Integrating Fleet Compatibility and Environmental Risk in Downhole Tool Investment Planning

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Abstract— The current downhole tool planning process in oil and gas drilling is based on a "first-come, first-served" approach that does not consider tool reliability and potential environmental risks, leading to non-optimal tool maintenance decision and unavailability due to tool failure. Considering these challenges, this paper proposes a new downhole tool investment planning solution that is primarily data-driven and provides decision-makers with information on annual equipment investments. The solution includes fleet compatibility assessment, environmental risk estimation, and investment planning optimization modeling and provides output in the form of a dashboard for decision-makers to make informed investment decisions regarding component replacement or tool upgrades. The use of the proposed solution is demonstrated through two real-life scenarios that show the solution's effectiveness in making the best tool upgrade decisions.

Keywords—maintenance decision-making, investment planning, field environment characterization, part replacement, tool compatibility

I. INTRODUCTION

Oil and gas drilling is a complex process involving well construction through the earth's surface. The well construction relies on a drilling string, a series of circular pipes that transmit the driving force and drilling fluids from the surface to the bottom of the well. The bottom hole assembly (BHA) is one of the critical components of the drilling string, consisting of various components, including the drilling bit, rotary steerable system (RSS) tools, measurement-while-drilling (MWD) tools, logging-while-drilling (LWD) tools, and other mechanical components such as drill collars, stabilizers, shock absorbers, jars, reamers, and heavy-weight drill pipes[1].

The RSS tools are designed to rotate and direct the drill bit in the desired direction, thus placing the well in the pre-defined region [2]. The MWD tools are responsible for powering the LWD and RSS tools and transmitting real-time information to the rig on the surface [3]. The LWD tools log various geological information, including formation gamma ray, resistivity, density, porosity, fluid permeability, etc., to aid formation evaluation, well placement, and drilling optimization [4]. These RSS, MWD, and LWD tools are complex electronic and mechanical devices that require maintenance, with each component consisting of multiple electronic boards, harnesses, detectors, and moving mechanical parts.

The current planning process for these tools is primarily based on a first come, first served logic. Specifically, once a contract is agreed upon between the client and the service provider company and a tentative shipment date is established, the maintenance technician will allocate available tools as per requirement, regardless of the tools' operational history and parts' revisions. In addition, the recovery process for the failed tools is lengthy and restricted by the delivery lead time of the new parts. Over time, sites have attempted to plan ahead for tools by forecasting drilling operations and creating inventory based on past failures. Nonetheless, this decision-making process was accomplished through the manual analysis of extensive data sheets and the reliance on expert opinions, which is time-consuming and subjective. Furthermore, this decision-making process neglected the impact of environmental factors on the drilling operations and tool reliability. Environmental risks can significantly impact the reliability of drilling tools required and result in the need for high-reliability tools in areas with high environmental risk [5].

To address these challenges, we develop a new downhole tool investment planning solution that is primarily driven by data. The solution systematically analyzes multiple existing data sources, such as historical drilling environment data, part reliability levels, parts failure occurrences, and cost, to deliver the most straightforward output to help decision-makers plan for yearly equipment investments to drive reliability improvements.

II. PROPOSED SOLUTION

The proposed solution has three cores, namely fleet compatibility assessment, environmental risk estimation, and investment planning optimization modeling. In this section, we will start by presenting a method to assess fleet compatibility. Subsequently, we will present how to estimate the environmental risks of oil fields. Following that, a mathematical optimization model for downhole tool investment planning problem will be formalized. Finally, an overview of the proposed solution framework including the three cores will be outlined.

A. *Fleet Compatibility Assessment*

In a previous study, we introduced an indicator called tool compatibility index to measure the degree of fitness of a tool for a given drilling environment [5]. The index integrates part criticality, part reliability level, and potential environmental risk. It is defined as follows:

$$I_j = \frac{\sum_{i=1}^{N} w_i z_{ij}}{\sum_{i=1}^{N} w_i} \times 100\% \qquad (1)$$

where N is the number of parts in the tool j, w_i is the criticality value of part i and is inferred from service quality statistics, z_{ij} is 1 if part i fits or is compatible with the given environment; otherwise, z_{ij} is 0. z_{ij} can be obtained based on the criticality rules defined by domain experts.

By applying the tool compatibility calculation to a fleet of downhole tools, one can get the compatibility indices for the entire fleet. Suppose we define a value I_{th} as the compatibility index threshold. In other words, if the tool compatibility index of tool j is greater than I_{th}, then this tool is considered compatible with the environment; otherwise, it is deemed incompatible. Then we can assess what percentage of tools in this fleet are compatible for the given environment, which is mathematically expressed as in (2).

$$Prt = \frac{\sum_{j=1}^{M} \mathbb{I}(I_j > I_{\text{th}})}{M} \qquad (2)$$

where M denotes number of tools in the fleet, I_j represents the tool compatibility index of tool j, and $\mathbb{I}$ is an indicator function.

B. *Environmental Risk Estimation*

As previously discussed in Sections 1 and 2, the conventional approach to downhole tool investment planning overlooks the potential environmental risks the drilling environment poses. The environmental risk is crucial as the conditions in which a downhole tool is operated can significantly affect its reliability, thus impacting drilling job efficiency and success. In light of this, properly assessing environmental risks is imperative when making an investment plan for tool upgrades. To address this issue, this paper presents a novel method for environmental risk estimation, as described in the following steps.

- Define three levels (i.e., Level 1, Level 2, Level 3) for each environment category (e.g., temperature, vibration, and shock). For example, the three levels of temperature can be defined as less than 100°C, between 100°C and 130C°, and greater than 130°C. These levels and environment category can be determined based on the technical specifications of the drilling tool.
- For each historical drilling job, extract the exposure time under each level of each environment category from the historical tool measurement database, where the drilling environmental information was recorded.
- For each historical drilling job, assign a risk level (e.g., low, medium, high) to each environment category based on two predefined time thresholds for each environment category and the exposure time computed in the above step. The flowchart for determining the risk level of the environment category g is depicted in Fig. 1, where ET_{g3} and ET_{g2} are the exposure time of Level 3 and Level 2 of environment category g, respectively; Th_{g3} and Th_{g2} are the time thresholds of Level 3 and Level 2 of environment category g, respectively. Again, the time thresholds can also be decided by the technical specifications of the drilling tool.

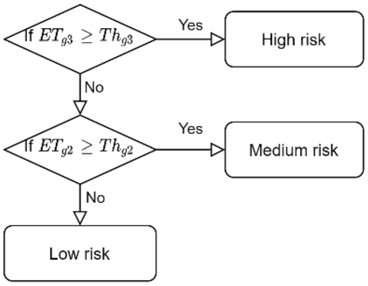


Fig. 1. Flowchart for determining the risk level of environment category *i* of a drilling job

- Group the jobs by field (location or geounit) and calculate the job percentage per risk level for each environment category. Note that a geo unit comprises several locations, and a location encompasses multiple fields.
- Compute a risk index of each environment category for the field (location or geo unit) as expressed in (3).

$$r_g = W \times P_{g2} + P_{g3} \tag{3}$$

where r_g denotes the risk index of environment category g; P_{g2} and P_{g3} represent the job percentages of medium-risk level and high-risk level, respectively; W is a weight defined by domain experts to consolidate the percentage of medium-risk jobs and high-risk jobs into a single value, usually within the range of 0.1 to 0.5.

By using Equation (3) for all fields, locations, or geounits, the environmental risk indices for each category of each field, location, or geounit can be calculated.

C. *Investment Planning Optimization Modeling*

From the above description of the environmental risk estimation method, one can see that the environmental risk index serves as a statistical representation of historical drilling jobs potentially exposed to hazardous conditions, such as elevated temperatures, shocks, and vibrations. This index can therefore be regarded as a probability or likelihood that a future drilling job will encounter a similarly risky environment.

It is imperative for the field (location or geo unit) to sustain a sufficient number of tools compatible with harsh environments to ensure the readiness for future drilling jobs that pose environmental risks such as high temperature, shock, and vibration. The percentage of compatible tools is recommended to be not less than the risk index plus an additional buffer within the range of 10% to 30%. This additional buffer serves as a precautionary measure to guarantee the continued availability of tools even in the event of unavailability caused by tool failures and maintenance needs.

Based on the fleet compatibility assessment, we can obtain the percentage of tools compatible with harsh or risky environments for the field (location or geounit). Suppose the field (location or geounit) does not have the number of compatible tools as recommended. In that case, an investment plan is necessary to determine the most cost-effective replacement of parts to ensure the adequate availability of compatible tools. This paper will focus on investment planning at the geounit level. The investment planning at the field level and the location level are similar.

Suppose the geounit has M tools and each tool has N parts, and the geounit does not have adequate compatible tools. A part will be compatible with the harsh environment if it is replaced with one of the latest revision design. Then, based on the above analysis, the investment planning optimization problem is formulized as follows:

- Decision variables

$$X_{ij} \in \{0,1\}, i = 1,2,\cdots,N; j = 1,2,\cdots M \tag{4}$$

where X_{ij} denotes if the part i in tool j is replaced, with 1 indicating replaced, and 0 meaning not.

- Objective function

$$\min \sum_{j=1}^{M} \sum_{i=1}^{N} X_{ij} c_i \tag{5}$$

where c_i denotes the replacement cost of part i.

- Constraints

$$X_{ij} = 0 \; if \; z_{ij} = 1 \tag{5}$$

$$z'_{ij} = z_{ij} + X_{ij} \tag{6}$$

$$Prt' \geq r + b \tag{7}$$

The first constraint means that if part i in tool j is compatible with the environment, then there is no need for replacement. In the second constraint, z'_{ij} is the compatible flag of part i in tool j after part replacement. In other words, if part i in tool j is replaced with a new part, then it is compatible with the environment; otherwise, its compatible flag remains unchanged. In the third constraint, r is the environmental risk index of the geounit; b is the buffer size; Prt' is the percentage of compatible tools after part replacement, which can be computed via (1) and (2).

The previously discussed optimization problem is a simple integer programming problem that can be solved using various methods, including conventional methods like cutting plane, branch and bound [6], or evolutionary algorithms [7]. Additionally, due to the binary nature of the decision variables, a brute-force search method can also be used to solve this problem, which is relatively simple to understand and implement. This paper will solve the optimization problem based on the brute-force search method, and the solution involves the following two steps:

- Determine the minimum cost for replacing parts of each incompatible tool to reach the compatibility threshold. This cost is obtained by enumerating all possible solutions of the decision variables of the tool. Furthermore, sort these minimum costs in ascending order.
- Based on the required number of compatible tools (i.e., $M \times (r + b)$) and the available number of compatible tools, one can determine the number of tools that need part replacements, referred to as m. Then the tools corresponding to the top m costs in Step 1 are the tools that require part replacement, and the sum of these m costs is the minimum value for the objective function.

By implementing the above-described modeling process for each environment category, one can obtain investment plan solutions for all environment categories.

D. Framework of the Proposed Solution

Based on the previously mentioned three cores, the proposed solution that integrates fleet compatibility and environmental risk in downhole tool investment planning is presented in Fig.2 and consists of three layers: data, model, and decision.

The data layer serves as the input and includes three sources of information:

- tool measurement data (e.g., temperature, shocks, and vibration)
- asset information (e.g., identity, components, and location)
- expert knowledge of criticality rules [5]

The model layer comprises three models (also the three cores), including an environmental risk estimation model, a fleet compatibility assessment model, and an investment planning optimization model. Using the tool measurement data, the first model calculates the risk indices of all environmental categories for the geounit. The second model determines the compatibility indices of all tools in the fleet and calculates the percentage of compatible tools. The third model integrates the compatible tools requirements based on the risk index and the compatibility information from the fleet compatibility assessment into an optimization model.

The decision layer serves as the output and is based on the solution from the optimization model solved using the brute-force search method. It decides which parts should be replaced and calculates the associated costs.

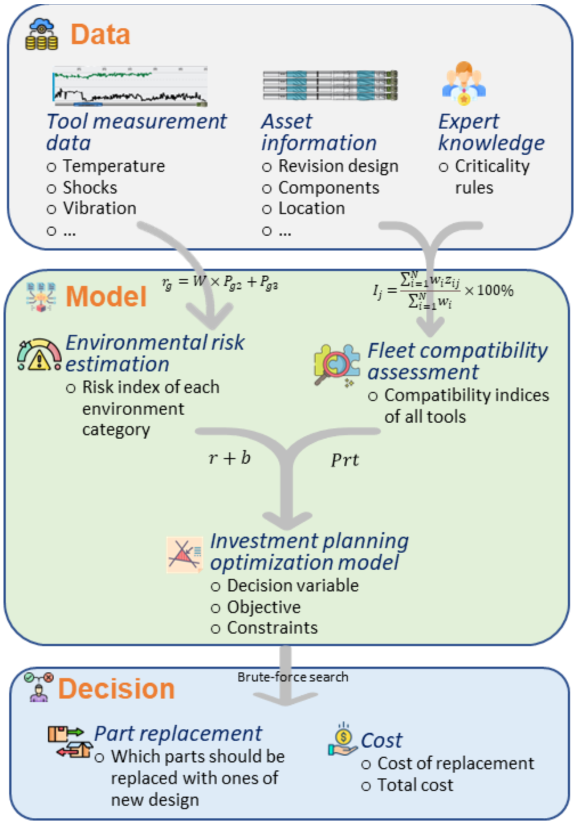


Fig. 2. Framework of the proposed solution

III. USE CASES

The output of the proposed solution is presented as a dashboard showcasing the investment plans for various geounits. This section provides a use case diagram and two real-life scenarios to exhibit the solution's effectiveness. Note that some information is not included due to confidentiality reasons.

A. *Use Case Diagram*

The use case diagram depicted in Fig. 3 highlights the interaction between the dashboard users, who are geounit managers, and the proposed solution. These managers make investment decisions about purchasing new tools or parts for their respective geounits. The dashboard provides them with a comprehensive view of relevant information. This aids them in making informed decisions, including the environmental indices of the locations within the selected geounit displayed on a map, the compatibility information of the entire fleet in the geounit presented in a table, the required percentage of compatible tools based on the risk index and buffer shown in a bar chart, and suggestions for part replacements and their associated costs shown in a table. In addition, the dashboard enables outputting the suggestion of new part order and associated cost for only the selected environment categories.

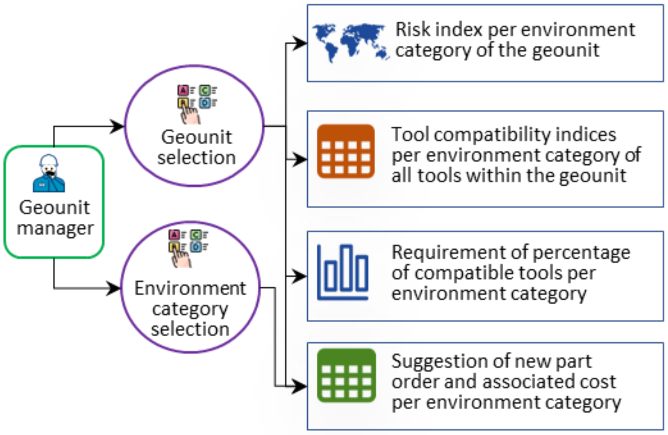


Fig. 3. Use case diagram

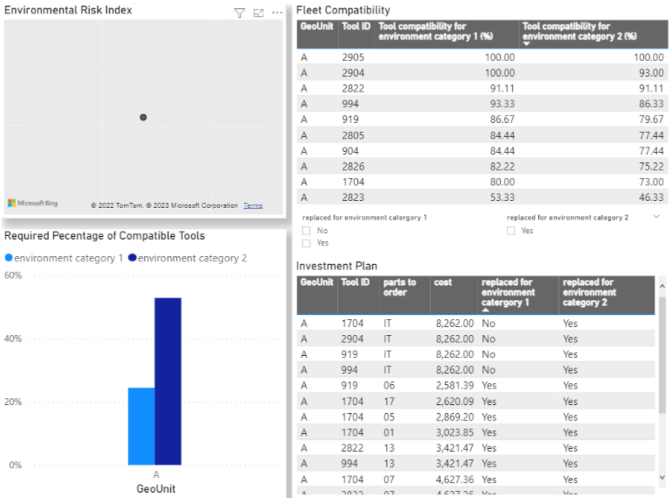
B. Application Scenarios

Two scenarios (see Fig. 4 and Fig. 5) are presented in this subsection to demonstrate the solution. The compatibility threshold and buffer are set in both scenarios to 93% and 20%, respectively. The colored circle in the environmental risk index diagram indicates the average risk indices for the two environmental categories, with darker colors indicating higher risk and lighter colors indicating lower risk.

The first scenario is about a geounit with a high-risk environment but low-percentage compatible tools. In this scenario, the environment risk index indicates that the environment is harsh. The compatibility information of the entire fleet shows that the current percentage of compatible tools is lower than the required percentage of compatible tools based on the risk index and buffer. The dashboard suggests several part replacements, and associated costs ensure the required number of compatible tools. The geounit manager can then make an informed decision based on the suggested part replacements and their costs and take the necessary action to invest in new parts to improve the compatibility of the fleet.

The second scenario is about a geounit with a low-risk environment. In this scenario, the environmental indices of the locations within the geounit indicate that the environment is relatively mild. The compatibility information of the entire fleet shows that the current percentage of compatible tools is already higher than the required percentage of compatible tools based on the risk index and buffer. The dashboard suggests no part replacements, indicating that the current fleet is sufficient to handle the environmental conditions. The geounit manager can save investment costs and allocate resources to other areas.

These scenarios demonstrate the effectiveness of the proposed solution in providing actionable information to the geounit managers for investment planning, taking into account both the environmental risk and the compatibility of the fleet. The solution enables managers to make informed decisions about which parts to replace and how much to invest, leading to improved reliability and cost savings in downhole tool operations.



Fleet Compatibility

GeoUnit	Tool ID	Tool compatibility for environment category 1 (%)	Tool compatibility for environment category 2 (%)
A	2905	100.00	100.00
A	2904	100.00	93.00
A	2822	91.11	91.11
A	994	93.33	86.33
A	919	86.67	79.67
A	2805	84.44	77.44
A	904	84.44	77.44
A	2826	82.22	75.22
A	1704	80.00	73.00
A	2823	53.33	46.33

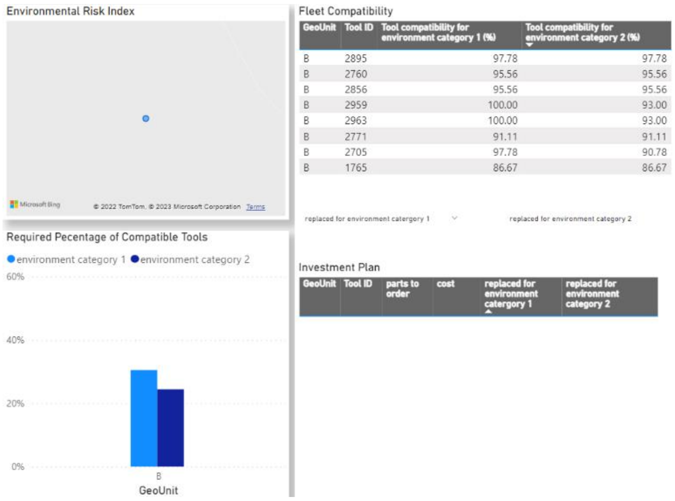
replaced for environment catergory 1
☐ No
☐ Yes

replaced for environment category 2
☐ Yes

Investment Plan

GeoUnit	Tool ID	parts to order	cost	replaced for environment catergory 1	replaced for environment category 2
A	1704	IT	8,262.00	No	Yes
A	2904	IT	8,262.00	No	Yes
A	919	IT	8,262.00	No	Yes
A	994	IT	8,262.00	No	Yes
A	919	06	2,581.39	Yes	Yes
A	1704	17	2,620.09	Yes	Yes
A	1704	05	2,869.20	Yes	Yes
A	1704	01	3,023.85	Yes	Yes
A	2822	13	3,421.47	Yes	Yes
A	994	13	3,421.47	Yes	Yes
A	1704	07	4,627.36	Yes	Yes

Fig. 4. Application Scenario 1



Fleet Compatibility

GeoUnit	Tool ID	Tool compatibility for environment category 1 (%)	Tool compatibility for environment category 2 (%)
B	2895	97.78	97.78
B	2760	95.56	95.56
B	2856	95.56	95.56
B	2959	100.00	93.00
B	2963	100.00	93.00
B	2771	91.11	91.11
B	2705	97.78	90.78
B	1765	86.67	86.67

replaced for environment catergory 1

replaced for environment category 2

Investment Plan

GeoUnit	Tool ID	parts to order	cost	replaced for environment catergory 1	replaced for environment category 2

Fig. 5. Application Scenario 2

IV. CONCLUSIONS AND FUTURE WORKS

In conclusion, the proposed investment planning solution provides cost-effective part replacement or tool upgrade decisions to improve the overall reliability and availability of the fleet of downhole tools. The solution integrates the tool compatibility indices of the entire fleet and field environmental risks based on historical tool measurement data. It overcomes the weakness of experience-based decision-making. The use case diagrams and application scenarios demonstrate the effectiveness of the proposed solution, providing comprehensive information to decision-makers about the compatibility indices of their tools and environmental risks of their geounit, as well as recommendations for part replacements and associated costs.

The proposed solution has shown great potential, and in future work, the solution can be further improved by considering tool transferring between geounits and part swapping between tools. Additionally, client importance and budget limitation could be used as additional constraints to the optimization problem. Furthermore, the solution could be extended to include predictive maintenance techniques to improve the reliability of drilling operations and minimize downtime.

ACKNOWLEDGMENT

This work has been supported by the EIPHI graduate school (contract “ANR-17-EURE-0002”) and the CIFRE fellowship (n^{o} 2020/0127).

REFERENCES

[1] SLB, “BHA,” *Explore the new Oilfield Glossary*. https://glossary.oilfield.slb.com/en/terms/b/bha (accessed Mar. 25, 2022).

[2] SLB, “Rotary_steerable_system,” *Explore the new Oilfield Glossary*. https://glossary.slb.com/en/terms/r/rotary_steerable_system (accessed Feb. 12, 2023).

[3] SLB, “Measurements-while-drilling,” *Explore the new Oilfield Glossary*. https://glossary.oilfield.slb.com/en/terms/m/measurements-while-drilling (accessed Mar. 25, 2022).

[4] SLB, “Logging-while-drilling,” *Explore the new Oilfield Glossary*. https://glossary.slb.com/en/terms/l/logging-while-drilling (accessed Feb. 12, 2023).

[5] Jinlong Kang, Christophe Varnier, Ahmed Mosallam, Noureddine Zerhouni, Fares Ben Youssef, and Nannan Shen, “Tool Compatibility Index: Indicator Enables Improved Tool Selection for Well Construction,” in *PHM Society European Conference*, 2022, vol. 7, pp. 239–244. doi: https://doi.org/10.36001/phme.2022.v7i1.3346.

[6] B. Kolman and R. E. Beck, “4 - Integer Programming,” in *Elementary Linear Programming with Applications (Second Edition)*, B. Kolman and R. E. Beck, Eds. San Diego: Academic Press, 1995, pp. 249–293. doi: 10.1016/B978-012417910-3/50007-3.

[7] C. Ryan, “Evolutionary Algorithms and Metaheuristics,” in *Encyclopedia of Physical Science and Technology (Third Edition)*, R. A. Meyers, Ed. New York: Academic Press, 2003, pp. 673–685. doi: 10.1016/B0-12-227410-5/00847-4.