

Operator-Enabled Context-Sensitive Decision Process for High-Risk Offshore Drilling Operations: Enhancing Contextual Knowledge, Advanced Situation Awareness, and Operational Resilience

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Abstract. The rapid evolution of automation along with other technologies has improved operational efficiency in modern industrial assets and systems, such as oil and gas drilling platforms. On the other hand, modern developments in offshore industry have also introduced solutions that are increasingly opaque and cognitively demanding for human operators. For instance, in the context of increasing reliance on Remote Operation Centers and highly automated operations, overdependence on data streams and alarm-based systems generate new decision patterns and knowledge demands, while affecting the contextual sensitivity of human operators. In complex and high-risk operational contexts, such as offshore drilling operations, cognitive interface of operators with actual contextual cues plays a vital role for taking proactive measures in advance owing to multiple complex scenarios that can escalate into unwanted situations. Based on an ongoing research project, this paper explores if and how a hybrid decision process can be incorporated during complex offshore operations ahead of the conventional alarm-based practice, in order to strengthen offshore drilling operators' cognitive capabilities for demanding decisions by enhancing their advanced situation awareness and contextual knowledge about high-risk operations.

1. Introduction

The offshore oil and gas drilling industry operates through complex processes that are continuously exposed to internal and external conditions, which can trigger various types of deviations and failures. Over decades, asset owners and operators have been pursuing greater system resilience and cost-effective solutions. In recent years there has been growing focus, for instance on digitalization and automation as integral parts of complex operations for achieving these objectives. However, despite ongoing technological progress, the sector remains far from having fully fledged solutions. For instance, drilling operations are conducted under uncertain and dynamically changing subsurface conditions, where lack of relevant contextual knowledge can affect reliable and safe operations of advanced technical systems [1]. Effective decision-making in drilling operations requires a better understanding of risk by the operating crew- for example identifying any conditions that can lead to unexpected outcomes. As Cayeux et al., [2] argue, this understanding depends on the ability to measure, recognize unwanted conditions and scenarios, weigh potential effects, and determine appropriate prevention and mitigation actions. Traditional risk-based approaches and alarm-based practices alone are inadequate to support operators in dynamic situations where unfamiliar or unexpected patterns exist [3]. Moreover, decision-making in modern drilling contexts has become more challenging due to new uncertainties embedded within increasingly advanced technological systems.

Just as Endsley and Jones [4], Zio and Pedroni [5] emphasize, human operators should remain an essential part in such decision environments. Their expertise and interpretation abilities of unwanted conditions, preferably with the support of better data-driven solutions, can assist in generating necessary levels of advanced situation awareness. Complex and dynamic operating environments demand a higher level of situation awareness, so-called Advanced Situation Awareness (see Bakhshandeh and Liyanage [6]), where operators must be able to remain sensitive and vigilant towards context-dependent conditions, able to perceive early signals, interpret deviation patterns, and assess if conditions may evolve towards unwanted consequences. However, current practices that keep human operators out of

the loop can introduce cognitive gaps and communication challenges hindering recognition of early warnings and awareness of the changing context. For instance, in offshore drilling operation context, when operators have to rely solely on indirect information such as logs, trend plots, and periodic reports particularly during demanding conditions, information sources often fail to convey the true context of what is happening downhole. This can increase the likelihood of misinterpretation or delayed intervention to prevent unwanted events and incidents, just as exemplified by industrial accidents such as Macondo Blowout and Explosion [7] and Pryor Trust Fatal Gas Well Blowout and Fire [8].

In offshore drilling operations, the ability of human operators to grasp the actual operational context, i.e. having contextual knowledge [3] is important for reducing ambiguities and enabling more effective decision-making contexts. Mitigating current limitations in offshore drilling contexts in this regard, therefore requires solutions that not only integrate multiple sources of online and offline data, but also that can transform information into meaningful and context-representative insights to enhance human sense-making abilities and thus can facilitate the early identification of warning signals and deviations.

As it appears, recent advancement in data-assisted technology within the offshore oil and gas industry [9], presents some unique opportunities as a decision-enabling partner for human operators through its reasoning and generative capabilities for various forms of industrial use that can contribute towards better operational resilience in high-risk assets. Focusing on current practices and needs in offshore drilling, this paper explores a hybrid solution as a context-sensitive decision-enabling approach for human-operators. The framework proposed here builds on current practices to enhance decision processes, rather than replacing them completely with a new approach, for instance utilizing previous studies that have shown how downhole annular pressure can be interpreted to establish associations with drilling problems [10] and how hole-cleaning conditions can be evaluated in real time [11]. Its purpose is to integrate three elements around the operators' decision context, namely: distributed downhole pressure measurements combined with surface data to indicate where a deviation develops; contextual reasoning that relates the deviation to geological, planning and historical knowledge; and a structured explanation that the human-operator can assess and can give feedback on. The framework also extends some earlier work on advanced situation awareness [6], deviations and the extended intervention window [12], the generic hybrid contextual decision solution (HCDS) [13], and early sense-making in industrial processes [3]. Using an illustrative hole-cleaning scenario from offshore drilling, the paper outlines how human–data technology interface could enhance conventional decision-making processes into a more data-assisted, knowledge-driven, and context-sensitive practice.

2. The context of the study and the focus

Offshore drilling is a complex and technically demanding process that involves drilling of wells below the seabed to extract oil and gas. Offshore drilling operations require an integration of advanced technology, equipment, operational crew, and highly interconnected systems to ensure safety and reliability. The complexity of such operations can also be elevated for instance by environmental factors such as environmental conditions, deep water, geological parameters, and remote locations [14]. This study specifically focusses on an operational context in offshore drilling where unwanted situations and conditions can be examined using high-frequency downhole data transmitted from pre-positioned sensors. When drilling a long horizontal section offshore, unwanted situations such as poor hole cleaning and pack-off events can occur due to various causes. In this paper, it is explored how downhole pressure variables can be selected as early indicators and can be analyzed to capture early-signs of potential deviations under such wellbore conditions. The study follows an approach in three steps: first, the decision problem in hole cleaning is systematized from the literature and domain knowledge; second, a hybrid decision-support framework is elaborated on; and third, its logic is illustrated through a practical scenario. The scenario is not based on actual field experiments or simulations based on field data collected but serves the purpose of proving the practical usability based on an illustrative approach in a real drilling context.

3. Hole cleaning during offshore drilling operations as a complex process and the need for early sense making

In drilling operations, hole cleaning represents one of the complex and interdependent operations. Its actual efficiency is governed by a multitude of direct and indirect interactive factors within the drilling environment as shown in Figure 1. Here the direct factors include the hydraulic and rheological behavior of drilling fluid such as plastic viscosity, yield point, gel strength, density, as well as other key hydraulic parameters as flow rate, annular velocity, annular pressure, and pump flowrate. In parallel, several mechanical and operational parameters for example, the rate of penetration (ROP), rotary speed (RPM), weight on bit (WOB), hole inclination, and drill-pipe eccentricity, also directly influence the cuttings generation and transport efficiency [15, 16]. Beyond these direct influences, a range of indirect factors further complicate the cleaning process. These include formation characteristics (lithology, fractures, and weak zones), cuttings morphology (size, density, and shape), thermal and pressure variations, and the efficiency of surface solids-control systems, and drilling practices [17].

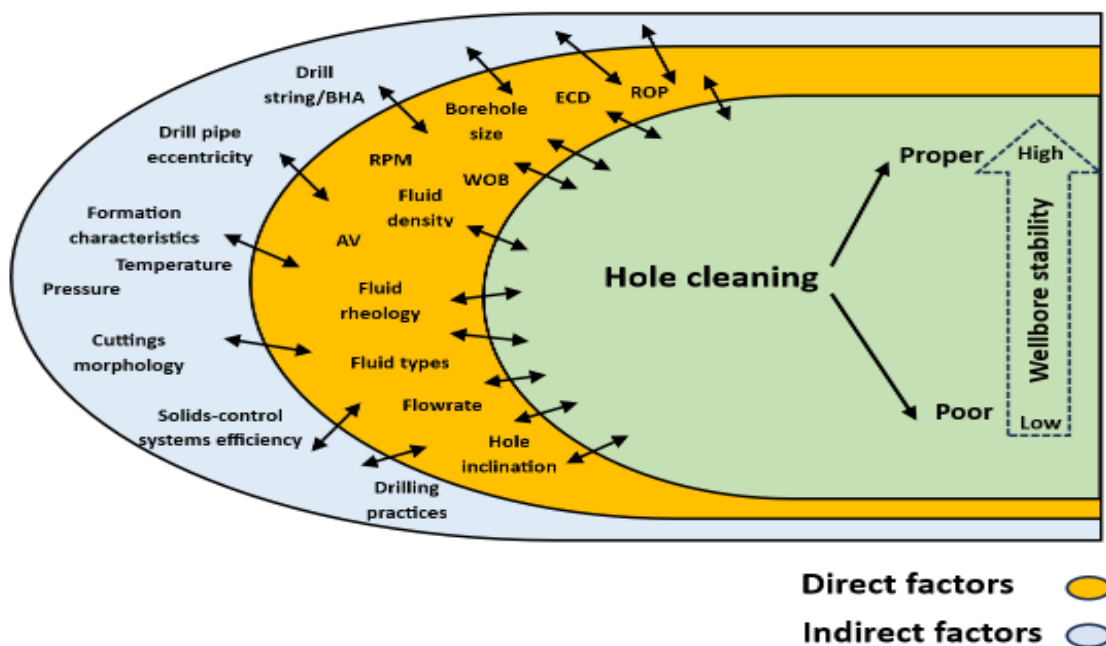


Figure 1. Direct and indirect factors affecting the complexity of hole cleaning

The interdependencies between fluid behavior, hydraulics, mechanical dynamics, and chemical interactions evolve continuously along the well trajectory over time. In particular, fluid rheology and density are functions of both temperature and pressure, meaning that variations in these parameters can significantly affect hole-cleaning efficiency. Elevated downhole temperatures generally reduce viscosity and gel strength, weakening the mud's ability to carry cuttings, while pressure variations alter fluid density, impacting hydraulic balance and cuttings transport (together, these effects are reflected in Equivalent Circulating Density or ECD).

Poor hole cleaning can lead to significant operational challenges, as it is both time-consuming and costly to manage. In severe cases, it may even result in well abandonment [18]. According to Qu et al. [19], nearly 70 percent of drilling time losses are attributed to stuck-pipe incidents, with approximately one-third of these cases resulting from inadequate hole cleaning. These demanding conditions underline

the need for effective strategies and proactive monitoring to ensure wellbore stability as well as to ensure safe and efficient drilling performance. Since these variables can influence hole cleaning process in diverse manners and since the process is highly context-sensitive, there are some practical difficulties to accurately comprehend or to optimize hole cleaning process through linear models or with fixed parameter limits.

Several models have been developed to predict and evaluate hole-cleaning performance in offshore drilling operations, ranging from empirical and statistical approaches to transient and mechanistic simulations (see, for example, [11, 20]). Although these approaches have improved real-time monitoring and have provided a quantitative understanding of cuttings transport, they remain largely parameter-dependent and context-limited. These models in most cases try to quantify outcomes without explaining the underlying patterns and causal associations in their predictions. In particular, the decision-making processes associated with many data-driven algorithms for hole cleaning remain opaque to human decision-makers, leading to misinterpretation of current events, inadequate awareness of actual context, and consequently delayed or erroneous decision-making. In this context, where human operators' cognitive tasks, system interactions, and environmental factors are increasingly intertwined, early sense-making of cues and deviations are beneficial before they propagate to such a level that cannot be controllable, endangering system safety and resilience. A hybrid approach can be quite effective in such decision environments that can combine the analytical and generative strengths of data-driven approach, together with the experiential knowledge of human operators and contextual reasoning.

4. Supporting risk-informed decisions, early sense-making of deviations, and the use of downhole annular pressure measurements

In the dynamic and fast-paced drilling environment discussed previously, it is the human operator's responsibility to monitor trends, detect unusual patterns or spikes, integrate signals with other drilling parameters to interpret and assess wellbore conditions and determine appropriate counteractions, which is far from a straightforward operational decision situation. Given the demanding downhole conditions during offshore drilling, continuous monitoring is a vital part of the decision-making context in order to ensure reliable and safe operations. In certain situations, even minor decision delays can allow escalation of conditions into significant operational hazards. Owing to these operational demands, this paper elaborates on how early signals can be captured by multiple downhole sensors, and together with other data sources and suitable decision interface, how it can support human operators during offshore drilling operations (Figure 2).

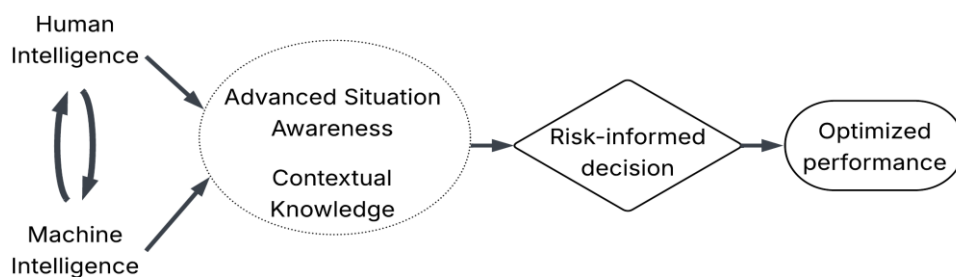


Figure 2. Synergy of Human–Machine intelligence for optimized performance, adapted from [21]

From a methodological perspective, when an unwanted condition or a deviation is sensed, the key data need to be extracted from relevant sources so that relevant reasoning can be generated based on an effective fusion of both available information-plot as well as operators' domain expertise. In order to convert this process into meaningful sense-making insights, a cause-and-effect approach needs to be utilized, which can potentially strengthen the situation awareness of human operators relatively early and thus enable them to intervene proactively.

Owing to some years of dedicated work in the domain of offshore drilling, both wired drill pipes and downhole sensors have recently enabled higher data transmission speeds with minimal loss (see for example [22–24]). Although a variety of such data-driven applications and digital solutions are being developed and applied, their inability to fully integrate downhole data with diverse data sources in real time and demanding decision contexts is still a limiting condition. Further efforts are therefore needed to better combine these data streams in order to support operators with a coherent, real-time view of downhole conditions and actionable recommendations. For instance, downhole annular pressure is now widely used across various drilling applications, because when it is interpreted alongside other downhole and surface parameters, it can enable early sense-making of emerging conditions [25]. For instance, when combined with other drilling data and pressure in the context of use of various drilling parameters, annular pressure measurements can help identify poor hole cleaning, pack-off, gas or liquid influx (kick), and lost circulation [10]. To interpret downhole annular pressure correctly, it is essential to recognize that the measured pressure consists of two components: static pressure, which results from the weight of the mud column, and dynamic pressure, which arises from fluid movement, rheological properties, and other operational factors [11]. While some parameters that influence dynamic pressure can be controlled by operators, others such as temperature and certain downhole conditions cannot be controlled in the same manner. A combination of these parameters defines the so-called Equivalent Circulating Density (ECD), which represents the effective density exerted by the drilling fluid column at a specific true vertical depth in the wellbore on the formation. Understanding ECD is an essential and a useful issue that can enable early sensing of wellbore stability issues and managing risks of drilling operations. Based on these new opportunities available, this paper elaborates on leveraging a hybrid-technique in the next section to strengthen the decision-making capabilities of operators in offshore oil & gas drilling environments.

5. The hybrid technique to support Operators' decision-making capabilities during offshore hole cleaning process

In order to establish a proper basis for the hybrid technique in a realistic operational context, a drilling hole section is used here that consists of multiple geological formations, including a challenging shale interval within a narrow pore- and fracture-gradient window. Downhole sensors are pre-positioned at different depths to provide continuous annular pressure measurements transmitted via wired drill pipe while drilling.

As discussed earlier, ECD derived from downhole annular pressure, when combined with other drilling parameters, can provide early insight into changing wellbore conditions. Although such measurements are increasingly available in current practice, they are often interpreted in isolation or reduced to numerical thresholds. The challenge, therefore, is not the lack of data, but the absence of a structured mechanism for transforming these distributed measurements into contextual, explainable knowledge that supports early decision-making under uncertain conditions. Figure 3 illustrates how these downhole pressure measurements in the chosen context can be utilized meaningfully, for instance by assessing how pressure varies along the wellbore and how deviations can be interpreted on that basis. This could be achieved through integrated sensing, pattern and event identification using data analytics, and 5W1H explanation interface (i.e. *What, Where, When, Why, Who, and How*) to support decision processes to help mitigating the potentials for unwanted events and incidents. The technique in principle consists of; *data acquisition, pattern identification, event detection, explanation engine, and knowledge base interaction*.

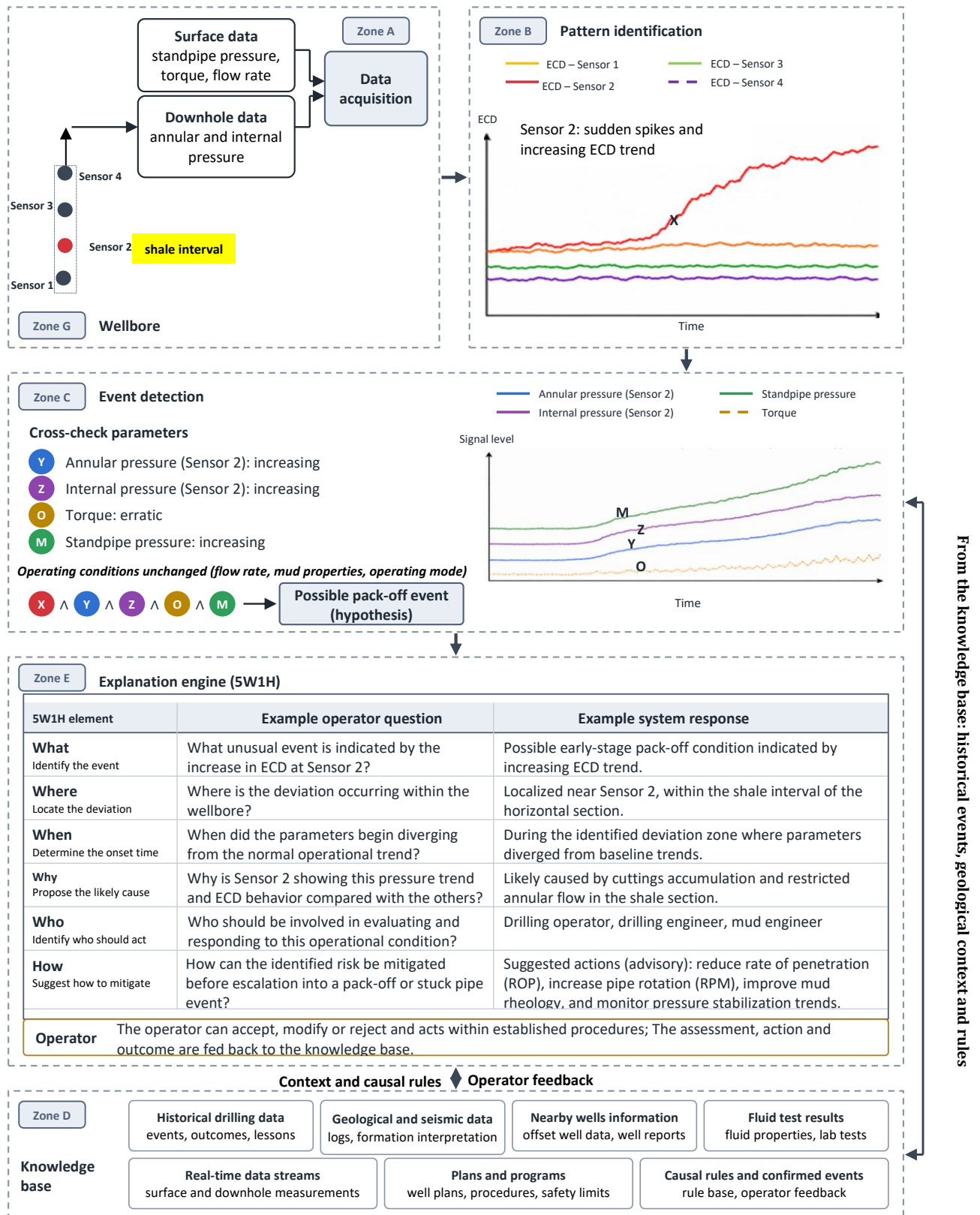


Figure 3. Workflow of the proposed HCDS-approach; adapted for hole cleaning process in offshore drilling operations.

The main elements of this approach are further elaborated below.

5.1. Data Acquisition

The workflow begins with data acquisition (Figure 3, zone A), where real-time drilling data can continuously be collected from downhole and surface sensors. This includes surface measurements such as pump flow rate, torque, and standpipe pressure, as well as subsurface parameters such as annular pressure. These datasets provide the foundation for necessary analysis in the early stages and for understanding of wellbore behavior.

5.2. Pattern Identification

In the pattern identification stage, the acquired data streams are analyzed to identify unusual patterns that may indicate deviations from usual operating conditions (for an overview of available pattern identification techniques, see [26]). This step is intended to detect and define early warning signals and characterize dynamic behaviors that might not be immediately visible to human operators. In the illustrative scenario, while drilling the section, variations in annular pressure measured by the second downhole sensor (Figure 3, zone G) are reflected as sudden spikes and increasing in ECD response (red curve at point X), as shown in Figure 3, zone B.

5.3. Event detection

This stage bridges the gap between raw data and operational interpretation, allowing the system to recognize early deviations and trigger further reasoning processes. The event detection process is supported by a dedicated knowledge-based system in which targets, operational variables, actual deviations, and influencing factors are defined. Such a Knowledge base can incorporate historical event records, geological information, and rule-based relationships, allowing the system to distinguish operational deviations from normal fluctuations and thus helping to ensure that detected events reflect operationally significant situations. In the illustrative scenario, once such patterns are identified by the second sensor, these irregularities are cross-checked against other parameters to confirm the event (Figure 3, zone C). An increase in internal pressure (purple curve at point Z), erratic drill string torque behavior (yellow curve at point O), an increase in standpipe pressure (green curve at point M), and an increase in annular pressure (blue curve at point Y) are consistent with cuttings build-up and an elevated risk of pack-off- corresponding to the shale interval identified in the geological logs. (highlighted in brown formation in Figure 3, zone G).

5.4. Explanation engine

The signals can also have other causes and do not on their own establish a pack-off. The framework therefore interprets them in context: changes that coincide with a change in flow rate, mud properties or operating mode are attributed to that change, and the distributed measurements help to separate a local restriction in the annulus, which raises pressure only at the sensors below it, from causes that affect the whole annulus.

The explainability layer, which is structured around the 5W1H framework, transforms detected events into human-understandable explanations. This layer is directly connected to the knowledge base (Figure 3, zone D), from which it retrieves contextual information, causal rules, and outputs from causal models to propose likely causes and explain the rationale behind detected events. Through this two-way interaction, the 5W1H structure is intended to make machine-generated insights transparent and traceable to their evidence. The 5W1H structure organizes the available evidence around the questions that an operator asks when making sense of a situation, since in such contexts the situation awareness largely remains a cognitive state of the operator [4]. The role of the structured output is to provide contextual knowledge as a foundation on which the operator can build such awareness, by facilitating comprehension of the current condition as well as with projections as to how it may further develop. As illustrated in Figure 3, zone E, unusual ECD patterns derived from the second downhole annular pressure sensor, in combination with other parameters, indicate what is occurring in the wellbore. The pre-

positioned sensor layout and wellbore geometry enable identification of where the deviation develops, while time-stamped data establishes when it emerges. Correlating these observations with drilling parameters and stored contextual knowledge, such as geological logs, historical events, and drilling plans, can support reasoning about why the deviation occurs and how it should be addressed, resulting in role-specific, advisory recommendations for operators. Each element of the explanation is presented with its supporting evidence, the alternative explanations that can exist, and a confidence level based on the extent of independent supporting signals. Recommendations that are generated are relevant to the operational context, for instance including the well's operating limits such as the pore and fracture pressure window and equipment limits, as well as to engineering reviews.

5.5. Knowledge base interaction

The knowledge base (Figure 3, zone D) functions as the system's memory. It can be derived from several sources such as well-specific information, geological logs, drilling plans, and historical records and confirmed events from nearby wells; causal relationships between drilling parameters documented in the literature; and the experience of drilling personnel, captured as rules. The knowledge base supports both the event detection and explainability layers by providing the contextual and evidential information required for reliable classification and reasoning. Conversely, it is continuously updated with new data, validated outcomes, and operator feedback, allowing the system's knowledge to evolve over time. The operator's assessment of each explanation (accepted, modified or rejected), the action taken and the observed outcome are recorded, are systematically added to the knowledge base as confirmed events or revised rules after engineering review. This dynamic interaction is intended to support more effective up-to-date reasoning under uncertainty in real operational contexts.

As illustrated in Figure 3, zone C, by incorporating causal relationships between parameters such as ECD and surface drilling variables, the knowledge base (Figure 3, zone D) facilitates reasoning about operational deviations and aids in assessing events such as pack-off. When combined with new data from multiple sources and stakeholders, the relevant knowledge stored in the system can support advisory recommendations to mitigate pack-off, with the aim of addressing issues early, before they develop into more severe problems such as stuck pipe.

In the hole-cleaning case elaborated here, the conventional monitoring practices often detect deviations only after significant changes in well stability has already occurred, thereby limiting the available time for effective intervention (i.e. $\Delta T1$ in Figure 4). In contrast, the proposed HCDS approach is intended to support earlier sense-making by identifying subtle patterns and correlations across multiple data sources before deviations fully develop. Such earlier identification is expected to extend the decision-making window (i.e. $\Delta T2$ in Figure 4) giving operators more time to respond proactively and effectively. Even though not all possible downhole scenarios can be fully captured due to inherent dynamics and uncertainties, integration of available data sources that are distributed across the entire system can provide meaningful and valuable insights into behavior patterns, unwanted conditions, and early-signs of deviations to a considerable extent.

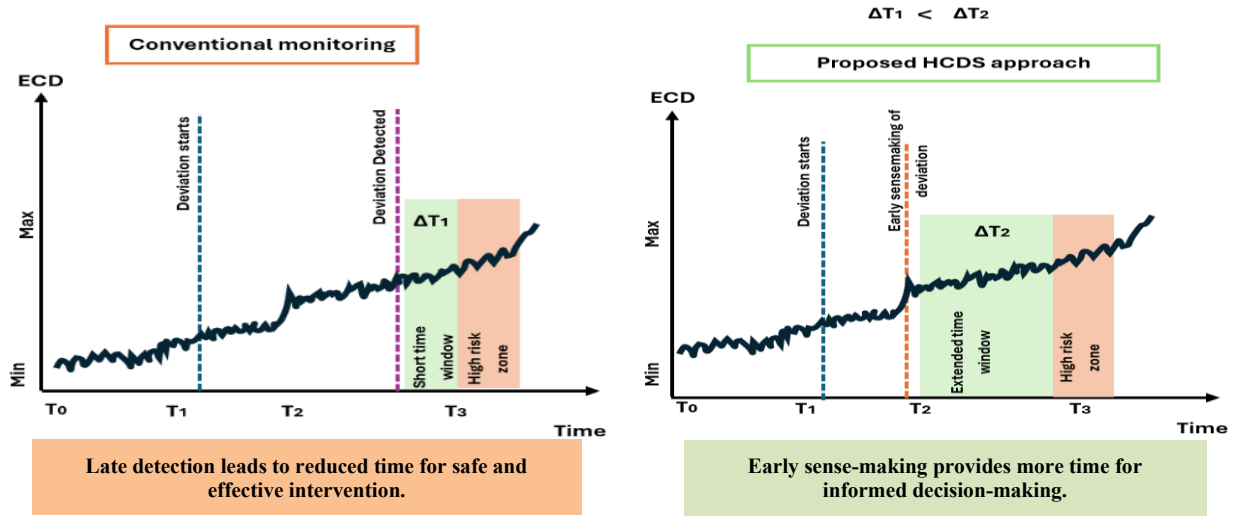


Figure 4. An illustrative comparison between conventional monitoring and the proposed HCDS approach for hole cleaning process in offshore drilling operations.

The relationship between available knowledge and operator awareness, which may traditionally seem linear, can no longer be considered neither linear nor simple in a number of modern industrial contexts [27]. When operational conditions are uncertain and demanding, early data must be transformed into meaningful insights that can support decision-making by human operators providing them with adequate time and intervention window contributing to ensure reliable and safe operations.

6. Conclusion

Advanced situation awareness and contextual knowledge play pivotal roles in decision-making in complex and dynamic environments such as offshore drilling operations. While new technologies such as data-assisted technologies can augment human capabilities in terms of creation of knowledge, there still remains a significant debate regarding how such generated knowledge can effectively elevate human operators' actual situation awareness to such levels to help optimize the systems' performance safeguarding reliability, safety, and resilience. In complex environments such as drilling operations, where certain disturbances naturally emerge from dynamic interactions and remain only partially controllable or predictable, early sense-making of deviations is essential because delays allow uncertainty and irregular behavior to grow, narrowing the time window for effective decision-making. In offshore drilling, where downhole conditions are not fully visible to operators, using downhole measurements such as annular pressure to capture unusual patterns before they evolve further into unwanted scenarios can be highly beneficial. However, early sense-making of deviations alone cannot guarantee better decision-making, especially when limited time windows can strain human cognitive abilities. Downhole data must be combined with surface data within an integrated system that is capable of interpreting the actual operational context in order to enhance contextual knowledge and situation awareness of human-operators.

Based on this perspective, this paper elaborated on the decision problems within offshore drilling operations with a specific focus on the demanding hole-cleaning process. It proposed and systematized a hybrid contextual decision-support (HCDS) approach that links data acquisition, pattern identification, event detection, and explanation engine with a continuously updated knowledge-based interactions. The practical scenario illustrated, captured unusual annular-pressure patterns as early signals and linked them to other parameters and underlying requirements, elaborating on how they can generate valuable contextual knowledge for operators, helping them to act proactively to mitigate unwanted scenarios and thereby to ensure operational reliability, safety, and resilience.

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