despite the constant mud flow rate and rheological properties. Also, the turbine RPM was found to have dropped from 4000 to 3700 RPM as confirmed by the MWD crew. Based on the observation and the advice from the RTOC to the operations team, all surface equipment was tested, and no leakages were found. Based on the evidence, it was decided to POOH to check drill string for leaks and a washout was observed on a drillpipe @ 2640 ft and laid down. The string was tested and ran back on bottom.

When drilling resumed, actual and simulated Standpipe pressures matched again as per Figure 12, and section successfully reached total depth.

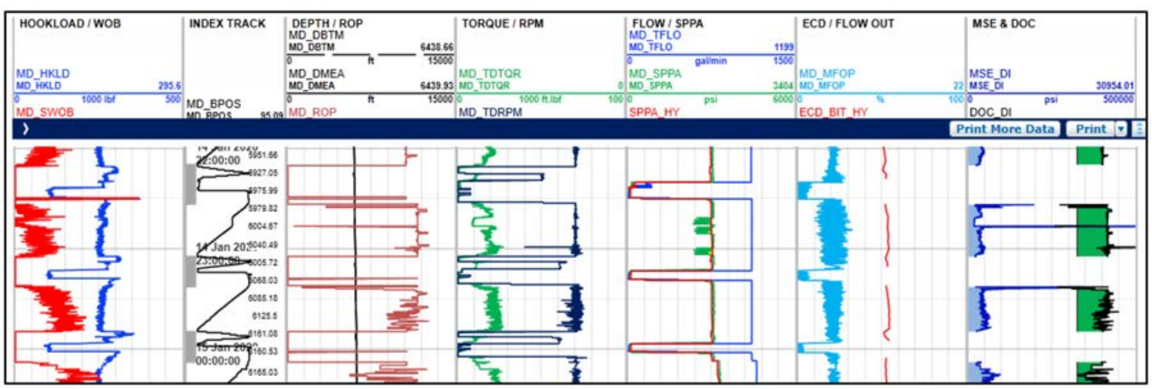

Figure 12—Modelled and Actual Standpipe Pressure during normal operations

Liner Running

The RTOC implemented the solution while successfully running the "Longest Liner" (around 24,000 ft in length). Figure 13 shows actual slack-off values over the broomstick plot for the entire duration. It can be observed that these consistently track a constant FF until 36,000 ft where the values diverge towards a slightly higher FF. In this case, given the steady behavior of the observed values, it was decided to proceed ahead and successfully landed the liner at the planned depth.

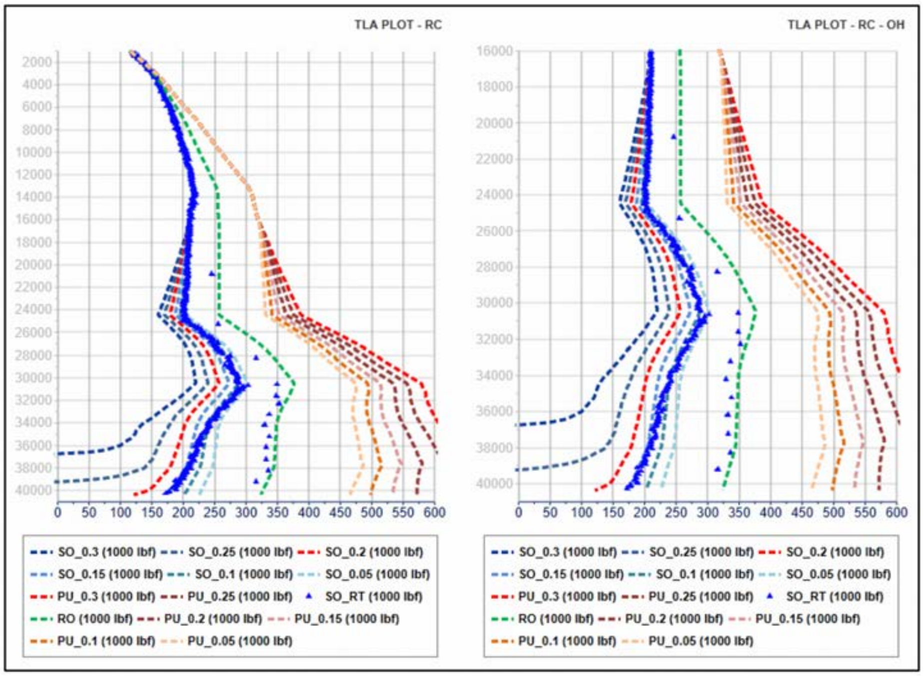

Figure 13—Broomstick versus Real Time Values for complete (left) and Open Hole section (right)

Pulling BHA Out of Hole

During a trip out of the hole on a 6" Motorized RSS BHA, it was observed that the Pick Up hookload values (red triangles on Figure 14) were initially trending towards 0.1 FF but unexpectedly increased at around 18500 ft. Therefore, it was decided to perform a "Wiper Trip".

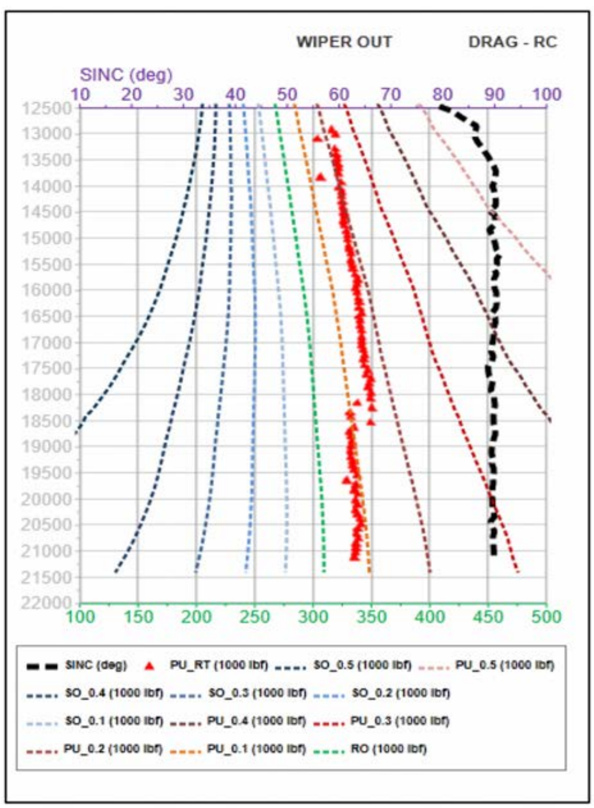

Figure 14—Drastic shift in observed "Pick Up" hookload values while tripping out with drilling BHA

After the wiper trip, as depicted on Figure 15, the BHA was pulled out of hole without backreaming and the observed pick-up trend was following the 0.1 FF curve as expected.

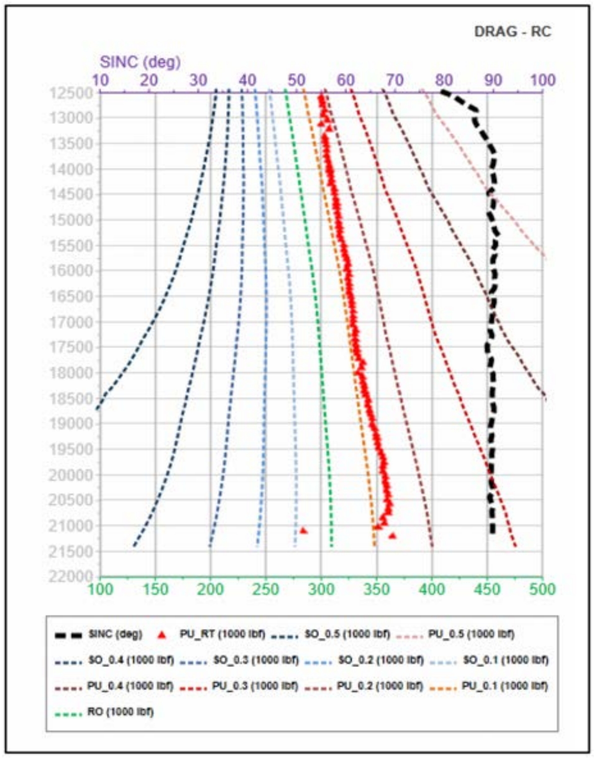

Figure 15—Pick Up Hookload values after "Wiper Trip"

Conclusions

The RTOC's digital twin approach has improved operations in terms of risk identification and lessons learnt, as illustrated through the case studies. Its high level of automation, enhanced capability in handling data quality and concise processing of data with reduced human intervention, produces systematic results through the digital models it generates.

The AutoStates and Reference Connection algorithms provide with the required automation level by replacing the need of human intervention during the processing of the data, without compromising the accuracy when compared with supervised methods like the Rig State.

Furthermore, the physics of the hydraulics and torque and drag modelling has been found to reflect reality, even in those cases that have achieved results beyond the known limits, such as the longest liner casing run in the region. This specific result reinforces the validity of the solution and provides confidence in the RTOC services as a trustful resource within the organization.

Nomenclature

BHA	Bottom Hole Assembly
BPOS	Block Position [m]
ComputedECD	Computed Equivalent Circulating Density [sg]
ComputedHKLD	Computed Hookload [kN]
ComputedSPP	Computed Standpipe Pressure [kPa]
ComputedTQA	Computed Surface Torque [kN.m]
DMSE	Downhole Mechanical Specific Energy (Pa)
DTQA	Downhole Torque [kN.m]

DWOB	Downhole Weight On Bit [kN]
ECD	Equivalent Circulating Density [sg]
ECD_BIT_HY	Simulated ECD [ppg]
EMW	Equivalent Mud Weight [sg]
FF	Friction Factor
FLWI	Mud Flow Rate In [l/min]
HKLD	Hookload [kN]
MD_BPOS	Block Position [ft]
MD_DBTM	Bit Depth [ft]
MD_DMEA	Hole Depth [ft]
MD_HKLD	Hookload [1000 lbf]
MD_MFOP	Mud Flow Out Percentage [%]
MD_ROP	Rate of Penetration [ft/h]
MD_SPPA	Standpipe Pressure [psi]
MD_SWOB	Weight on Bit [1000 lbf]
MD_TDRPM	Top Drive RPM [c/min]
MD_TDTRQ	Top Drive TRQ [1000 ft.lbf]
MD_TFLO	Total Flow in [gal/min]
MSE	Mechanical Specific Energy (Pa)
PU	Pick Up
QA	Quality Assurance
QC	Quality Check
ROP	Rate of Penetration [m/h]
RPM	Rotation Per Minute [c/min]
RSS	Rotary Steerable System
SO	Slack Off
SPP	Standpipe Pressure [kPa]
SPPA_HY	Simulated SPPA [psi]
TQA	Surface Torque [kN.m]
TRPM	Total Rotation Per Minute [c/min]
WITSML	Wellsite Information Transfer Standard
WOB	Surface Weight on bit [kN]

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