Eduvest – Journal of Universal Studies
Volume 6 Number 8, August, 2026
p- ISSN 2775-3735- e-ISSN 2775-3727

Transforming Indigenous Local Operator Competencies Toward Automation-Based Operations in Underground Mines: A Case Study of PT Freeport Indonesia's GBC Mine

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Keywords
Local Human Resource Competency; Mining Automation; Soft Systems Methodology; Habit Formation; Indigenous Papuan Workers; Mining Work Safety.

ABSTRACT
The accelerated adoption of Industry 4.0 in underground mining has created a significant gap between mandated automation and local workforce readiness, particularly among indigenous Papuan workers with limited technological exposure. This study examines the competency gap dynamics among haulage operators at PT Freeport Indonesia's Grasberg Block Cave (GBC) Mine using a mixed-method approach based on Soft Systems Methodology (SSM). Survey analysis of 30 respondents reveals that technical competency for remote operations is at a moderate level (mean= 3.37), significantly different from the high level of learning readiness (mean= 4.33). A group of operators from seven indigenous Papuan tribes recorded the lowest technical competency score (mean= 2.55) but demonstrated strong learning readiness (mean= 4.18). Triangulation of quantitative data, in-depth interviews, and secondary operational data confirms that the primary barriers were not motivation or safety awareness, but rather limitations in the capability development architecture: limited time for structured practice, limited mentoring capacity, and the absence of pre-employment pathways tailored to the sociocultural backgrounds of local communities. Analytic Hierarchy Process (AHP) was used to prioritize five strategic alternatives, with the highest results in Precision TNA and andragogy-based training redesign (score 0.368), followed by a 4-level remote training program with habit formation architecture (score 0.317), and the establishment of the 7 Papuan Tribe Pre-Mining School (score 0.204) as a long-term structural solution. These findings contribute to the literature on socio-technical systems management, local workforce integration in high-risk industries, and the application of andragogy in the context of digital transformation in developing countries.

INTRODUCTION

Anyone who has ever been directly involved in the haulage level of an underground mine understands that the numbers in production reports never fully capture what is really happening there (Davrajh et al., 2023; Onifade et al., 2022; Walker, 2023). Behind the throughput statistics and ore targets are human skid-steer operators working in the darkness, amid the sound of locomotives and the constant pressure of shift work. This research stems from a growing concern arising from direct field observations: that the pace of automation technology adoption in underground mining, particularly at PT Freeport Indonesia's Grasberg Block Cave (GBC)

Mine, has outpaced the development of the human capabilities that should support it. When mandatory remote operations were implemented, the least-asked question was the most crucial: were our operators, especially those from Indigenous Papuan communities, truly ready? Not ready on paper, but ready in the true sense having experience, having mentors, and having systems designed to support their learning journey.

In Indonesia, this context is further complicated by two interacting factors. First, regional autonomy regulations and the obligation to empower local workers, particularly Indigenous Papuans, through the Special Autonomy Law, create a moral and legal imperative to integrate local communities into modern industrial production chains. Second, most local job candidates come from backgrounds with limited exposure to digital and industrial environments, so adopting new technologies requires a far more systematic and culturally inclusive approach to capability development than conventional training allows.

PT Freeport Indonesia (PTFI), through its Grasberg Block Cave (GBC) mine operations in Papua, addresses this challenge on a concrete and measurable scale (Gusprita & Damayanti, 2024; Sokoy, 2025; Wulandari et al., 2025). The haulage system at GBC utilizes unmanned, remotely controlled locomotives, but supporting activities particularly track clearing using skid-steer loaders remain dominated by manual operations. With only two of the eight skid-steer units equipped with remote capabilities, and only two of the average eight operators per crew having remote operation experience, there is a significant gap between mandated automation and the actual capabilities of the workforce. This is not simply a technical issue; it reflects a misalignment between the pace of technological transformation and the maturity of human resource development systems (El Garem, 2026; Khatoon et al., 2025; Mantzaris & Myloni, 2023; Nazarova & Rudenko, 2023; Zamba, 2026).

Previous studies on mining automation have predominantly focused on technological aspects, such as equipment design, system integration, and operational efficiency (Schwab, 2016; Brynjolfsson & McAfee, 2014), while largely overlooking the human capability dimension critical to successful implementation. Research on workforce development in the mining sector has examined competency frameworks and training effectiveness (Spencer & Spencer, 1993; Boyatzis, 1982), yet these studies have primarily been conducted in developed-country contexts with established educational infrastructures, limiting their applicability to developing regions such as Papua. Studies on Indigenous workforce participation in extractive industries (Cooney & Sherwood, 2020; Tan et al., 2023) have highlighted cultural and social barriers but have not adequately addressed the specific competency gaps emerging from the transition to automation-based operations.

A significant gap exists in the literature regarding the integration of local Indigenous workers into automated mining environments. While human factors research has examined operator performance and safety in high-risk industries (Leveson, 2011; Wickens, 1992), few studies have explored competency development pathways for workers with limited prior exposure to digital and automated systems. Furthermore, the application of andragogical principles (Knowles, 1980) to industrial training in developing-country contexts, particularly among Indigenous populations, remains under-researched. Soft Systems Methodology (Checkland, 1981) has been used to analyze complex socio-technical problems, but its application to Indigenous workforce integration in mining automation is novel. This study addresses these gaps by examining competency gap dynamics at GBC Mine through an

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integrated SSM–AHP–Andragogy framework, offering insights into how mining companies in developing countries can manage digital transitions while fulfilling commitments to local workforce empowerment.

This research aims to: (1) analyze the root causes of competency gaps that hinder the adoption of automation at the haulage level, (2) identify structural barriers in the recruitment, training, and retention systems for local operators, and (3) formulate sustainable strategic recommendations to improve the quantity and quality of local human resources at GBC Mine, with an emphasis on developing automation capabilities aligned with the sociocultural context of Indigenous Papuan communities. This research's scientific contribution lies in the integration of the SSM framework with the principles of mature andragogy in a high-risk industrial context, offering a replicable analytical model for mining companies in developing countries facing similar challenges in managing the digital transition while respecting the sovereignty of the local workforce.

METHOD

Research Design and Approach

This research used a qualitative-dominant mixed-methods approach rooted in Checkland's (1981) Soft Systems Methodology (SSM) as the primary analytical framework. SSM was chosen because the competency gap issue at the GBC Mine haulage level represents a complex socio-technical system involving interactions between human resources, automation technology, operational procedures, and the indigenous community context. This approach allows for the integration of quantitative evidence (survey and operational data) with a rich qualitative understanding of the inhibiting mechanisms that cannot be captured through numbers alone.

Research Context and Location

The research was conducted at the haulage level of the Grasberg Block Cave (GBC) Mine, PT Freeport Indonesia, Papua. GBC operates four active haulage tracks (Tracks 20, 30, 40, and 50) using an unmanned locomotive system controlled from a remote-control room. Track clearing activities are carried out using skid steer loaders, most of which are still manually operated. This context was chosen because it represents the real-world conditions of automation transformation in the Indonesian underground mining industry, with the added complexity of requiring the empowerment of indigenous Papuan workers.

Data Collection

Data was collected through three complementary channels. First, a structured survey using a 1–5 Likert scale was administered to 30 respondents consisting of skid steer operators, haulage supervisors, and contractor representatives actively involved in GBC's haulage operations. The survey instrument covered five dimensions: technical competence (T1–T5), safety competence (S1–S6), workload and situational awareness (W1–W4), readiness to learn (A1–A5), and perceptions of safety-production linkages (P1–P5). Second, semi-structured interviews were conducted with three categories of informants: GBC production engineers, management representatives, and field contractor supervisors. Third, secondary data were collected from Institute Pertambangan Nemangkawi (IPN) training records, equipment availability statistics, operational incident reports, and standard operating procedure documents.

Data Analysis

Qualitative analysis was conducted through an adapted seven-stage SSM learning cycle, starting with problem situation identification, problem expression using CATWOE analysis, developing a conceptual model of the ideal system, and comparing the conceptual model with actual operational conditions (SSM Stage 5). Supporting quantitative analysis included descriptive statistics for survey data and the Analytic Hierarchy Process (AHP) method with five weighted criteria to prioritize strategic intervention alternatives. Triangulation was conducted by integrating three streams of evidence: quantitative survey data, qualitative interview narratives, and operational secondary data to strengthen causal interpretations within a socio-technical framework.

RESULT AND DISCUSSION

Operational Gap Profile

Analysis of actual operational conditions revealed three layers of mutually reinforcing gaps. From an equipment perspective, only two of the eight skid steer units are equipped with remote operation systems, while the remaining six units still rely on manual operation. From a workforce perspective, with an average of eight operators per crew compared to the requirement of 15 adjusted for VSAT (Vacation, Sickness, Absent, Training) factors of 80%, there is a deficit of seven operators per crew. From a competency perspective, only two of the eight operators per crew have adequate remote operation experience.

Table 1 summarizes the actual performance gap compared to the established standards:

Table 1. GBC Mine Haulage Level Operational Performance Gap Analysis

Area	Ideal Conditions	Actual Condition	Operational Impact
Number of Operators/Crew	15 people/crew (VSAT factor 80%)	7–8 people/crew	Not all haulage lines can be operated optimally; waiting times extend the production cycle.
Remote Competency	All crew are certified remote Level 1–3	2 of 8 operators/crew have remote experience	Safety risks are increasing; automation adoption is hampered in high-risk areas.
Skid Steer Remote Availability	All units have remote capacity	2 of 8 units have remote capacity	Line cleaning in wet material spillage area was suboptimal; response was slow.

Source: Authors' compilation based on PT Freeport Indonesia GBC Mine operational data and field observations, 2026

The survey of 30 respondents (n=30) yielded analytically informative patterns. The only dimension at a moderate level was technical competency (mean = 3.373), while all other dimensions, such as safety competency, situational awareness, readiness to learn, and perceived safety-production linkages, were at high levels.

Table 2. Competency Survey Dimension Scores (Likert Scale 1–5, n=30)

Competency Dimensions	Average	Standard Deviation	Interpretation
Technical Competence (T1–T5)	3,373	1,102	Moderate - major gap; intervention priority

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Safety Competence / SOP Implementation (S1–S6)	3,978	0,676	High - strong knowledge; needs strengthening of field execution
Workload / Situational Awareness (W1–W4)	4,100	0,803	High - operators realize the urgency of automation
Readiness to Learn (A1–A5)	4,333	0,902	High - positive capital for training programs
Safety-Production Linkage (P1–P5)	4,367	0,806	High - operators understand business relevance

Source: Primary survey data analysis (n=30 respondents), 2026

When the data is disaggregated by ethnic group, sharp but diagnostically significant differences are apparent. The 7 Indigenous Papuan Operator Group recorded the lowest technical competency score (mean = 2.550), with the most critical items being T4 - remote operation independence (mean = 2.333) and T5 - awareness of remote system limitations (mean = 2.167). However, this group demonstrated very high readiness to learn (mean = 4.183) and perceived value of simulator training (A5 = 4.417), comparable to the non-Papuan group.

This pattern has crucial diagnostic implications: the technical competency barriers in the 7 Indigenous Papuan Operator Group are not rooted in motivational deficits or low safety awareness, but rather in gaps in exposure and practice specific to remote technology systems. These are capability gaps determined by system design, not individual capacity.

Triangulation: Three Converging Streams of Evidence

The survey findings were consistently corroborated by interviews and secondary data. From interviews with representative production engineers, management, and contractor supervisors, five recurring themes of barriers were consistently identified: (1) uneven distribution of remote operations competencies among crews, (2) limited practice time protected from production pressures, (3) insufficient mentoring and trainer capacity, and (4) production target pressures that risk compromising adherence to safety protocols.

Thematic coding analysis of the survey's open-ended responses revealed the code PRACTICE_LIMIT (limited training and practice time) with 41 occurrences, followed by SA_WETMUCK (wet material safety awareness) with 23 occurrences, and MENTORING (mentoring and trainer support) with 12 occurrences. Secondary data from IPN training records confirmed that 10 of the 12 trainees from the 7 Suku group remained at the basic skill level.

The convergence of these three streams of evidence supports a cohesive causal interpretation: the rollout of automation technology has outpaced the maturity of systems developing the capabilities necessary to support consistent and secure remote-based execution. This is not an individual failure; it is a property of the system.

What is most memorable about this entire data collection process isn't the numbers, although the T4 figures of 2,333 and T5 of 2,167 for the 7 Tribes group speak for themselves. What's most memorable is the consistency of the narrative emerging from three different sources: surveys, interviews, and operational data, all pointing in the same direction. It's not the operators who are the problem. It's the system that's not yet fully developed.

SSM Analysis: Conceptual Model vs. Reality Gap

The implementation of SSM Phase 5 identified six categories of gaps between the ideal system conceptual model and actual field conditions. The most critical gaps (potentially leading to immediate fatal risks) were: (1) the absence of a structured training follow-up architecture; literature shows that 88% of conventional training programs fail to achieve permanent work behavior change (Lally et al.'s, 2010); (2) the absence of a formalized Tribal Mentoring System, with only two of the eight operators per crew having remote work experience; (3) the placement of non-certified operators in high-risk areas due to staffing shortages; and (4) a deficit of seven operators per crew from the VSAT-adjusted standard. High-level gaps included the absence of a structured pre-employment pathway for youth from the seven Tribes, as well as the absence of formal measurements of the Remote Adoption Rate (RAR) and Crew Competency Index (CCI).

Perhaps the most surprising and ultimately encouraging finding of this study is the high learning readiness recorded precisely among the group with the lowest technical competency scores. The Seven Indigenous Papuan operators recorded an average learning readiness score of 4.18 and a perceived simulator value score of 4.42, figures broadly comparable to non-Papuan groups with much longer exposure to digital systems. This is not a statistical anomaly. It is a signal that should fundamentally reshape how indigenous workforce development programs in the mining industry are designed: stop asking if they can learn, and start asking if our systems are designed to support how they learn.

This study's findings have implications that extend beyond the specific context of the GBC Mine. First, the pattern of disparity between high learning readiness and low technical competency in the local indigenous workforce is a phenomenon consistently reported in workforce development literature in developing countries (Cooney & Sherwood, 2020). This strengthens the argument that development programs fail not because communities are incapable of learning, but because program design fails to account for the disparate adoption curves for discontinuous skills transitions.

Second, these findings contribute to the discussion on “technology readiness” in the context of Industry 4.0 in developing countries. While the dominant literature focuses on technological infrastructure readiness, this study demonstrates that the real barriers often lie at the human capability layer of the system and, in particular, in the capability development architecture designed to support technological adoption. Mandating automation without corresponding investment in human capability development does not eliminate risk but rather shifts it.

Third, the integrated SSM-AHP-Andragogy framework developed in this study offers a methodological template that can be adapted by other mining companies operating in regions with indigenous communities. This framework explicitly recognizes that inclusive digital transformation requires simultaneous investment in both technology and people, and that these two dimensions are interdependent rather than sequential. A company cannot complete the technological transformation first and then address the human side; both must be developed in parallel.

There are important limitations that need to be acknowledged. This study is limited to the haulage level of the GBC Mine, and while its analytical foundation is sound, empirical validation in other operational contexts is needed. The qualitative dimension of the SSM analysis, although triangulated across three data streams, remains subject to the interpretative constraints inherent in the methodology. Future research should prioritize longitudinal measurement of the Remote Adoption Rate (RAR) and Crew Competency Index (CCI) as formal operational KPIs to track the quantitative impact of recommended interventions over time.

CONCLUSION

This research’s journey began with a simple but challenging question: why, amidst the company's commitment to automation and a local workforce, does the gap between mandated remote operations and actual operator capabilities persist? The answer, after conducting surveys, interviews, document analysis, and SSM-AHP modeling, turned out not to be the people. It was the system: an incomplete training system, an undivided mentoring system, and an underdeveloped workforce pipeline for the communities that needed it most.Three key findings provide a strong foundation for these strategic recommendations. First, the sharp divergence between high learning readiness (4.33) and moderate technical competency (3.37), with the 7 Tribes group recording the lowest technical score (2.55) despite their high learning readiness (4.18), demonstrates that the barriers are structural, not individual. Second, triangulation of three data streams confirmed that limited practice and insufficient mentoring capacity were the dominant barriers. Third, AHP modeling validated that investments in Precision TNA and andragogy-based training redesign yielded the highest combined value in competency improvement, safety impact, and sustainability. The key managerial implication is that mandating automation without transforming human capabilities only transfers risk, not eliminating it. Investments in SPT-7S and TMS go beyond mere business justification; they respond to the moral responsibility of companies operating in indigenous territories to ensure landowner communities have real and dignified access to economic benefits and industry knowledge. Therefore, it is recommended that PT Freeport Indonesia immediately implement Precision TNA and andragogy-based training redesign as the primary strategic intervention, followed by the four-level remote training program with habit formation architecture, while establishing the Seven Papuan Tribe Pre-Mining School as a long-term structural solution to create a sustainable pipeline of qualified local operators. Management should also formalize the measurement of Remote Adoption Rate (RAR) and Crew Competency Index (CCI) as operational KPIs, allocate dedicated practice time protected from production pressures, and integrate cultural contextualization and tribal mentoring systems into training curricula. For policymakers, it is recommended that regional regulations on local workforce empowerment be accompanied by technical assistance and funding mechanisms to support structured pre-employment pathways and on-the-job training programs that are culturally sensitive and aligned with industry needs. This research opens up opportunities for further studies, particularly on the comparative effectiveness of tribal-based mentoring models in other high-risk industrial contexts, as well as the development of measurement instruments for RAR and CCI as industry-standard KPIs.

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