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Identifying Knowledge Gaps in Geological Information Understanding within the POI–ATE Process at PT Freeport Indonesia

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Abstract

Background: Geological information supports technical and operational decision-making in underground mining; however, its interpretation may vary across stakeholder groups. At PT Freeport Indonesia (PTFI), the Plan of Intent (POI)–Approval to Excavate (ATE) process requires personnel from Geology, Geotech, and Engineering to review geological information before excavation in the Deep Mill Level Zone (DMLZ).
Objective: This study examines patterns in stakeholder perceptions to identify areas of knowledge alignment and gaps within the POI–ATE process.
Methods: An exploratory quantitative survey was conducted with 38 respondents from Geology (information sender), Geotech, and Engineering (information receivers). Responses were analyzed using descriptive statistics, independent-samples *t*-tests, Hedges' *g* effect sizes, and item-level gap analysis, with the findings interpreted through a Supported–Tentative–Preliminary framework. Subsequently, semi-structured interviews with six decision-makers were conducted to develop and prioritize improvement alternatives using the Simple Multi-Attribute Rating Technique (SMART).
Results: The findings indicated moderate-to-high perceptions across five dimensions, with no statistically significant differences between information senders and receivers and predominantly very small to small effect sizes. Findings concerning understanding of report content, the need for discussion, delays, rework, and stakeholder-oriented reporting were well supported, whereas findings concerning clarification at the approval stage, report complexity, and systematic evaluation remained preliminary.
Conclusion: SMART ranked the Clear and Decision-Focused ATE Report (A1) first among the four business-solution alternatives, making it the highest-priority alternative for pilot evaluation; this ranking remained stable across seven weighting scenarios.

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INTRODUCTION

Geoscience knowledge is inherently affected by uncertainty (Pérez-Díaz et al., 2020). Geological information may not communicate this uncertainty clearly. Carlson (2025) emphasizes that mining project difficulties can reflect failures to identify critical knowledge gaps, as well as geological uncertainty itself. In the present study, the organizational problem concerns how technical groups interpret and apply the same information. Prayudi et al. (2025) describe anticipation, engagement, communication, and adaptation in external crisis communication. These principles offer a conceptual analogy for internal technical exchanges rather than a

validated model of POI–ATE communication. Existing communication perspectives explain why differences in interpretation may arise, but they do not establish how consistently Geology, Geotech, and Engineering understand geological information within PTFI's internal approval workflow. This study addresses this context-specific measurement gap by examining stakeholder perceptions and subsequently prioritizing improvements.

Uncertainty in geoscience includes objective uncertainty arising from natural variability and limitations in data, methods, and technology, as well as subjective uncertainty arising from differences in knowledge, experience, judgment, and interpretation (Pérez-Díaz et al., 2020). Geological models represent best-estimate interpretations; therefore, their assumptions, limitations, and associated confidence levels need to be communicated to users. This study focuses on subjective uncertainty in stakeholder interpretation rather than testing geological data accuracy or reducing objective uncertainty. Core Understanding assesses perceived comprehension; Factors and Sensemaking examines perceived interpretation conditions; Decision Efficiency and Accuracy and Awareness and Impact Recognition examine perceived consequences; and Improvement and Actionability examines improvement needs. Practitioners' experience and judgment may influence interpretation, but this study does not directly measure heuristics or cognitive biases. The mining cases presented in Table 1 illustrate the practical consequences associated with insufficient recognition of geological uncertainty.

Table 1

Selected Cases of Insufficient Geological Understanding in Mining Projects.

Project	Cause	Impact
Newcrest Mining – Telfer, Australia	Overestimated grade reliability from poor understanding of heterogeneous gold distribution	18% reduction in contained gold resources
Rubicon Minerals – Phoenix Gold, Canada	Misinterpreted structural orientation and geological complexity	Resource fell by >85%; underground operations shut down
Discovery Metals – Boseto Mine, Botswana	Feasibility assessment did not adequately recognize actual oxidation depth, orebody geometry, and blasting-related dilution	Mine built for US$175 million, closed in 2015, and later sold for US$35 million
Centamin – Sukari Gold Mine, Egypt	Geological conditions differed from expectations (thicker transition zone, lower grades, greater dilution)	All-in sustaining costs +16%; production −17%

Source: Adapted from Carlson (2025)

Carlson (2025) argues that such failures arise not only from geological uncertainty itself but also from organizations' failure to identify critical knowledge gaps and use available geological information effectively. This distinction is directly relevant to the present study, as stakeholders may receive identical information yet interpret and apply it differently according to their respective responsibilities. Dhungana et al. (2025) explain this pattern conceptually: information senders (e.g., scientists or, in this context, Geology) tend to emphasize data quality, model assumptions, and technical limitations, whereas information receivers (decision-makers or, in this context, Geotech and Engineering) tend to emphasize practical implications and actionable information. These differing priorities can create a communication gap even when both parties rely on the same underlying information. This dynamic is particularly relevant in the DMLZ, which forms part of the Ertsberg East Skarn System. Its multistage magmatic intrusions, structurally controlled and lithologically heterogeneous mineralization, and kilometer-scale extent produce spatially variable subsurface conditions and varying levels of confidence across locations (Sieber et al., 2020; Sonntag Hoerlle et al., 2022). These characteristics create precisely the type of geological setting in which sender–receiver communication gaps can have particularly significant consequences.

PTFI operates underground mines as its primary production sources following its transition from open-pit operations (Freeport-McMoRan Inc., 2022). Underground headings are

developed progressively based on interpreted ground conditions that cannot be fully observed before excavation. Consequently, planning assumptions must be translated consistently into field-level decisions as development progresses. Because Geology, Geotech, and Engineering apply geological information within their respective technical responsibilities, this transition increases the need to communicate location-specific concerns, uncertainty, and operational implications throughout the POI–ATE process.

This issue is particularly relevant to PT Freeport Indonesia (PTFI), where stakeholders from different technical disciplines must interpret uncertain geological information to support time-sensitive underground mining decisions. PTFI uses two sequential mechanisms for heading-development decisions: the Plan of Intent (POI), an analytical and predictive planning stage that produces a collectively approved design, and the Approval to Excavate (ATE), an operational stage that translates the approved design into field-level excavation decisions. Between January 2025 and March 2026, PTFI's Mining Data Manager (MDM) system recorded approximately 112 POI approvals and 875 ATE approvals in the Deep Mill Level Zone (DMLZ), indicating that a relatively limited number of planning decisions give rise to a substantially larger number of execution decisions. This relationship suggests that misunderstandings at the initial planning stage may propagate and amplify across subsequent operational activities.

Although Geology, Geotech, and Engineering are all required to review geological information before excavation, PTFI has not systematically assessed how consistently these stakeholders understand and interpret that information. The key business issue is therefore PTFI's limited visibility into stakeholder alignment within the POI–ATE process, which constrains its ability to ensure that a consistent understanding of geological information supports efficient and effective decision-making in DMLZ operations.

This research addresses four questions: (1) To what extent do stakeholders understand geological information within the POI–ATE process? (2) What factors influence differences in stakeholder understanding and interpretation of geological information? (3) How do differences in stakeholder understanding influence decision-making effectiveness, efficiency, and risk recognition? and (4) What improvements can enhance alignment in stakeholder understanding and support more effective decision-making? Correspondingly, this study aims to assess the level of stakeholder understanding, identify the factors that drive differences in interpretation, analyze the implications of these differences for decision-making, and propose improvements to strengthen communication, alignment, and decision quality across Geology, Geotech, and Engineering in the DMLZ POI–ATE process. The research is limited to internal DMLZ stakeholders, examines perceptions rather than the technical accuracy of geological data, and relies on self-reported survey and interview data that may not capture all operational conditions. Accordingly, the findings should be interpreted within the specific context of the DMLZ POI–ATE process. RQ1–RQ3 are addressed through dimension- and item-level survey analyses, whereas RQ4 is addressed through improvement perceptions, decision-maker interviews, and SMART prioritization.

Conceptually, this study examines potential differences in stakeholder interpretation in relation to the desired state of sufficiently aligned understanding to support effective, efficient, and risk-informed decisions. The five research dimensions operationalize perceived understanding, interpretation factors, decision consequences, and improvement needs. The framework examines stakeholder perceptions and does not establish the technical accuracy of geological information or causal effects on operational performance.

METHOD

This research employed an exploratory quantitative survey design intended to identify patterns in stakeholder perceptions rather than test a confirmatory model, as the extent of stakeholder alignment in the POI–ATE process had not previously been systematically examined. A structured questionnaire comprising 25 perception-based statements, each rated on a five-point Likert scale, was distributed to 38 purposively selected respondents from Geology (the information sender), Geotech, and Engineering (the information receivers) who had direct working experience with the POI–ATE workflow. Purposive rather than random sampling was necessary because respondents needed practical, hands-on experience with the POI–ATE process for their responses to be meaningful. This approach was consistent with Etikan et al. (2016) and

Zrineh (2026) recommendation that purposive sampling is most appropriate when a study requires participants with rich, specific knowledge of the phenomenon under investigation. Respondents' years of experience varied and were used only to describe the sample rather than as a comparison variable. The questionnaire items were grouped into five research dimensions aligned with the four research questions: Core Understanding, Factors and Sensemaking, Decision Efficiency and Accuracy, Awareness and Impact Recognition, and Improvement and Actionability. To reduce response-pattern bias, the items were not grouped sequentially by dimension in the questionnaire, and several were negatively worded to capture concerns such as misunderstanding, misinterpretation, and report complexity. These negatively worded items were reverse-coded before analysis to ensure that higher scores consistently reflected more positive perceptions. The 38 respondents constituted the purposively recruited study sample; however, the manuscript did not document a complete count of the eligible population or establish that recruitment covered all POI–ATE participants. Accordingly, sample adequacy was limited to the exploratory description of these respondents rather than a census, representative population inference, or adequately powered confirmatory comparison.

Before the main analysis, item validity was assessed using the Corrected Item-Total Correlation (CITC), with $r \geq 0.30$ classified as valid, while internal-consistency reliability was assessed using Cronbach's alpha ($\alpha \geq 0.70$ = reliable; 0.60–0.69 = acceptable; 0.50–0.59 = marginal; < 0.50 = low), following the validity- and reliability-testing procedures recommended for quantitative survey instruments by Sürücü and Maslakçı (2020) and Arslan (2022). Given the exploratory nature of the research, items with weaker validity or reliability were retained when theoretically relevant. A Supported–Tentative–Preliminary framework was also used to qualify the strength of each subsequent finding: Supported findings were reliable at the dimension level or valid for both compared groups at the item level; Tentative findings were acceptable or marginal at the dimension level; and Preliminary findings had low reliability at the dimension level or were flagged for review at the item level. With 38 respondents divided among three groups, group-level CITC and Cronbach's alpha estimates may have been unstable. The Supported–Tentative–Preliminary labels qualified the reported internal-consistency evidence but did not establish psychometric stability. Negative alpha values were also interpreted cautiously because they indicated potential problems with the affected dimension scores.

Dimension-level perceptions (mean scores) and response variability (standard deviations) were interpreted using the Mean-Likert Scale classification adapted from Alkharusi (2022). Independent-samples t-tests (two-sample tests assuming unequal variances) were used to compare mean perceptions between Geology and each receiver group. Hedges' g effect sizes (< 0.20 = very small; 0.20–0.49 = small; 0.50–0.79 = medium; ≥ 0.80 = large) were calculated to assess the practical, rather than merely statistical, significance of any observed differences (Iacobucci et al., 2023; Lakens, 2013; Yagin et al., 2024). These conventional thresholds were retained as a common reference point, consistent with Brydges (2019) and Zieliński (2026)caution that generic effect-size benchmarks should be treated as provisional guides rather than fixed cutoffs when field-specific norms have not yet been established. Item-level gap analysis was subsequently conducted to identify the specific questionnaire items driving each observed pattern.

In the second stage, semi-structured interviews were conducted individually with six decision-makers (two each from Geology, Geotech, and Engineering) to develop and prioritize improvement alternatives. Interview proposals were consolidated thematically into a set of business-solution alternatives, which were subsequently evaluated using the Simple Multi-Attribute Rating Technique (SMART). The evaluation criteria and weights were derived from the quantitative findings and recurring interview themes, following the emerging good-practice guidance for structuring criteria and eliciting weights in multi-criteria decision analysis provided by Marsh et al. (2016) and van Schaik et al. (2026). Each decision-maker independently scored every alternative against each criterion using a five-point contribution scale. The scores were aggregated and combined with the criterion weights following the additive SMART model, $V(Ai) = \Sigma(wj \times sij)$ (Taherdoost & Mohebi, 2024). A sensitivity analysis was subsequently performed by varying the criterion weights to assess the robustness of the resulting ranking. Engagement, transparent technical communication, and post-decision learning informed the interpretation of

the proposed improvements. The crisis-communication model was used as a conceptual analogy rather than as an independently tested POI–ATE model.

The five research dimensions were each mapped to a specific research question to ensure that the questionnaire directly generated the evidence needed to address them (Table 2).

Table 2
Linkage between Research Questions and Research Dimensions

Research Question	Research Dimension
RQ1: To what extent do stakeholders understand geological information?	Core Understanding
RQ2: What factors influence differences in understanding and interpretation?	Factors and Sensemaking
RQ3: How do differences influence decision effectiveness, efficiency, and risk recognition?	Decision Efficiency and Accuracy; Awareness and Impact Recognition
RQ4: What improvements can enhance alignment and decision-making?	Improvement and Actionability

This sender–receiver framing followed directly from the conceptual link established in the Introduction: Geology, as the information sender, emphasized data quality, model reliability, and interpretation confidence, whereas Geotech and Engineering, as the receivers, translated that information into ground-behavior assessments, stability and design decisions, and field-level execution decisions, respectively. Measuring perceptions separately for the sender and each receiver group, rather than pooling all respondents, allowed the analysis to identify where, if anywhere, the translation of geological information across these functional boundaries broke down. Table 3 presents the classification scheme used to interpret the descriptive mean and standard-deviation scores reported in the Results section, adapted from (Alkharusi, 2022).

Table 3
Mean-Score and Standard-Deviation Classification for Perception Level and Response Consistency

Mean Score	Perception Level	Standard Deviation	Response Consistency
1.00 – 1.80	Very Low	< 0.41	Very High Consistency
1.81 – 2.61	Low	0.41 – 0.80	High Consistency
2.62 – 3.42	Moderate	0.81 – 1.20	Moderate Consistency
3.43 – 4.23	High	1.21 – 1.60	Low Consistency
4.24 – 5.00	Very High	> 1.60	Very Low Consistency

Source: Adapted from Alkharusi (2022)

RESULTS AND DISCUSSION

Respondent Profile and Measurement Quality

The 38 respondents represented Geology, Geotech, and Engineering, with varying levels of POI–ATE experience, capturing diverse stakeholder perspectives. Experience level was used solely to describe the respondent profile and was not included as a statistical comparison variable. Table 4 presents the percentage of valid items (CITC ≥ 0.30) for each stakeholder group and dimension, while Table 5 presents the corresponding Cronbach's alpha reliability coefficients.

Table 4
Percentage of Valid Items (CITC ≥ 0.30) by Stakeholder Group and Dimension.

Dimension	Geology Valid Items	Geotech Valid Items	Engineering Valid Items
Core Understanding	100%	100%	80%
Factors and Sensemaking	85.7%	71.4%	42.9%
Decision Efficiency and Accuracy	66.7%	66.7%	100%
Awareness and Impact Recognition	80%	0%	20%

Dimension	Geology Valid Items	Geotech Valid Items	Engineering Valid Items
Improvement and Actionability	80%	80%	80%

Table 5
Reliability (Cronbach's α) by Stakeholder Group and Dimension.

Dimension	Geology α	Geotech α	Engineering α
Core Understanding	0.842 (Reliable)	0.773 (Reliable)	0.554 (Marginal)
Factors and Sensemaking	0.763 (Reliable)	0.629 (Acceptable)	−0.131 (Low)
Decision Efficiency and Accuracy	0.588 (Marginal)	0.553 (Marginal)	0.847 (Reliable)
Awareness and Impact Recognition	0.802 (Reliable)	−0.118 (Low)	0.132 (Low)
Improvement and Actionability	0.648 (Acceptable)	0.609 (Acceptable)	0.622 (Acceptable)

Core Understanding and Improvement and Actionability exhibited the most consistent validity and reliability patterns across all three groups. Factors and Sensemaking and Decision Efficiency and Accuracy exhibited mixed patterns, while Awareness and Impact Recognition exhibited the weakest pattern, particularly among the two receiver groups. These results are presented as evidence of measurement quality and are used in the Discussion to qualify the interpretive weight that can be assigned to each dimension-level finding.

Dimension-Level Perception, Statistical Testing, and Effect Size

Table 6 presents the mean perception scores and response-consistency measures for each stakeholder group across the five research dimensions, classified according to the scheme presented in Table 3.

Table 6
Dimension-Level Perception and Consistency by Stakeholder Group.

Dimension	Geology Percep.	Geology Consist.	Geotech Percep.	Geotech Consist.	Engineering Percep.	Engineering Consist.
Core Understanding	3.61	0.71	3.68	0.82	3.35	0.85
Factors and Sensemaking	2.91	1.22	2.96	1.25	2.94	1.02
Decision Efficiency and Accuracy	3.76	0.73	3.85	0.69	3.76	0.46
Awareness and Impact Recognition	4.16	0.75	4.06	0.89	3.95	0.63
Improvement and Actionability	4.06	0.64	3.92	0.63	3.75	0.64

Note. Perception = mean score (1.00–5.00; higher = more positive perception); Consistency = standard deviation (lower = more consistent responses).

By combining the descriptive scores in Table 6 with the reliability evidence in Table 5, each dimension-level finding was classified as Supported, Tentative, or Preliminary for each stakeholder group (Table 7).

Table 7
Dimension-Level Finding Classification by Stakeholder Group (Supported / Tentative / Preliminary, with Perception Level).

Dimension	Geology	Geotech	Engineering
Core Understanding	Supported (High)	Supported (High)	Tentative (Moderate)
Factors and Sensemaking	Supported (Moderate)	Tentative (Moderate)	Preliminary (Moderate)
Decision Efficiency and Accuracy	Tentative (High)	Tentative (High)	Supported (High)
Awareness and Impact Recognition	Supported (High)	Preliminary (High)	Preliminary (High)
Improvement and Actionability	Tentative (High)	Tentative (High)	Tentative (High)

Table 8 presents the p-values from the independent-samples t tests and Hedges' g effect sizes for both sender–receiver pairs across the five dimensions.

Table 8
Independent-Samples t-Test and Hedges' g Effect Size by Dimension and Stakeholder Pair (all p > .05).

Dimension	Geology–Geotech p-value	Geology–Geotech Hedges' g	Geology–Engineering p-value	Geology–Engineering Hedges' g
Core Understanding	.837	0.077 (very small)	.307	0.377 (small)
Factors and Sensemaking	.850	0.070 (very small)	.904	0.043 (very small)
Decision Efficiency and Accuracy	.744	0.124 (very small)	.989	0.006 (very small)
Awareness and Impact Recognition	.682	0.152 (very small)	.361	0.334 (small)
Improvement and Actionability	.477	0.267 (small)	.111	0.622 (medium)

No dimension-level comparison reached statistical significance for either stakeholder pair (all $p > .05$), and the effect sizes were predominantly very small to small. The only exception was Improvement and Actionability between Geology and Engineering, which exhibited a medium effect size ($g = 0.622$).

Item-Level Results

The item-level gap analysis identified the specific questionnaire items underlying each dimension-level pattern. For Core Understanding, Item Q1 (understanding of report content) was Supported across all groups, whereas Item Q12 (clarification during approval stages) showed the largest gap for Engineering but remained Preliminary. For Factors and Sensemaking, Item Q11 (need for discussion) was Supported, particularly for Geotech, whereas Item Q7 (report complexity) and Item Q17 (differing stakeholder interpretations) remained Preliminary. For Decision Efficiency and Accuracy and Awareness and Impact Recognition, the strongest Supported item-level finding concerned the perceived relationship between misunderstanding and delays, rework, and changes to plans or designs. In contrast, items addressing decision accuracy, cost, safety, operational risk, correct information use, and the frequency of misunderstandings remained Preliminary. For Improvement and Actionability, Items Q9 (use of geology in mining plans), Q8 (reporting tailored to stakeholder needs), and Q24 (report structure and key highlights) were Supported, whereas Item Q18 (need for systematic evaluation), which showed the largest gap within this dimension, remained Preliminary.

Interview Results

The six interviews with decision-makers (two each from Geology, Geotech, and Engineering) generated proposals that were organized into three functional summaries. Geology's main perceived issues concerned inconsistently applied reporting standards, excessively detailed and time-consuming reports, unclear communication of geological confidence, and limited field feedback. Its proposed directions included standardized reporting guidelines, simplified operational reports, report automation, explicit confidence levels, and formalized field feedback. Geotech's main issues concerned report complexity and misalignment with decision-making needs, as well as concerns about reporting consistency, review quality, competency, and historical decision records. Its proposed directions included simplified, user-focused reporting, Go/No-Go guidance, standardized reporting and review procedures, cross-functional alignment, status dashboards, structured onboarding, and decision records. Engineering's main issues concerned the need for concise, location-specific, and field-applicable information amid time constraints, inconsistent review practices, unclear decision-making authority, and limited revision tracking. Its proposed directions included operations-focused reporting, visual concern maps, standardized ATE reviews, faster report turnaround, verification checkpoints, revision tracking, and clearer Stop/Go authority.

These proposals were consolidated through thematic analysis and weighted according to their frequency and a normalized stakeholder priority score, resulting in four business-solution alternatives: A1 – Clear and Decision-Focused ATE Report; A2 – Standardized ATE Reporting and Review; A3 – Improved ATE Workflow and Decision Roles; and A4 – Decision Tracking and Field Feedback System. Across the three functions, Geology's proposals focused on improving the consistency and quality of information at its source, Geotech's proposals emphasized translating technical information into outputs that better supported downstream decisions, and Engineering's proposals prioritized concise, actionable information that could be applied within operational timelines. Despite these differences in emphasis, all three functions converged on four recurring themes: report clarity and operational usefulness, consistency in preparation and review, workflow efficiency and decision-making authority, and decision records and field feedback. These themes formed the basis for the four consolidated alternatives.

SMART Evaluation Results

The four alternatives were evaluated by the six decision-makers against five weighted criteria: Interpretation Alignment (C1, 25%), Operational Decision Support (C2, 30%), Risk and Uncertainty Communication (C3, 15%), Systematic Evaluation and Learning (C4, 15%), and Implementation Practicality (C5, 15%). The evaluation employed the additive SMART model, $V(Ai) = \Sigma(wj \times sij)$. Table 9 presents the aggregated scores and rankings.

Table 9

SMART Evaluation Scores and Ranking of Business-Solution Alternatives.

Alternative	C1 (.25)	C2 (.30)	C3 (.15)	C4 (.15)	C5 (.15)	Score	Rank
A1. Clear and Decision-Focused ATE Report	4.50	4.50	4.17	2.67	4.17	4.13	1
A2. Standardized ATE Reporting and Review	3.83	4.00	3.17	4.17	4.17	3.88	2
A3. Improved ATE Workflow and Decision Roles	3.00	3.33	3.17	4.00	3.50	3.35	3
A4. Decision Tracking and Field Feedback System	**2.83**	3.33	**3.17**	4.17	**3.17**	**3.28**	**4**

Note. C1 = Interpretation Alignment; C2 = Operational Decision Support; C3 = Risk and Uncertainty Communication; C4 = Systematic Evaluation and Learning; C5 = Implementation Practicality. Scores use the weighted additive SMART model. Ranks are based on the complete criterion scores of all four alternatives.

Among the four alternatives, A1 ranked first (4.13), followed by A2 (3.88), A3 (3.35), and A4 (3.28). Table 10 presents recalculations under seven weighting scenarios using the displayed

criterion means, which were held constant across scenarios. Minor differences from previously reported totals may reflect rounding.

Table 10

Sensitivity Analysis of SMART Evaluation Results across Seven Weighting Scenarios. Note. Weights are reported as relative inputs and divided by their sum for calculation. The inputs for all seven scenarios sum to 100. Totals use the displayed criterion means in Table 9 for all four alternatives (A1–A4)

Scenario	C1	C2	C3	C4	C5	A1	A2	A3	A4
Base Model	25	30	15	15	15	4.13	3.88	3.35	3.28
Equal Weights	20	20	20	20	20	4.00	3.87	3.40	3.33
Higher C1 Weight	35	**28**	13	12	12	4.20	3.87	3.29	3.22
Higher C2 Weight	23	40	13	12	12	4.20	3.89	3.33	3.28
Higher C3 Weight	23	28	25	12	12	4.16	3.79	3.31	3.26
Higher C4 Weight	23	28	12	25	12	3.96	3.92	3.42	3.39
Higher C5 Weight	23	28	12	12	25	4.16	3.92	3.36	3.26

The overall ranking A1 > A2 > A3 > A4 remained stable across all seven recalculated scenarios. A1's score ranged from 3.96 to 4.20, whereas A2's ranged from 3.79 to 3.92. The smallest difference between A1 and A2 (3.96 versus 3.92) occurred under the Higher C4 Weight scenario. A4 ranked last in every scenario, with scores ranging from 3.22 to 3.39; however, its margin below A3 was narrow (0.03–0.10), and the smallest difference (3.42 versus 3.39) also occurred under the Higher C4 Weight scenario. A1 is therefore the leading priority among the four alternatives. This ranking does not demonstrate operational effectiveness.

Proposed Implementation Plan

A phased implementation plan for A1, structured using the 5W+1H framework, is presented in Table 11.

Table 11

Implementation Plan for the Clear and Decision-Focused ATE Report (5W+1H).

Element	Proposed Implementation
What	Develop and pilot a Clear and Decision-Focused ATE Report containing mandatory geological concerns, concern locations, operational implications, recommended actions, Go/No-Go guidance, and confidence levels.
Why	Improve the clarity, usability, and operational relevance of geological information while reducing unnecessary technical detail and supporting more efficient review and decision-making.
Where	Selected POI–ATE cases involving Geology, Geotech, Engineering, and relevant Operations representatives.
Who	Geology prepares the report; Geotech and Engineering review its technical and operational relevance; Operations assesses field usability; a designated process owner coordinates the pilot.
When	Progressively, through design, validation, pilot application, evaluation, refinement, and broader rollout, following the operational schedule and stakeholder availability.
How	Develop the draft format, validate it through cross-functional review, apply it to selected cases, evaluate performance, refine content and guidance, and formalize the approved format for broader use.

Discussion

RQ1 – Extent of Stakeholder Understanding

Geology and Geotech reported similarly High levels of Core Understanding, whereas Engineering reported a Moderate level of perception with greater response variability (Table 6). This pattern was Supported for Geology and Geotech but only Tentative for Engineering because

of its lower measurement reliability (Table 7). No statistically significant sender–receiver difference was observed, although the Geology–Engineering comparison exhibited a small effect size (Table 8). At the item level, stakeholders generally understood the core content of the reports, and technical terminology was not a major concern for Geotech. The most notable gap concerned approval-stage clarification for Engineering, although this finding remained Preliminary. Dhungana et al. (2025) explain that information senders and receivers tend to emphasize different aspects of the same information: senders focus on data quality and technical limitations, whereas receivers focus on practical implications. Engineering's comparatively lower score may reflect differences in information needs; however, the survey does not establish the reason for this pattern. Overall, respondents reported Moderate-to-High levels of Core Understanding. These perceptions do not establish objectively adequate understanding or rule out broader knowledge gaps.

RQ2 – Factors Influencing Understanding and Interpretation

Factors and Sensemaking was descriptively the weakest of the five dimensions, with all groups reporting only Moderate perceptions (Table 6). The reliability evidence qualified this finding as Supported for Geology, Tentative for Geotech, and Preliminary for Engineering (Table 7). No statistically significant or practically meaningful sender–receiver difference was identified (Table 8). At the item level, the need for discussion was the most strongly Supported factor, particularly for Geotech, whereas report complexity and differing stakeholder interpretations remained Preliminary. This pattern is consistent with (Pérez-Díaz et al., 2020), who note that stakeholders operating with different conceptual models may interpret identical geological information differently. It is also reinforced by the interview evidence, in which participants identified limited cross-functional discussion, informal or incomplete feedback, time constraints, and inconsistent competency levels as barriers to clarification. Collectively, these results suggest that discussion is the most practically actionable mechanism for narrowing interpretation differences, although report complexity and differing interpretations require further and more conclusive evidence before they can be treated as established factors.

RQ3 – Implications for Decision-Making Effectiveness, Efficiency, and Risk Recognition

Decision Efficiency and Accuracy and Awareness and Impact Recognition both showed High perception levels across all groups (Table 6), but their reliability patterns were mixed. Decision Efficiency and Accuracy was classified as Tentative for Geology and Geotech and Supported for Engineering, whereas Awareness and Impact Recognition was Supported only for Geology and Preliminary for both receiver groups (Table 7). Again, no statistically significant or practically meaningful sender–receiver difference emerged (Table 8). The strongest Supported item-level evidence across both dimensions concerned the perceived relationship between misunderstanding geological information and delays, rework, and changes to plans or designs. In contrast, perceived effects on decision accuracy, cost, safety, operational risk, correct information use, and the frequency of misunderstandings remained Preliminary. This finding is consistent with Carlson (2025), who documents how unresolved geological uncertainty can affect mining project schedules, costs, and operational performance (Table 1), and with Dhungana et al. (2025), who argue that scientific information must be translated into practical, decision-relevant meaning before it can be applied effectively. The interview evidence provides further nuance: Geology, Geotech, and Engineering appeared to prioritize different consequences of misunderstanding according to their respective responsibilities. Geology emphasized data accuracy and confidence, whereas Geotech and Engineering emphasized rework, design changes, and field adjustments. This suggests differences in how the functions perceive operational consequences. However, the data do not establish that differences in understanding caused these consequences or demonstrate overall decision-making quality.

RQ4 – Improvements and the Recommended Intervention

Improvement and Actionability showed High perception levels and high response consistency across all groups (Table 6). However, the dimension-level finding remained Tentative because reliability was only Acceptable across the three groups (Table 7). The Geology–

Engineering comparison also exhibited a medium effect size (g = 0.622), representing the only case in this study in which a descriptive difference was accompanied by a medium effect size (Table 8). Item-level results showed Supported agreement on the value of geology in mining plans, reporting tailored to stakeholder needs, and clearer report structures, whereas the need for systematic and traceable decision evaluation remained Preliminary. These patterns, together with the interview findings, provided the empirical basis for the four consolidated alternatives and the criteria used to evaluate them (Table 9).

The criterion weights reflect the relative strength of the evidence presented above (Taherdoost & Mohebi, 2024). Operational Decision Support received the highest weight (30%) because delays, rework, and design changes were the most strongly Supported perceived consequences of misunderstanding. Interpretation Alignment received the second-highest weight (25%) because discussion and potential interpretation differences were identified as central to addressing the sender–receiver gap. Risk and Uncertainty Communication, Systematic Evaluation and Learning, and Implementation Practicality each received a moderate weight (15%) because their underlying findings remained Preliminary or reflected feasibility considerations rather than established evidence. Under this weighting scheme, A1 (Clear and Decision-Focused ATE Report) ranked first. The recalculated sensitivity analysis (Table 10) supports this ranking: A1 remained the highest-ranked of the four alternatives across all seven scenarios, whereas A4 consistently ranked last, largely because of its comparatively low Interpretation Alignment score (C1 = 2.83). Its lead over A2 narrowed only when Systematic Evaluation and Learning was emphasized, which was precisely the criterion on which A1 received its lowest score (C4 = 2.67) and A2 received its highest score (C4 = 4.17). A1 and A2 may therefore serve complementary purposes: A1 addresses the immediate communication and decision-support needs, whereas A2's standardized reporting and review processes could subsequently reinforce the consistent implementation of A1.

Because the SMART ranking reflects stakeholders' assessments of each alternative's expected contribution rather than its demonstrated operational effects, A1 should be treated as the highest implementation priority rather than as a proven solution. The phased pilot presented in Table 11 is therefore intended to generate the missing operational evidence concerning report clarity, preparation time, clarification frequency, stakeholder acceptance, and operational usefulness before broader implementation. This approach is consistent with Prayudi et al. (2025) emphasis on structured evaluation and organizational learning as stages of effective communication improvement and with Stebbins (2001) and Stebbins (2025) caution that exploratory findings such as these should inform, but not replace, a subsequent evaluation stage.

Theoretical and Managerial Implications

Theoretically, this study applies the sender–receiver perspectives on uncertainty communication proposed by Dhungana et al. (2025) and Pérez-Díaz et al. (2020) to an internal, cross-functional operational setting. The distinction between information providers' emphasis on data quality and technical limitations and information users' emphasis on practical implications offers a possible interpretation of the descriptive perception patterns. However, this distinction was not tested as an explanatory mechanism. The Supported–Tentative–Preliminary framework qualifies the measurement evidence underlying these perceptions without independently verifying the existence of knowledge gaps or the accuracy of geological information. Abubakar et al. (2019) and Vveinhardt et al. (2026) work on knowledge management, decision-making styles, and organizational performance provides broader context; however, the present study does not examine effects on organizational performance.

Managerially, the findings support piloting clearer ATE reporting and structured opportunities for clarification. The absence of statistically significant dimension-level differences does not establish equivalence or eliminate the possibility of localized understanding needs. Discussion was the most strongly Supported interpretation factor, whereas the finding concerning Engineering's approval-stage clarification needs remained Preliminary. Brief cross-functional clarification opportunities therefore warrant evaluation alongside the proposed report. The Clear and Decision-Focused ATE Report emphasizes concern locations, operational implications, and Go/No-Go guidance in response to the perceived relationships between misunderstanding, delays, rework, and design changes. These interventions are recommendations whose operational

effects should be assessed through the phased pilot presented in Table 11.

Limitations

Several limitations should be considered when interpreting these results. First, the research included only internal DMLZ stakeholders; therefore, the findings may not be generalizable to other operations, mine types, or organizational contexts without further replication. Second, the analysis examined stakeholder perceptions rather than the technical accuracy of the underlying geological data or models. Consequently, a Supported finding indicates a consistent perception pattern, not an independently verified fact about geological conditions. Third, the sample of 38 survey respondents and six interviewees provides context-specific exploratory evidence but limits statistical power. No prospective power calculation or complete population denominator was documented. Furthermore, the uneven validity and reliability patterns across dimensions and stakeholder groups (Tables 4–5), particularly the low reliability observed for Awareness and Impact Recognition among Geotech and Engineering, meant that several dimension-level findings could only be classified as Tentative or Preliminary rather than treated as confirmed evidence. Finally, because the SMART evaluation relied on researcher-assigned criteria and weights, together with stakeholders' assessments of expected contributions, the resulting ranking reflects anticipated rather than demonstrated performance. Moreover, although the sensitivity analysis showed a stable ranking of all four alternatives, the narrow margin between A3 and A4 (0.03–0.10) indicates that their relative positions should be interpreted with caution.

Relation to Prior Mining Case Evidence

The mining project cases presented in Table 1 illustrate the potential consequences of misjudging geological uncertainty. Their reported technical causes and impacts provide context for examining how geological information is interpreted in mining decisions. However, they do not establish that the projects lacked pre-excavation review mechanisms or that their failures resulted from the same communication issues examined in this study. Within PTFI's POI–ATE process, respondents reported Moderate-to-High levels of Core Understanding alongside perceived needs for clearer, location-specific, and confidence-qualified guidance. The proposed Clear and Decision-Focused ATE Report addresses these perceived needs, but its ability to prevent operational problems remains to be evaluated.

CONCLUSION

This study assessed stakeholder understanding, factors influencing interpretation, perceived decision-making consequences, and improvement priorities within PTFI's DMLZ POI–ATE process. Geology and Geotech reported High levels of Core Understanding, whereas Engineering reported Moderate understanding accompanied by weaker measurement reliability. No dimension-level sender–receiver difference reached statistical significance; however, this does not establish equivalence or rule out localized gaps. Discussion was the most strongly Supported interpretation factor, whereas report complexity and differing interpretations remained Preliminary. The strongest Supported item-level perceptions concerned the relationship between misunderstanding and delays, rework, and changes to plans or designs. In contrast, perceived effects on decision accuracy, cost, safety, and operational risk remained Preliminary. These findings describe self-reported perceptions rather than demonstrated causal effects or independently verified geological understanding.

To address the improvement objective, the SMART evaluation prioritized the Clear and Decision-Focused ATE Report (A1), which received a score of 4.13 and ranked first among the four alternatives across all seven recalculated weighting scenarios, followed by A2, A3, and A4. This ranking represents expected contributions under the selected criteria and weights; its operational effectiveness has yet to be established. PTFI should pilot A1 and assess report clarity, preparation time, clarification frequency, stakeholder acceptance, and operational usefulness before broader implementation, while considering complementary elements of A2–A4 as further evidence becomes available. This study contributes a context-specific framework for identifying perception patterns and qualifying their measurement strength. Future research should employ larger and

more balanced samples, replicate the analysis across other operations, and combine stakeholder perceptions with technical validation, direct observation, and operational records to determine whether the proposed intervention reduces delays, rework, and design changes.

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AUTHOR CONTRIBUTIONS

Andreas Yudha Sugiyanto contributed to the conceptualization of the research, development of the research framework, data collection, data analysis, interpretation of the findings, and preparation of the original manuscript. Utomo Sarjono Putro contributed to academic supervision, methodological refinement, interpretation of the findings, critical review, and revision of the manuscript. Both authors contributed to the development of the study, reviewed and approved the final version of the manuscript, and take responsibility for the integrity and accuracy of the research.

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