Modelling and Simulation

The Drilling Systems Automation Roadmap Modelling and Simulations section provides an overview of the transition of models and simulations from current applications to the needs in an automated environment.

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Functional Description

Modelling and simulation are used in well design and planning to define system capabilities and maximum operating envelopes. Modelling and simulation can enable automation through developing data that cannot be measured by sensors.

Modelling is understood as the purposeful abstraction of reality, resulting in the formal specification of a conceptualization and its underlying assumptions and constraints. Models are used to support the implementation of an executable version. Although usually on a computer, physically scaled models have also been used.

The execution of a model over time is understood as the simulation. Modelling helps predict the behavior of a complex system and attempts to minimize undesirable effects through simulation. While modelling targets the conceptualization, simulation primarily focuses on implementation; modelling resides on the abstraction level and simulation resides on the implementation level. Simulation can be used when the real system cannot be engaged, because it may be inaccessible or dangerous or unacceptable to engage, as is the case in many downhole characteristics of the drill string and BHA, fluid circulation and formations.

In the context of drilling, simulations are defined as processes designed to replicate one or more aspects of the drilling process. The complexity is such that multiple simulations can be applied simultaneously, which requires each simulation to have a strong awareness of the ecosystem of all simulations operating at the same time. It is highly probable that a simulation will rely on the output from other simulations that are running simultaneously or were run previously. Because any number may operate at the same time, the number of interactions of these simulations are limitless.

Most simulations are run in advisory mode during which a human may interrogate and validate results to confirm the output prior to acting on it. As drilling automation matures, dependency on accurate simulations and the underlying models (algorithms) that drive these simulations becomes more relevant because the results are instantly consumed and delivered as control instructions to machines. Consequently, the human validation workflow will no longer be the primary control but will move to a supervisory level.

The objective of simulations and modelling is to map the ecosystem and bring a degree of controlled engagement to the various simulations available to the drilling automation process. Understanding how and when each system participates is critical. The objective of the industry roadmap is also to ensure that the ecosystem remains agnostic, which ensures that any simulations brought into the drilling automation systems architecture can be easily adopted. This approach enables progressive development in the drilling automation space through participation of any party in compliance with the architecture.

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Simulations are the perceived results of one aspect of the drilling system and may depend on certain knowns, such as the mechanical properties of elements in the drill string. Simulations may also depend on unknowns, such as the exact rock properties at the drill bit during drilling operations. Because the exact rock properties at the bit cannot be measured, they are simulated using a suite of engineering models. A simulation may derive the rock properties as a simulation itself or it may infer the rock properties based on some discreet part of a larger simulation, such as a penetration-rate optimization simulation.

When fostering an open ecosystem and depending on how the simulation interacts with the overall drilling automation process, the complexity of inputs and dependencies may require an expansive level of detail. For example, in a torque and drag simulation, a pipe-stretch model developed on the foundation of drill pipe properties relies on a temperature model to determine the exact physical characteristics of the pipe at various depths. The wellbore surveying model influences the determination of touch points along the well trajectory. A hydraulics model is used to determine the fluids effect along the annulus of the wellbore as well as the hydraulic loads on the complete system. The earth model derives lubricity friction-factor values and formation pressures along the borehole. These interrelationships can easily become very complex even for a conventional torque and drag simulation.

Overarching dependencies exist within the simulation challenge itself but collaborative dependencies on other broader application types may be required. For example, when automating tripping pipe, the detailed hydraulics model, the detailed rock strength model and the torque and drag model all must work together in a multivariate approach. At the same time, all this activity is dependent on understanding the drill state, that is, knowing when the drill string is in or out of slips, moving up or down or rotating.

An additional key dependency is the state of the well, which is the highest order for defining what simulations take priority at any given time. For example, if the system is drilling ahead driven by an ROP optimization model with a directional control model steering the well, a prioritization simulation can determine that the directional requirements take precedence over the ROP requirements. In the event of a sudden influx, the well-control simulation jumps to top priority. To navigate these multiple levels of dependency, it is first necessary to investigate how each simulation participates within the drilling framework and how robust it is at any given time.

Common models are listed below:

- Torque and Drag
- Rate of Penetration
- Seismic (1D – 4D)
- Mechanical Earth Model
- Shock and Vibration
- Pore Pressure
- Wellbore Survey

- Anti-collision model
- Casing load model
- BHA prediction model
- Drill bit cutting model
- Well control simulation
- Cement displacement model
- Well Placement
- Hydraulics models (fluid properties, ECD prediction, hole cleaning)
- Drilling Hazards

Performance targets

The goal for the drilling industry is to develop a standard format that allows any simulation to be safely and efficiently assessed for insertion into the overall automation systems architecture without disruptive consequences. Achieving this requires the industry to define a drilling applications multidimensional decision tree that controls the hierarchy of participating simulations in the system at various drill states and well states. This hierarchy must be based on a long list of common well-known simulations and models.

Model Uncertainties

A challenge for the industry is to characterize the uncertainties in models used to design wells and to plan and manage the drilling process. Well bore position uncertainty, through the development of error models that show ellipsoids of uncertainty surrounding any portion in a well, is the type of analysis that needs to be undertaken on other drilling data and drilling models.

A key example of this type analysis is the model for well pore and fracture gradient. The initial model has a degree of uncertainty that is not normally characterized. The actual drilling data can be used to update this model and provide a more certain model of the pore and fracture gradient. Understanding the uncertainties in these models will improve decision making by humans and, later, by automated systems.

Sensor Specification

Sensor data must include metadata that defines key characteristics of the measured data such that the automated system knows both the type and the value of the information it is using. The metadata must include key aspects, such as a common time stamp, so that data from various sensors can be correlated for control or for modelling and thence control. Metadata also must include information showing how accurately that the data represents the physical parameter it is purporting to represent. Basically, metadata helps determine sensor accuracy and how representative is the data value of the measured parameter. For example, the parameter, WOB, is determined from string weight, which may in fact be a drill line tension measurement made far from the true string weight location, which significantly impacts the accuracy of this data. In addition to the accuracy, precision and repeatability of the sensor, the sensors' history must be known—specifically the calibration type and date—to determine how well the sensor data can be relied upon as a true representation of reality.

The drilling industry will need to apply the type of verification and validation procedures that are typically applied in high technology automated industries, such as commercial aviation and aerospace. These procedures must follow systems engineering methodologies for sensors and for systems that import the data from the sensors and process and display it and forward it to other applications. The PMBOK guide, a standard adopted by IEEE, defines verification and validation as follows in its fourth edition:

- Verification. The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation.
- Validation. The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with verification. [1]

Verification and Validation (V&V) is a well-developed and well-defined practice based upon systems engineering. V&V processes determine if products (sensors and systems) of a given activity conform to the requirements of that activity and if the sensor and software satisfies their intended use and user needs. As defined in the IEEE standards, V&V processes include activities such as assessment, analysis, evaluation, review, inspection and testing of software products and processes. The extent to which IV&V is applied is defined by user requirements, combined with expert opinion on restricting interventions to those sufficient for assurance. Realistic, fit-for-purpose, and effective IV&V programs are driven by industry experts to which the program applies.

Current Situation

Many simulations and models have been created across the industry by various participants. These fall into the following categories:

- Industry accepted simulations and models that have been developed and published into the public domain (e.g. ellipsoids of bore hole position uncertainty).
- Proprietary simulations and models that are owned or used by a party for its own operations management and decision making and appear to third parties as a 'black box'.
- Proprietary simulations that are made available as a service to any party and are transparent to the user.

Some simulations and models have been verified by operational data while others are presented as poorly or unverified 'black boxes.' One risk of current practices is that simulations and models do not account for errors in many measurements for deriving the simulation or for verifying the simulation accuracy.

Examples of current models and simulations include:

- Drill string dynamics models have developed into very sophisticated models requiring high computational power to process. These models give good insight to the behaviors of the bit, the BHA and the drillstring without claiming to be highly accurate. Newer models are being introduced that are based on more sophisticated techniques, which will create faster analysis and reduced computing power requirements.
- Mechanical Specific Energy (MSE)models have provided significant insight to managing drill string energy and have resulted in improved drilling performance.
- Torque and drag models provide understanding the friction forces on the drillstring, which leads to an understanding of the 'weight' absorption along the well bore and thus realizing the real weight on bit.
- Guiding directional decision-making models predict the trajectory of a drilling assembly allowing the input parameters to yield the intended result with minimum increase in borehole tortuosity.
- Borehole cleaning models for horizontal and long reach wells model complex interactions of mud rheology, drill string rotation, flow rate and bore hole trajectory in delivering cuttings removal, which requires a comprehensive understanding to avoid trouble time (nonproductive time).

For purposes of drilling automation, models and simulations that are used for well planning are being migrated to the real-time domain to be used in real-time diagnostics. Examples of this migration include borehole hydraulics, pressure management, hole cleaning and casing wear. This migration creates new demands on these models, especially in terms of both accuracy of output and real-time computation.

Problem Statement

Key Questions pertaining to models include:

- What does the model do?
- How will the model interface with the system?
- What resources will be required of the model?
- How is the model validated?
- How frequently will this data validate?
- How is the validation data validated?
- What are the consequences to the drilling system of a poorly validated model or of poorly validated data?

Barriers

Black boxes

Numerous processing services claim to analyze data and produce results that will enable the driller to improve drilling performance. Possible shortcomings of these offerings include:

- Drillers will rarely drill off third party systems and will remain with their own control system interface because that is the measure by which they are actually judged. A primary issue is liability of the drilling contractor in the event of a system induced incident.
- Third party data processing offerings have rarely been systematically tested against a known situation to evaluate their interpretations.
- If the data sources are inaccurate or the data is not representative of model or simulation’s expected input, a “garbage in- gospel-out” situation may develop.
- Bad data may be used on models and simulation without attention to the impact of the bad data.

Needs

Numerous data points in drilling operations will never be accessed by an appropriate sensor and therefore will require a model to provide the best insight to this ‘inferred data.’ To ensure models can reliably be applied to automation, several needs must be addressed.

Models must be verified, validated, certified and benchmarked, and key model assumptions need to be apparent and transparent to the end user. Furthermore, model limitations have to be clearly stated so they are not applied outside their applicable envelope and the methodology of calculations used in the models must be understood.

Drilling and wellbore state definitions are required to enable the correct model hierarchy to automatically implement. Systems Architecture provides the map for the application of models and simulations; it defines their interaction through the Systems of Interest, data sourcing through the mapping of use cases against Systems of Interest, and model hierarchy of application from states definition.

Critical Success Factors

It is important to develop a common industry framework for the relationship of models that allows various models to be incorporated in an interoperable manner having the correct hierarchy of application. Many companies are developing models and simulations as a product offering to the industry for normal drilling and for later application to automated drilling. Although these ad hoc applications yield results, because of the architecture of interdependencies with other models and the quality of data sources from outside the providers influence is not understood or managed, they also add risk.

Way Ahead

Many models exist in the planning phase that can be converted to real-time applications able to provide feedback to the drilling process. Many calculations are performed with poorly defined output, such as ROP, which is poorly defined as to how it is calculated. These calculations need better mathematical definitions to ensure distinctions between measurement variants. A framework is needed for differentiating raw measurements from derived measurements and for how to integrate this into an automated system. This framework will depend upon the information model used by the data aggregator and upon standards developed by the industry.

A comprehensive overview of models provides characterization of these models and their attributes including:

- Model analysis—Simulation process and model description
- Model speed—response time to changed inputs
- M&S as a function of well complexity
- Applicable drill states under which the model will be operating
- Data inputs required
- Calculations provided by model
- Data Quality Dependencies
- Automation Action what model will make happen
- Control Data Frequency—rate at which control data is coming to the model
- Consequence of Failure—worst case consequence if model misbehaves
- Failure Mitigation—how worst case is mitigated

This characterization must be completed to gain a comprehensive view of all models applied to DSA. Without this approach, risks of failures and financial loss remain.

Models that have been applied in desktop mode in planning are being migrated to the cloud where they can be accessed more readily for application during drilling operations with results input to the driller's control for drilling decisions. This creates an opportunity to apply real-time modelling with an effective graphics interface connected into the drilling control system for the driller to take advantage of these models for supervisory or autonomous control.

Models and simulations will hierarchically be employed according to the DSA Decision Making and Control Framework based on ISA 95 / MES – see Systems Architecture Section. For effective application, the Reference Architecture can address the high level and common interaction between the models for a basis of standardization across the industry. Interactions in specific applications will eventually be detailed in the solutions architecture after a long period of ad hoc individual bottoms-up application with the inherent risk of this approach.

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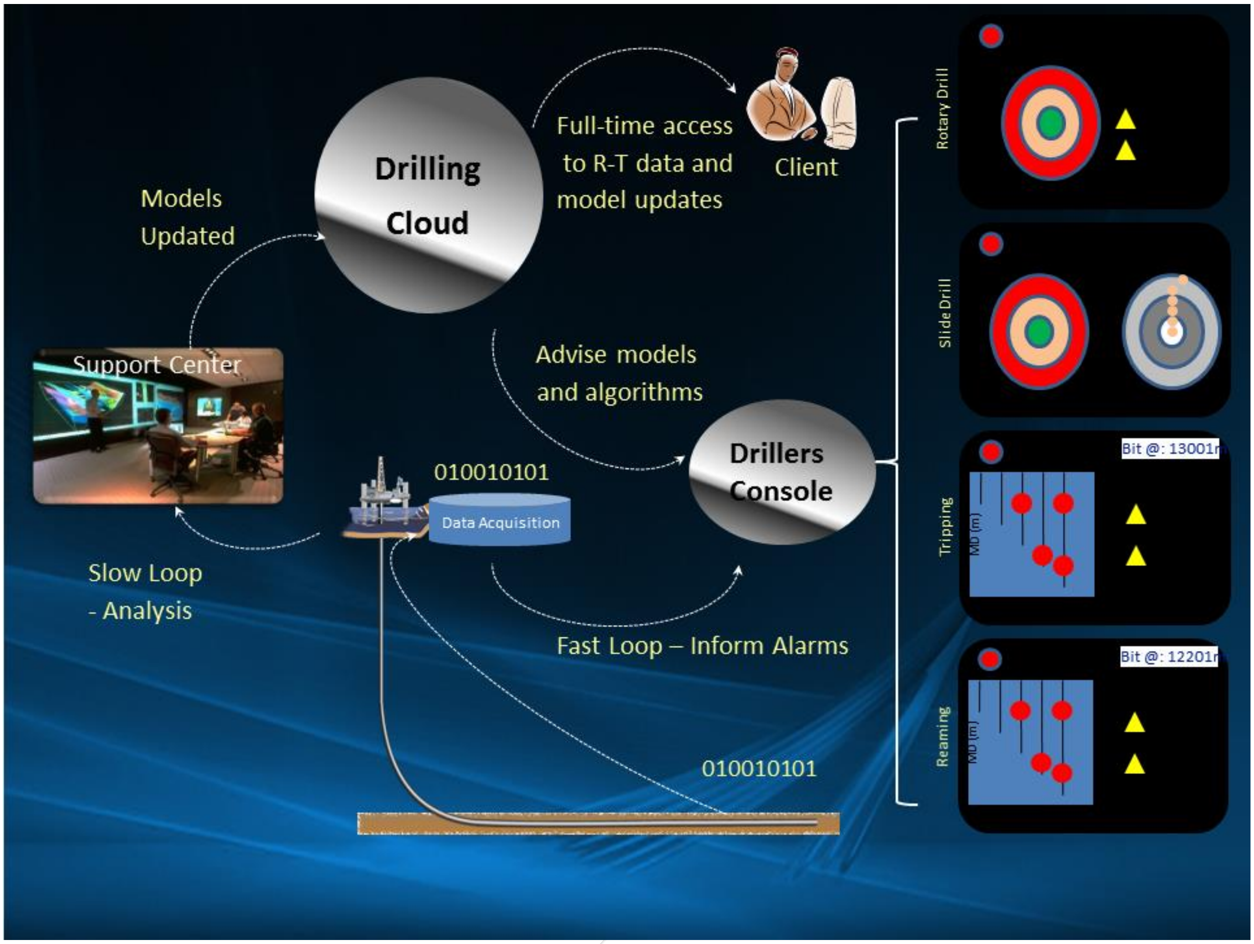

Figure 1: Overview of Models in a Future DSA Environment

The industry needs to develop a program whereby models and simulations are assessed in a controlled manner that allows them to be verified, validated, certified and benchmarked. Within this process, aspects of the model and simulation need to be formally communicated and must include key model assumptions, must model limitations to avoid application outside their envelope, and document the methodologies of the calculations used in the models.

Digital Twins

Digital twins are starting to be employed in the drilling operations industry.[2, 3] A digital twin is a computer-generated replica of a physical asset. In drilling, this could be a rig or some key components of a rig or, in the future, a well. A digital twin is intended to behave exactly like its physical counterpart in the past, present and possible future. This enables a real-time parallel twin to manifest attributes of the real thing, which provides the opportunity to digitize the real world and use this as an input to drilling systems automation. Digital twins are expected to become a key tool supporting the advance of drilling systems automation.

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Tabulation of Models

	Simulation / Model	Fast Loop	Slow Loop	Well Complexity	Applicable Drill States	Rotation	Pumping	movement	Hookload	Other Data	Data Quality Dependencies	Automation Action	Control Data Frequency	Consequence of Failure	Consequence Control
tructi	**Name and describe the nature of the simulation / model**	Select model data output speed. Ie. Fast for real-time, slow for predictive	Select model data output speed. Ie. Fast for real-time, slow for predictive	Is the output of the model a function of well complexity?	Select applicable drill states for when the model will be active or predictive	Physical descriptors for rotation, pumping, movement and hookload will autofill based on rig state selections				Input any other data that will be required for the model or simulation. This can be input data, qualifying data, or output data	Input dependencies that will drive quality of model output. Purpose is to allow a validation loop prior to executing an automation action	Describe any automation actions resulting from the model, either predictive or executable	Select the appropriate speed the model will drive each automation control	Describe any consequenced of failure if the model predictions are incorrect	For each consequence of failure describe appropriate control measures to limit worst consequence
1	**Rate of Penetration - Instructive: real-time control instructions to maximize ROP based on a predictive model**	Yes	No	No	DrillRot DrillSlide	✓ x	✓ ✓	↓ ↓	Low Low	Resistivity, GR, Porosity, Permeability	Calibrated rig sensors	WOB (+/-) RPM (+/-) Flow rate (+/-)	Seconds Seconds Seconds	1. Excessive WOB = damaged BHA 2. Low WOB = lost efficiency 3. Excessive Pump = equipment damage 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage 6. Low RPM = lost efficiency, hole cleaning risk	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. APWD, Performance validation - offsets 5. Threshold limit 6. APWD, Performance validation - offsets
2	**Rate of Penetration - Predictive: pre-drill model developed through offset data analysis or mechanical earth model**	No	Yes	No	DrillRot DrillSlide	✓ x	✓ ✓	↓ ↓	Low Low	Resistivity, GR, Porosity, Permeability, compressive strength	Quality, quantity of offset data	WOB (+/-) RPM (+/-) Flow rate (+/-)	Minutes Minutes Minutes	1. Excessive WOB = damaged BHA 2. Low WOB = lost efficiency 3. Excessive Pump = equipment damage 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage, rig limits 6. Low RPM = lost efficiency, hole cleaning risk, stalling	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. APWD, Performance validation - offsets 5. Threshold limit, rig requirements 6. hole cleaning prediction,drive syste (rig, downhole) requirements
3	**Drilling Dynamics - predictive: shock and vibration modelling based on FEA analysis of drilling conditions**	No	Yes	Yes	DrillRot DrillSlide RihPumpRot RihPump PoohPumpRot PoohPump StaticPumpRot StaticPump	✓ x ✓ x ✓ x ✓ x	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	↓ ↓ ↓ ↓ ↑ ↑ x x	Low Low Low Low High High ~T ~T	Drill string components and dimensions, fluid properties, borehole properties (orientation, dimensions, rugosity) Rock properties,	input data quality, quantity	WOB (+/-) RPM (+/-) Flow rate (+/-)	Minutes Minutes Minutes	1. Excessive WOB = damaged BHA 2. Low WOB = lost efficiency 3. Excessive Pump = equipment damage 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage, rig limits 6. Low RPM = lost efficiency, hole cleaning risk, stalling	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. APWD, Performance validation - offsets 5. Threshold limit, rig requirements 6. hole cleaning prediction,drive syste (rig, downhole) requirements
4	**Drilling Dynamics - reactive: shock and vibration management based on real-time drilling conditions. **Note: telemetry will dictate drill states when model can be active**	Yes	No	No	DrillRot DrillSlide RihPumpRot RihPump PoohPumpRot PoohPump StaticPumpRot StaticPump	✓ x ✓ x ✓ x ✓ x	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	↓ ↓ ↓ ↓ ↑ ↑ x x	Low Low Low Low High High ~T ~T	Downhole data: Multi-point Accelerometer and Magnetometer, APWD. Rock property indicators, offset data	Downhole sensor calibration, telemetry rate, telemetry interferences	WOB (+/-) RPM (+/-) Flow rate (+/-)	Seconds Seconds Seconds	1. Excessive WOB = damaged BHA 2. Low WOB = lost efficiency 3. Excessive Pump = equipment damage 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage 6. Low RPM = lost efficiency, hole cleaning risk	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. APWD, Performance validation - offsets 5. Threshold limit 6. APWD, Performance validation - offsets
5	**Hydraulics: Hole cleaning - predictive**	No	Yes	Yes	DrillRot DrillSlide RihPumpRot RihPump Rih PoohPumpRot Pooh StaticPumpRot StaticPump	✓ x ✓ x x ✓ x ✓ x	✓ ✓ ✓ ✓ x ✓ x ✓ ✓	↓ ↓ ↓ ↓ ↓ ↑ ↑ x x	Low Low Low Low Low High High ~T ~T	Drill string components and dimensions, fluid properties, borehole properties (orientation, dimensions, rugosity) Rock properties, cuttings load	input data quality, quantity	WOB (+/-) RPM (+/-) Flow rate (+/-) cleanup cycle properties cleanup cycle time trip speed	Minutes Minutes Minutes Hours Seconds	1. Excessive WOB = cuttings loading 2. Low WOB = lost efficiency 3. Excessive Pump = packoff 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage 6. Low RPM = lost efficiency, hole cleaning risk 7. Poor clean-up properties = hole cleaning risk 8. short cycle time = hole cleaning risk 9. long cycle time = lost efficiency, washout 10. Fast trip speed = stuck pipe 11. Slow trip speed = lost efficiency	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. Performance validation - offsets 5. Threshold limit, rig requirements 6. hole cleaning prediction,drive syste (rig, downhole) requirements 7. Performance validation - offsets 8. Performance validation - offsets 9. Performance validation - offsets 10. Performance validation - offsets 11. Performance validation - offsets
6	**Hydraulics: Pressure management - predictive**	No	Yes	Yes	DrillRot DrillSlide RihPumpRot RihPump Rih PoohPumpRot Pooh StaticPumpRot StaticPump	✓ x ✓ x x ✓ x ✓ x	✓ ✓ ✓ ✓ x ✓ x ✓ ✓	↓ ↓ ↓ ↓ ↓ ↑ ↑ x x	Low Low Low Low Low High High ~T ~T	Drill string components and dimensions, fluid properties, borehole properties (orientation, dimensions, rugosity) Rock properties, cuttings load	input data quality, quantity	WOB (+/-) RPM (+/-) Flow rate (+/-) cleanup cycle properties cleanup cycle time trip speed	Minutes Minutes Minutes Hours Seconds	1. Excessive WOB = cuttings loading 2. Low WOB = lost efficiency 3. Excessive Pump = packoff 4. Low pump = hole cleaning risk (stuck pipe) 5. High RPM = equipment damage 6. Low RPM = lost efficiency, hole cleaning risk 7. Poor clean-up properties = hole cleaning risk 8. short cycle time = hole cleaning risk 9. long cycle time = lost efficiency, washout 10. Fast trip speed = surge/swab 11. Slow trip speed = lost efficiency	1. Threshold limit 2. Performance validation - offsets 3. Threshold limit 4. Performance validation - offsets 5. Threshold limit, rig requirements 6. hole cleaning prediction,drive syste (rig, downhole) requirements 7. Performance validation - offsets 8. Performance validation - offsets 9. Performance validation - offsets 10. Threshold limit 11. Performance validation - offsets
7	**Hydraulics: Pressure management - instructive**	No	Yes												
8	**Rate of Penetration - Real Time**	No	No												
9	**Wellbore Surveying**	Yes	No												
10	**Anti-collision**	Yes	No												
11	**Trajectory Control**	Yes	No												
12	**Well Placement**	Yes	No												
13	**Torque and Drag**	Yes	No												
14	**Mechanical Earth Model**	Yes	No												
15	**Pore Pressure Prediction**	Yes	No												
16	**Casing Design**	Yes	No												
17	**Casing Running**	Yes	No												
18	**Cement Displacement**	Yes	No												
19	**Drilling Hazards**	Yes	No												
20	**Well Control - Predictive**	Yes	No												
21	**Well Control - Active**	Yes	No												

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