Level of Competency in Evaluate Environmental Impact Since the Implementation Good Mining Practice – A Case Study of Orebody with the Complexity of Geometallurgy

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ABSTRACT

Implementing strategies that meet green mining requirements has become mandatory for coal and mineral operators in Indonesia. The government of Indonesia through the DEMR (Directorate of Energy, Coal and Mineral Resources) has establish the good mining practise (GMP) as one of essential reference to conduct mining activities in safest way, healthy and less of environmental harm. To be able achieve this target for implementation GMP, it will require individual and organizational maturity with a certain level of competencies to working through all the stage processes of the mining. Starting from the stage of conceptual design, development-construction, production up until final stage of mine closure. The aspect of geometallurgy and its impact from side of environmental by extracting the mine orebody will call for collaboration within the different of discipline and knowledge background ensure a good decision can be made. Having an orebody at complexity of geometallurgy may need some specific requirements of mine infrastructure enable mineral extraction and ore dressing activities at the mill site to be conducted in efficient, safest and low environmental harm.

The sulphide orebody presenting multiple type of rocks at the numerous geochemical aspect who will further risk our environment at improperly handle them through the mining process. Content of high pyrites in the orebody could generate the large amount of rock acid and suffering the environment on directly release it into river. Therefore, engineering and designing of the mine along requirement infrastructures and determination of best operation scenario for properly handling the pyrites as part of extraction mineral process activities become more essential to the business. This written paper aiming exercise the complexity of geometallurgy at the Grasberg District orebody Freeport Indonesia and its determination solution for mineral extraction activities with the collaboration among different of knowledge background geologist, mining, metallurgy, environmental, economic-accounting and several others. Part of exercise to also look into the needs of level competencies along with the assessment on current availability of formal educational course supporting these requirements.

Study and evaluation are being conducted through the system dynamic simulation methodology by reviewing effectiveness of process on each activity of the mining. In analyst the scenario 3 under the system dynamic simulation, it founded large of deviation at number of actual wet drawpoints compared to the plan. The plan mismatch is also extended to the volume of pyrites delivers into the mill facilities. While geotechnical aspect seems to be in well managed, the green mining concept and the GMP implementation perspectives remain on gaps that is look for improvement considering an ideal composition of skill.

INTRODUCTION

The current mining regulations in Indonesia that serve as a direct reference for implementation in the field are the Minister of Mining and Mineral Resources Decree 1827 through the implementation of Good Mining Practices (GMP). This serves as the primary basis for mining operations, emphasizing 5 main aspects, including:

a. Mining Occupational Safety and Health

- Risk identification and control systems

- ✈ Operating procedures and work implementation procedures prioritizing safety ✈ Establishing the use of protective equipment
- ✈ Providing education and training to ensure worker competency

b. **Mining Operational Safety / Manage the maintenance and servicing system for facilities, infrastructure, and mining equipment installations**

- ✈ Secure electrical, hydraulic, and other machinery equipment
- ✈ Ensure the feasibility of operational facilities
- ✈ Ensure workers have the necessary technical competencies to work safely and effectively ✈ Conduct periodic evaluations of mining technical studies.

c. Environmental Management and Monitoring

Conducting management and monitoring activities that include river water quality, air quality, emissions, noise and vibration, potential acid mine drainage, biodiversity of flora and fauna, and soil quality.

d. Resource Conservation Involves efforts to use resources efficiently and sustainably such as waste reduction and increased mineral recovery.

e. Management of Mine Waste according to environmental quality standards Management of mine waste whether solid, liquid, or gas.

All aspects mentioned above requires support at involvement of people who has sufficient level ofexpertise working towardsmain goal of implementationGood Mining Practices (GMP) across the organization. The Government, through the Ministry of Manpower, also regulates the Indonesian National Competency Standards (SKKNI) No. 230 and 117 for mining operations in purpose ensuring implementation is aligned with the GMP programs. In other countries with more advanced on their mining industries and technology, a framework of mining knowledge has been developed and use as a basis in measure level of expertise for developmine through conducted proper management of safety, occupational health, and environmental assessment. Referring to the basic standards of an international mining industry, the framework of mining engineering knowledge is established to meet the following aspects:

Fundamental knowledge of science & engineering

Science & Mathematics: Mathematics & statistic: Chemistry, Physics; Toxicology: Human anatomy and physiology: Psychology
Mining: Mining life cycle; Mining methods; Mining equipment; Mining processes
Ground control plans – principles and methods: Fundamentals of rock mechanics.

Leadership, organization, and work culture

Leadership: Key leadership models: Leadership styles: Management vs leadership activities;
Leadership competencies linked to safety; Leadership development; Linkage to culture & climate; Assessment of leadership problems.
Culture: Fundamentals of safety culture: Culture/climate assessment/measurement: Culture enhancement
Loss control and economics: Basic mining economics & terminology: Modelling direct & indirect loss
Responsibility and accountability: Differentiating responsibility and accountability; Applying responsibility and accountability to safety and health management; Discipline (versus responsibility and accountability); Management by objectives.

Safety, Health, Environmental protection, and Risk Management

Risk management: Mining-specific hazards; Non-specific hazards; Energy sources; Hazard Identification techniques; Situational awareness; Risk assessment approaches and techniques; Risk controls; Fatal risk management principles; Characteristic of risk; Acceptable risk; Safe operations procedures; Hierarchy of control; Personal protective equipment; Risk control verification; Management of change.
Human factors/behaviour: Key theories of human behaviour; Key elements of human error; Assessment of error & at-risk behaviour; Error and behaviour measurement; Error mitigation techniques; Mobile equipment design; Fixed equipment design; Fatigue and alertness assurance; Fitness for duty.
Occupational hygiene: Basic principles of occupational hygiene; Methods of exposure assessment; Occupational exposure limits (OELs); Exposure assessment data analysis.
Occupational health: Basic principles of occupational medicine; Linkage between exposure and dysfunction; Mining-specific occupational disease; Non-specific occupational disease (e.g. NIHL); Medical surveillance; Working with health professionals and other stakeholders; Principles of ergonomic; Ergonomic risk assessment; Ergonomic risk mitigation
Education, training and competency: Adult learning theory; Education and training methods; Education and training needs assessment; On-the-job training, safe work instruction, task training, competency verification; Training and education effective assessment.
Emergency and crisis management; Emergency preparedness and response; Mine rescue organization and training; incident management and communication
Incident reporting & investigation: Incident definitions and categorization; nearmiss reporting; investigation and analysis; incident investigation techniques; Key models and theories

Governance system, regulations, and insurance

Management systems: Principles of safety management systems; Governance, structure & functionality; Consensus management system standards; Management system metrics; Management system auditing; Continuous improvement principles.
Regulation and legislation: Regulatory requirements of area(s) of responsibility for health and safety professionals; Integrating management systems and regulation; Techniques of regulatory compliance

Professionalism, ethics, and business behaviour

Professional skills: Strategy development and program management; Persuasion (ability to influence opinion); Inter-personal communication (verbal, non-verbal and written); Project management; Personnel and performance management; Interpreting relevant safety and health research; Using information technology (hardware and software for safety and health); Data analysis, trending, interpretation and action (upon); Time management; Problem-solving, Delegation; Managing up; Networking and collaboration; Advocacy (internal and external); Recognition and reinforcement.
Professional ethics: Related codes of ethics.

The framework of mining engineering knowledge then compared with the below levels of the documented process in determining the organization is level of maturity.

Figure 1: The maturity level pyramid in an organization

The level of organization maturity is identified by conducting observation at the following description of behaviours.

Process Level		Description
1	Initial	Process this level are typically undocumented and in state of dynamic changes, tending to be driven in an ad hoc, uncontrolled, and reactive manner by users of events. This provides a chaotic and unstable environment. Success is likely to depend on individual efforts, and is not considered to be repeatable, because processes would not be sufficiently defined and documented to allow them to be replicated.
2	Repeatable	Some of the processes are repeatable, possibly with consistent results. Process discipline is unlikely to be rigorous, but where it exists, it may help to ensure that existing processes are maintained during times of stress.
3	Defined	There are sets of defined and documented standard processes established and subject to some degree of improvement overtime. These standard processes are in place (i.e. they are the AS IS processes) and used to establish consistency of process performance across the organization.
4	Managed	Using process metrics, management can effectively control the AS-IS process (e.g. for software development). In particular, management can identify ways to adjust and adapt the process to particular project without measurable losses of quality or deviation from specifications. Process capability is established from this level.
5	Optimizing	The focus is on continually improving process performance through both incremental and innovative technological changes/improvements.

Study and evaluation on organizational behaviour will explain how effective their people when working towards solution and deliver with a certain level of success into their organization. This mining engineering framework knowledge can be allied into these 5 levels of process maturity to understand the level of their effectiveness in the organization. It regardless of whether they are working independently or collaboratively in a teamwork for a certain design task, result can be present as something to measure confirming the level of maturity.

This written paper aims investigate the level of process maturity and the level of expertise needs in effectively designing the mining operation under the complexities of geometallurgy of orebody. This study to outline a prevention program to mitigate the risks that may arise as result of the happens of orebody exploitation under the negative rock chemical influence who can leading into environmental quality degradation. The risks cover any potential impacts into safety, health, and the mine environmental itself as well as the surrounding public community areas. Prevention programs happen through the engineering design process performing by the person who is experts in their field and working collaboratively as a team. Research and analysis areconducted in studyingGrasberg orebody along its complexity of geometallurgy to determine a best mine operation scenario. Engagement of expertfrom different knowledge background forming under an assigned teamwork who work for Grasberg study will becompared with an international common practice for geometallurgy group assessment. Effectiveness of result from this join study can be review for its alignment with the successful factor criteria for managing the block cave mine. This respectively at the key result area of successful perform the blending pyriteANC at remain maintaining the stability of opening, setup mine drainage and dewatering system at better of controlling the volume of water flowing into the cave and properly sequencing the cave. Learn into this study review of Grasberg orebody will then recommend a best composition of skill background in overcome same situation of complexity geometallurgy orebody and attaining successful implementation of Indonesian’s GMP.

LITERATURE REVIEW

Geometallurgical studies in an orebody require the presence of multidisciplinary knowledge and expertise to achieve optimal results in mining operations. The aim is to produce a mining operation engineering design with result of good planning, execution, and supervision activities that meet function stipulated under the Government of Indonesia’s Good Mining Practices (GMP). Geometallurgy relies on a good understanding of the characteristics of the ore body and its relation to designing the mining operation activities enhancing benefits. It started from designing the mineral extraction process until final products can be marketed economically. Therefore,it forms into requirement of an interconnection between different background knowledge in doing an integration data and information review which can be sufficiently understand the characteristics of ore bodies, investigate optimization the mining operations throughout engineering design process, and adopt technology processing along with the economic valuation of minerals. Geometallurgy assessment is a complex of study process at involvement of various expert in different background knowledge. Nichola McKay et al. (2016), through his research and technical paper entitled strategic and tactical geometallurgy – a systematic process to add and sustain resource value, emphasized the importance of strategic thinking and tactical action in achieving the goal of optimizing the mining value chain. Strategic geometallurgy involves long-term thinking and planning by measuring and modelling the values of block mineral in the orebodies throughout the mining lives. Tactical geometallurgy is implementing in the short-term by performing robust production control improve the efficiency on mineral block allocation. Max Frenzel et al. (December 2023) on their research and technical paper entitled Geometallurgy: Present and Future, introduce the fundamental concepts in geometallurgy studies present the current practice and potential future development to optimize the value benefits. Both of research (Nichola and Max) describing process and activities relation to the study optimization of geometallurgy; however, they do not provide a reference to the level of expect personnel expertisein carrying out these processes and activities. Chirgwin's map (December 2021) on his research entitled 'skill development and training of future workers in mining automation control rooms' provides a reference in develop workers' skills supporting effective operation and management of technology mining. Research illustrates requirement of competencies, level of worker skills, and training needs along the application of future technology optimizing the results of mining operations. Nevertheless, the research and writing do not specifically discuss the fulfilment of specialization in the concept of managing environmental impacts due to the chemical composition of minerals inside of the ore body. Gregory Trencher et al. (2018) through research and technical paper writing entitled Evaluating core competencies development in sustainability and environmental master’s programs: An empirical analysis, presents an argument for the effectiveness of developing a competency for sustainable development goals through formal environmental education and its relation to the needs of modern industrial applications today.It distinguished ongoing development under the environmental aspects which presenting many distortions in the implementation. Study happens in general and does not specifically review the geometallurgy aspect and its implementation for the mining industry. Viktor Lishchuk, through his research entitled 'bringing predictability into a geometallurgical program:An iron ore case study provides recommendation in essence of geometallurgy studies that are applying under proper techniques and programs since the early stages of mining operations. The scope of activities coverstesting hypothesis, and the use methods reduce the degree of uncertainty for production planning, in respective views of geometallurgical aspect.

The study and research focus on case studies happens for open-pit mining operations under varying depths of reserve block deposits. Research limit to review the open-pit mining operations and not to discuss studies related to the underground mining. Margarida Rodrigues et al. (2022) through the research entitled 'mapping the literature on Social Responsibility and Stakeholder Pressure in the Mining Industry' emphasize the importance of knowledge in examining the social impacts for communities and becoming another need of expertise in mining plan. Research do not specifically address the skill requirements for geometallurgy studies and the environmental impacts of the rock chemical composition in the ore bodies. Farhad Faramarzi et al. (2019) in their research and written technical paper entitled 'Simulating the impact of ore competence variability on process performance – case study of a large copper mine' arguing the there is increasing the need of expertise in quantifying the characteristics of ore bodies when designing the mine and processing facility. This is related to effort of comminutions ore to deal with requirement of process under the high energy needs. This study not extended into review the rock characterization in underground mining who also contribute into higher cost and the complexity of block minerals. Viktor Lishchuk et al. (2019) in their research and writing entitled 'Toward integrated geometallurgical approach: critical review of current practice and future trends' stressed the importance of expertise in geometallurgical studies for managing the risks of mining production operations and improve economic performance in the mining industry. The condition implies the need for collaboration from the early stages of mining operations (automation engineer, maintenance engineer, environmental engineer, data analyst) to achieve maximum production benefits despite the complexities and heterogeneities of geological-mineralogical rock situations. Geometallurgy, which was previously in collaboration between geology and mineral processing only will no longer be considered sufficient due to the needs of other discipline knowledge. It respectively in look into the plan integration targeting mine value chain achievement. This research and writing have not compared with the standards of expertise established for each of the processes undertaken. Moshood Onifade et al. (2024), through research and journal writing titled 'advancing toward sustainability: the emergence of green mining technologies and practices,' conclude that the main target for future mining is to significantly reduce energy consumption and minimize ecological disruption.To achieve this target, a study is needed that combines several initiatives across different fields of discipline that can qualitatively and quantitatively develop operational concepts with reduced greenhouse gas emissions, low energy consumption, and decreased use of chemicals. Research and writing do not elaborate on the expertise needed for the main targets of future mines that are environmentally friendly. Juxing Tang et al. (2024) through their research and journal writing entitled 'Potential and Future Direction for Copper Resource Exploration in China' conducted a study on the magnitude of copper mineral production in the future by analyzing the percentage of mining stages in several countries. This is done through the percentage of reserve value, current copper mining production operations, and the volume of copper refining. The research study shows that with the concept of down streaming in the mining industry, there will be a need for an understanding of the importance of fulfilling strategies for locating reserves that are aligned with the investments in purification and processing infrastructure that have been made. Strategies for exploring copper minerals and understanding geology-mineralogy then become one area of knowledge that will play an important role in achieving production operation targets with the concept of upstream-downstream integration in mining operations. The research study shows that with the concept of downstreaming in the mining industry, there will be a need for an understanding of the importance of fulfilling strategies for locating reserves that are aligned with the investments in purification and processing infrastructure that have been made. Strategies for exploring copper minerals and understanding geology-mineralogy then become one area of knowledge that will play an important role in achieving production operation targets with the concept of upstream-downstream integration in mining operations. The activities carried out will reduce the risk impact on an effective and efficient production operation due to errors in the design engineering of mining operations. M Daniel et al. (2018) in their research and journal writing titled efficiency, economics, energy and emissions – emerging criteria for comminution circuit decision making provide a reference concept for evaluating efficiency through the

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engineering of mining operation systems aimed at achieving optimal energy use and economically viable project value. The impact on the environment is the main basis for the evaluation conducted to optimize energy use and reduce carbon combustion. E Sepulveda et al. (2018) in their research and journal writing titled 'The Optimisation of Block Caving .

Production Scheduling with Geometallurgical Uncertainty – A Multi Objective Approach' provide a reference in formulating the effectiveness of mining operations using the block caving method through a study of net smelter return (penalty financing related to the rejection of element content in the concentrate) and volatility value at risk due to deviations between planning and actual field operations. Elboy Qurbonov et al. (2024) through their research and journal writing titled 'Analysis of Engineering Geological and Hydrogeological Processes in Underground Mining' emphasize the analysis conducted as part of the effectiveness of mining operations through joint studies in hydrogeological research. The 4 most recent research and studies that have been conducted provide a reference for the processes and steps that need to be taken to achieve production operation targets with minimal environmental impact from a geometallurgical aspect. However, it has not yet fully integrated these activities and processes into a single framework and the need for skills fulfillment to achieve optimal future mining operation targets related to energy use and minimizing ecological environmental impacts due to the complexity of mineral characteristics in an ore body. This is particularly relevant to underground mining patterns which have their own complexities with impacts arising from the chemical composition of the rock in the ore body. This research and writing provide a review and recommendations for the standard skills needed in underground mining operation engineering activities aimed at reducing environmental impact and complying with government regulations on the implementation of good mining practices. Most of research-studies which in previously conducted do not specify the level of expertise or the composition of multidisciplinary teams required to implement geometallurgy in an underground block caving context with complex sulphide geology.

C. Challenges and Strategies of Eco-Innovation

The execution of tasks with specific competencies and standards of expertise meeting the green mining context and criteria for Good Mining Practices (GMP) is one of important thing in today mining industry. The simulation result at various cost deviation as present for below operation scenario 3 shows something ineffectively happens in designing the mines. The 3rd scenario presenting option for do nothing on requirement of modifying the millplant since the presence of pyrites in orebody by do as is in the block cave mine. Simulation scenario using the system dynamic indicates the cost consequences to be high in area of environmental with trending more increase at spending around the later stage of mine and may after post closure. This early indication leading to investigate the skill factor attribute into thisineffective of designing the block cave mine and only relying tosolution for modifying the mill-plant facilities.

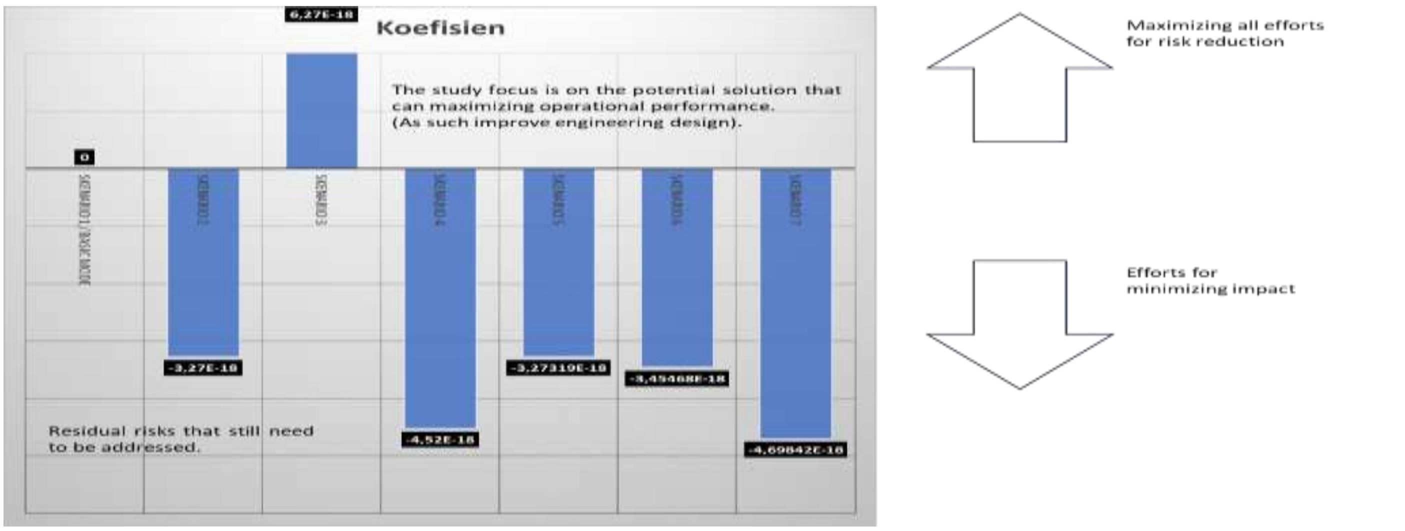

Figure 2: Simulation of operation scenario 3 through the system dynamic methods (Full Capacity 160KTPD with pyrite handling at the mine) viewed from the context of risk management perspective.

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All scenario options develop in considering of focusing improvement in mining area only or in mill plant facility only or it can be both combinations. Scenario 1 will be the basic mode of do nothing at action while rest other scenarios to investigate various option at the needs of actions. All of needs action will be linked into consequences and receiving benefits that must in properly analyst for a solid recommendation solution.

The system dynamics model simulation enable to provide a result of analysis under multiple scenarios and the complexities of benefit-impact. Scenario 3 assumed full production at 160 ktpd with pyrite handling performed primarily at the mine and no modifications to the mill plant. The model tracked cost components related to drainage and dewatering, acid mine water treatment, and incremental energy demand. The simulation horizon was from year X to year Y, with time steps of Z months

In referring to scenario simulation 3, the resolution in minimize the impact since the presence of acid mine drainage shall replacing with the concept of maximizing the engineering design effort from early stage of mining to better of managing the risk.

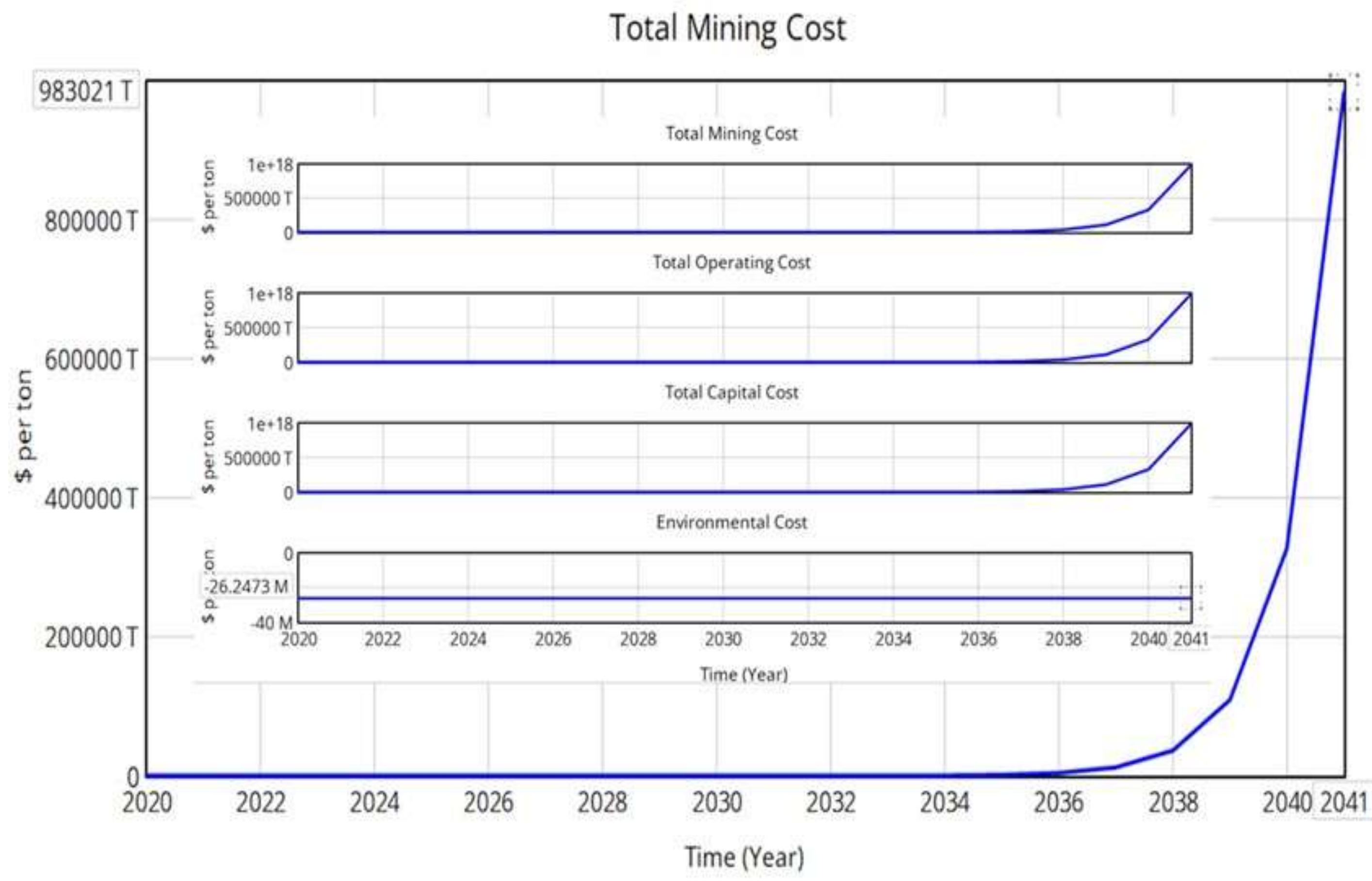

Figure 3: Future cost-spending trends by implementing operation scenario 3. Indicating increase near the end stage of mining operation.

The cost impact directly felt into the needs of facilities and infrastructure for managing the pyrite and those of activities in associated to the handling of acid mine water before being released back into the nature. The construction of additional comminution facilities (new SAG) and separation circuits of Copper Cleaner (CUCL) as example not only provides additional cost for capital investment in the early stages of development and generating increases on operating cost but will also leading into demand for more electrical supplies. This creates further spending impact into another environment risk due to the use of fossil fuels in generating more electricity. As such control emission along it associated cost-taxes in provision of decarbonization, air pollution and so forth. Thus, the task analysis in the area of engineering function for mining design improve engineering inefficiency in first place become more essential. It respectively with regards of the availability and number involvement of the appropriate skill-sets for joining the group task review.

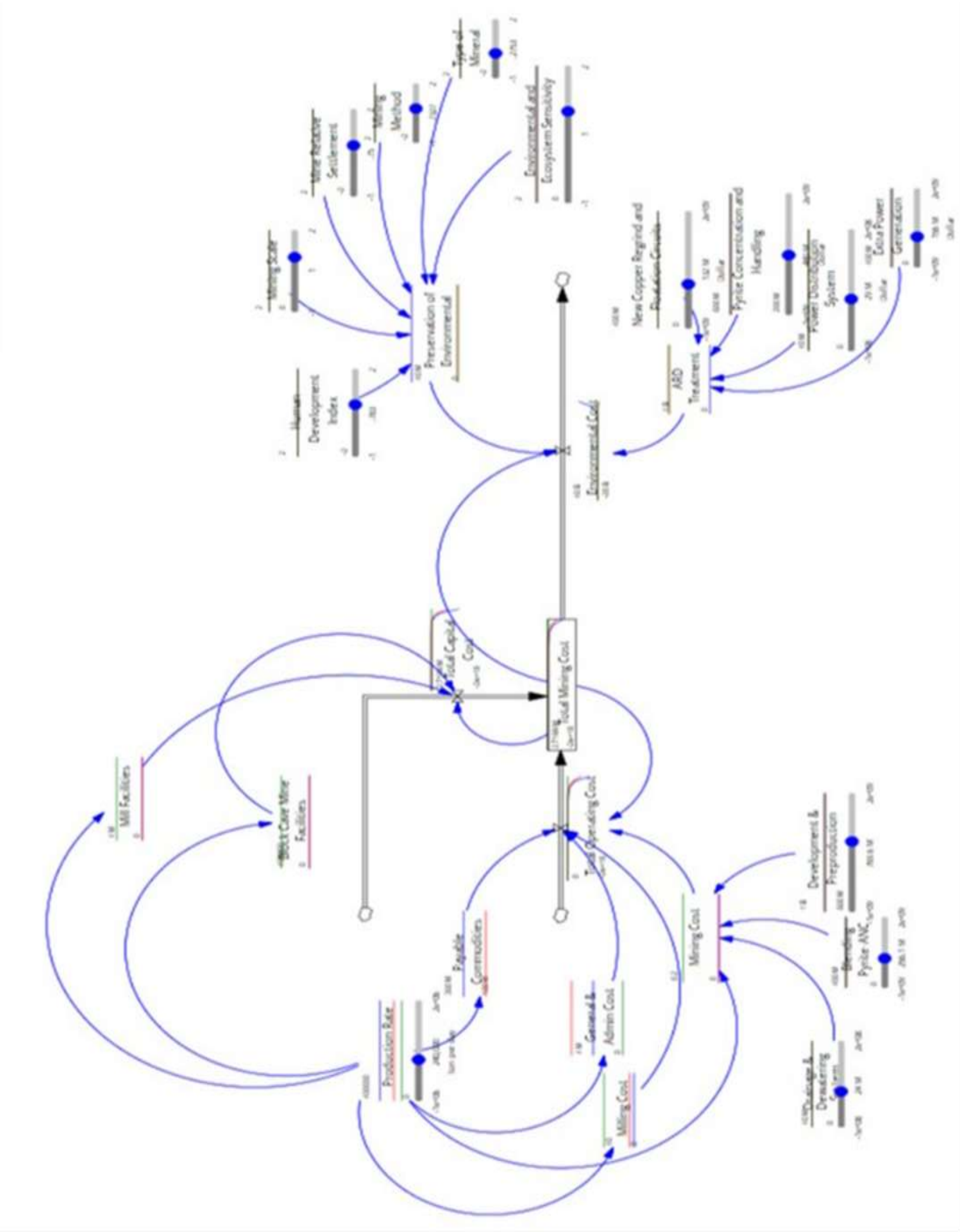

Figure 4: System Dynamic simulation

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

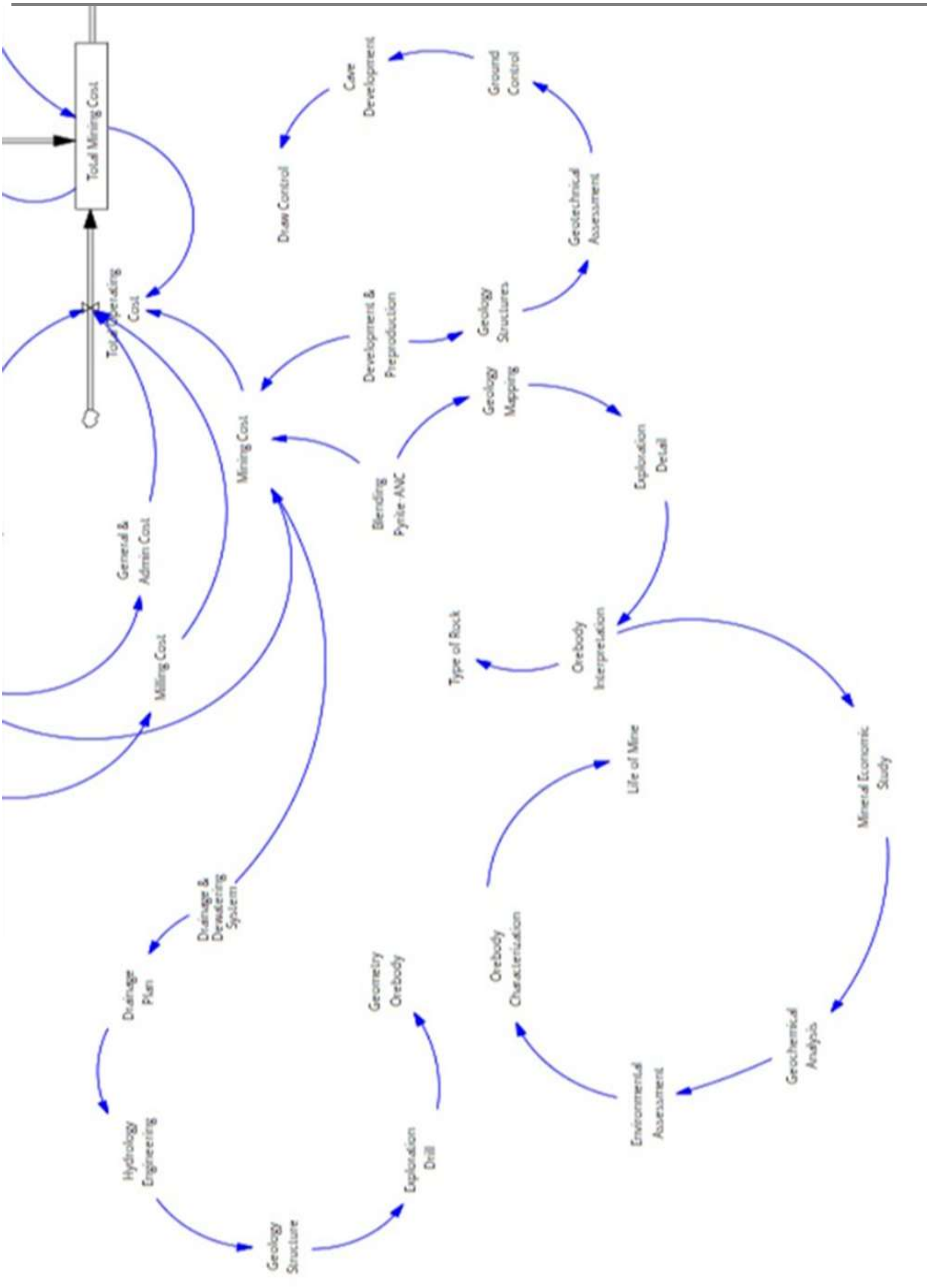

Figure 5: System Dynamic simulation on area focus for improvements

The scenario simulation that has been conducted previously in the context of efficient cost has revealed potential activities that require improvement, including management of drainage systems and mine dewatering, pyriteANC mixing operations, and regulation of development sequences and pre-production stages.The study of these three aspects along with the level of effectiveness of the task implementation that should be carried out (based on applicable national and international standards) compared to the current actual implementation. The knowledge backgroundalong its expertise level and number involvement of the assigned person into join review design can provide insights into the effectiveness of conducted works.An analysis was also carried out on the formal education curriculum in mining engineering to assess the alignment of knowledge development with the needs of the future mining industry needs for a green and smart mining concept. This research study mainly in focusingthe aspects related to environmental impactwhich caused by the presencerock chemical pyrites in the ore body. The analysis was conducted within the data collection through:

1. Technical data at source of feasibility study
2. Interviews with involved personnel
3. Job observations
4. Creating questionnaires
5. Collecting information regarding task descriptions related to the job

Task analysis in the planning of mining operations is conducted with the main focus on 3 areas related to technical design for the risk mitigation of acid mine drainage generated by the presence of pyrite.

D. Mapping of Skill Needs

The results of the simulation evaluation conducted show several critical activities in underground mining operations using the block caving mine method that can affect the effectiveness of acid mine drainage management. This is particularly related to the handling of pyrite in the ore body with the potential risk of creating acid mine drainage. The study of mining engineering and planning activities with the availability of the requirement expect skill sets in providing technical reference for organizational, will be the evaluation area. In look into the standard mining engineering framework, requirement of knowledge for properly managing the aspect of geometallurgy is beyond the single expertise of mine engineer. Maturity level stand point indicating no documentation of procedure specifically in develop for provide guideline designing mine in properly handle the pyrite along generating risk of acid mine drainage. It means, there shall be a join review to happens between different knowledge background ensuring mine design is accommodating this requirement of properly managing the pyrite. The observation, survey, interview and job description review are then conducted to understand composition requirements. The level of involvement can be concluded through the following tabulation matrix:

Mining Engineer	Geologist	Geotech	Hydrologist	Economic Mineral	Metallurgist	Material Science	Environmentalist	Geophysics	OHS	Laws / Social
16	13	8	11	11	14	14	14	12	8	10
12%	10%	6%	8%	8%	11%	11%	11%	9%	6%	8%

The value percentage which obtained through the survey is tracing based on the main activities related to technical assessment in area of development and pre-production of block cave mine, blending scenario of pyriteANC, and managing the excessive water through the drainage and mine dewatering engineering designation.

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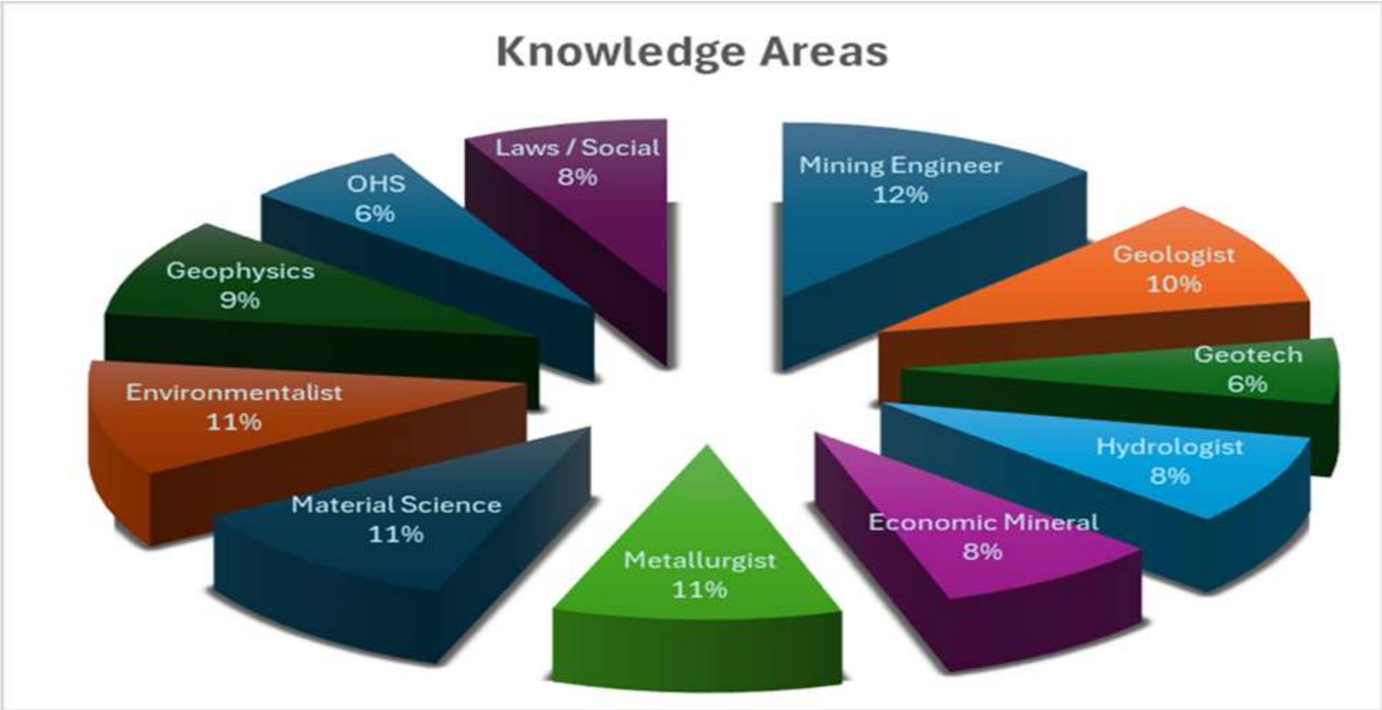


Figure 5: The percentage of involvement needs from different areas of knowledge in the study of the operational engineering tasks of mining with pyrite handling.

The breakdown analysis of the three main activities of mining engineering in handling pyrite materials can be detailed as follows.

Development and Preproduction Activities

The stage of development and pre-production for applying method of block cave minein the Grasberg orebody playing into one of key control preventpotential risk of acid mine water due to the presence of pyrite. It can be done through properly establish sequence ofundercutting and cavingconsidering the block mapping on ore type and pyrite-ANC. This sequence then further recommendsthe planning for development and preproduction activities supporting the production scenario. As part of development and preproduction activity itself, geotechnical aspect will be part of review concerning stability of opening and ground control requirements. All that goes into single needs of geological data to learn the mineral composition, geological structures and rock characterizations. Therefore, the interrelation between these activities conducted will provide effective and optimum recommendationfor stage of mine development and preproduction.

Assesment Areas	Knowledge Areas										
	Mining Engineer	Geologist	Geotech	Hydrologist	Economic Mineral	Metallurgist	Material Science	Environmentalist	Geophysics	OHS	Laws / Social
Geology Structures	1	1	1	1		1			1	1	
Geotechnical Assessment	1	1	1	1			1		1	1	
Ground Control	1		1	1					1	1	
Cave Development	1		1	1	1	1	1	1	1	1	1
Draw Control	1				1	1	1	1			1
Total	5	2	4	4	2	3	3	2	4	4	2
%	14%	6%	11%	11%	6%	9%	9%	6%	11%	11%	6%

Mapping of geological rock structures (Geology Structures)

The analysis of geological rock structures will influence the ground control system deploying for the block cave mines. It led into recommend the application of ground support for tunnel stability openings around the stage of development until production from any potential geotechnical issues. The study of geological rock structures in the Grasberg orebody concerning the handling of pyrite as part of development and preproduction activities is on way of properly sequencing the undercut and caving. The mapping of geological structures conducted through the survey on the percentage of material densities, specifically by investigatethe RQD (Rock Quality Design) value.The RQD values in zone of high composition pyrite varies between 0 to 100%, but is generally found in the category with low values "poor" or < 50%. In mapping tooverall Grasberg orebody shows the composition of volcanic breccia rocks of andesite type (80%), tuff (5%-15%), igneous rocks (5%), and limestone (1%) which generally intersect and mix with tuff and andesite rocks. Rocks at mineral content are grouped as pyrite 1-3%, chalcopyrite 2-5%, bornite 0.3-0.5%, and magnetite 5-7%.The investigation of geological processes in the past describes the formation of breccia rock because of thickening caused by the collapse of carbonate rock walls by acidic magmatic fluids. In addition to the low RQD value, the mineralization processes in the past created geological structures in the form of faults and joints that will also affect stability with the management of separate geotechnical aspects. Learn into this mineralogy process in the Grasberg orebody to indicated there are various geological structures involve concerning geotechnical aspects.The low RQD value provides an understanding of the optimal fragmentation achievement but also presents challenges in terms of maintaining the stability of the openings during the development and production phases. Therefore, planning the sequence of mining with a main focus on maintaining the balance of draw order from the cave is playing an essential roles.

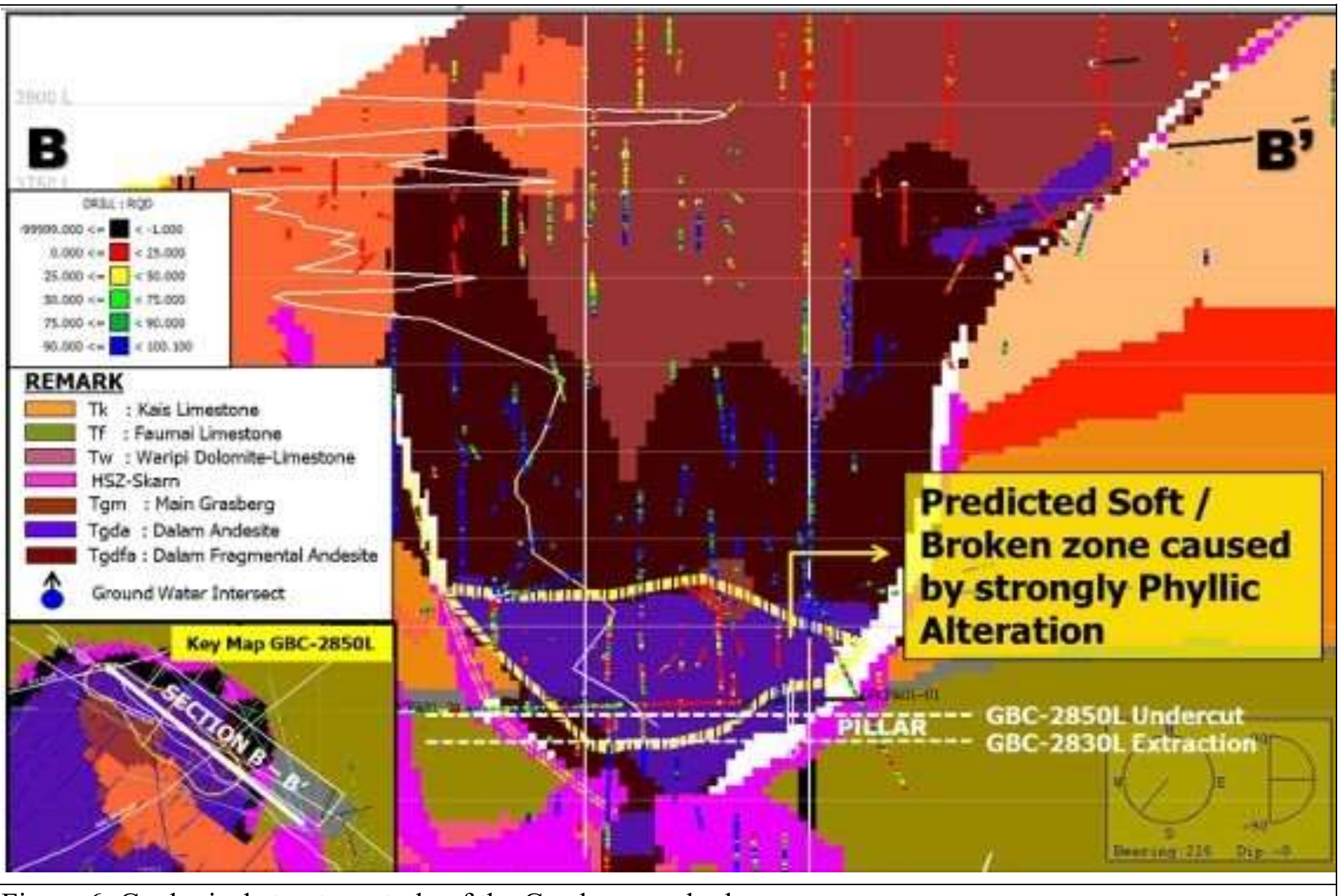


Figure 6: Geological structure study of the Grasberg ore body

Meeting the objectives target in effectively managing the cave, the following engineering task must be performing by the team.

a. The analysis of the geological structure.

Involves knowledge in the form of:

Mining engineer, the conceptual of mining operations using the block cave method, planning the direction of undercutting and the draw order to meet production balance scenarios and geotechnical aspect concern.

1. Geotech, analysis of rock characterization and geological structures, identification of potential weakening point, rock deformation evaluation and ground support designation
2. Hydrological, potential discharge and volume of water due to the presence of geological rock structures along the possibility of the happen mud rush in the draw points
3. Metallurgical, chemical composition of rocks, efforts for size reduction (comminution strategies) for optimization of plant operations.
4. Geophysics, interpreting geological rock structure data and enhancing the potential for fractures or faults through geophysical studies.
5. Occupational Health and Safety (OHS), aspects of health and safety in mining viewed from the risks in data collection.

b. Geotechnical Assessment

Mapping for effective fragmentation and ground control purposes, requires a study of geotechnical aspects on primary concerning the determination of the direction of under cutting based geological conditions and ground support designation. Recommendation for direction and planning for cave sequence to include the timing for installation and availabilities of rock support systems in production level before the commencement of under cutting and drawbell blast. The implemented of ground control method through the verification of rock fragmentation results, crack mapping, geotechnical event records, and monitoring of microseismic activities. Data analysis of rock movement and deformation will serve as the basis in determination the direction of cave development. The geotechnical assessment involves knowledge competencies in the form of:

1. Mining engineer, planning for cave and ground support installation in views of undercutting direction. Ground control to include planning mitigation and perform rehabilitation in damaged areas following the happens of rock deformations and other geotechnical events.
2. Geotech, interpretation of the reading results from geotechnical measurement stations and recommend implement cave monitoring system.
3. Hydrological, interpretation of water volume data in the drain hole and evaluate volume of water flowing into the cave.
4. Geophysics, analysis of rock movement through geophysical studies.
5. Occupational Health and Safety (OHS), aspects of health and safety in mining viewed from the risks in implementation.

c. Ground Control

Mapping for effective fragmentation purposes requires a study of geotechnical aspects, primarily concerning the determination of the direction of cave based on the geological conditions of the rock. The implementation of ground control system is through the review of geological characterization, rock mass evaluation, stress orientation, quality of blasting and actual condition of ground. The study of ground control involves knowledge competencies in the form of:

1. Mining engineer, planning for ground support installation, implement effective blast to reduce overcut and other program prevent the deformation around the opening.
2. Geotech, interpretation of the reading results from geotechnical reading stations
3. Hydrological, interpretation of water volume data in the cave
4. Geophysics, analysis of rock deformation and cracking development through geophysical studies.
5. Occupational Health and Safety (OHS), aspects of health and safety in mining viewed from the risks in implementation.

d. Cave Development

The good of result fragmentation lead into successful managing the undercutting and propagate the cave. The determination of area to be caved is based on completeness ground support recommend by the Geotechas the safe distance in follow to the hydraulic radius calculation. Stress distribution since of the progressing of cave and undercutting lead into designing of excavation methods. Cave development in consider to the presence of rock chemistry will need an evaluation for X,Y and Z axis in balance requirement of economical benefits and environmental issues.The study of the cave development involves knowledge competencies in the form of:

1. Mining engineer, planning for cave development in consider of fragmentation program and orientation of stress distribution who led into design the excavation models. Investigate the option for post undercutting versus advance undercutting.
2. Geotech, stress orientation evaluation and ground control assessment. Review geotechnical concern since of evaluation X,Y,Z axis in cave development.
3. Hydrological, evaluate volume of water since the planning for cave
4. Mineral Economics, mapping extraction areas to maximize economic benefits
5. Metallurgist, the chemical composition of rocks, mineral content levels, and their correlation with processing operations at the factory.
6. Materials Engineering, the economic value of mining commodities along with other impact of presence gangue and waste
7. Environmentalist, the study of geochemical aspects of rocks and the potential negative impacts on the environment.Cave development adjustment since of requirement pyrite management ✈ Geophysics, interpretation of ground movement based on geophysical anomaly studies.
8. Occupational Health and Safety (OHS), aspects of health and safety in mining viewed from the risks associated with the work.
9. Law/Social, licensing, legality, and documentation of other approvals related to mining operations and compliance with government regulatory standards.

Draw control

Proper handling of geotechnical aspects in mining operations through cave production by ensuring that ground stress poses into right direction. Performing mucking from the cave and leave brow is open prevent ground stress build up in the mine and generate the geotechnical events. Performing control referring to the reading results of geotechnical station as such microseismic, convergent stations, and other technologies that can detect the movement and rock deformation become an essential program supporting development and preproduction activities. Draw control activity to include the study and evaluate fragmentation along the happens of discontinuity of mucking process due the frequency rock hang-up. The study of the draw control involves knowledge competencies in the form of:

1. Mining engineer, ensuring planning for draw order is within the objective of balance production and requirement of managing the pyrite. meeting the plan in attain economic benefit value.
2. Mineral economics, adjusting the mapping of the extraction area based on studies of economic benefits and the price of metal commodities as well as benefit impact since of requirement balance composition pyrite-ANC.
3. Metallurgist, studying the chemical composition of rocks, the mineral content grade based on samples taken from the extraction space and its correlation to the optimization of material processing at the plant.
4. Environmentalists, the study of geochemical aspects of rocks and potential negative impacts on the environment based on sample data pick up from the drawpoint or undercut cave.
5. Geophysics, interpretation of rock deformation based on geophysical anomalies and readings from geotechnical stations.
6. Occupational health and safety (OHS), health and safety aspects of mining examined from the risks at work.
7. Law/Social, permits, legality, taxes, penalties, and documentation of other approvals concerning the mining operation period and compliance with government regulatory standards.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

2. Blending Pyrites – ANC

The Grasberg Igneous Complex (GIC) or the Grasberg volcanic rock complex has a vertical dimension of 1,600 m and a width that varies between 200 meters to over 1,000 meters. The mineral content with high copper and gold grades is located in the central part of the ore body. The marginal boundary of the ore body is in a non-formative zone with pyrite rock types and a small composition of magnetite and chalcopyrite. This area is referred to as the Heavy Sulphide Zone (HSZ) with a thickness dimension of 100 m and is included in the reserve block for subsidence planning.

Assesment Areas	Knowledge Areas										
	Mining Engineer	Geologist	Geotech	Hydrologist	Economic Mineral	Metallurgist	Material Science	Environmentalist	Geophysics	OHS	Laws / Social
Geology Mapping	1	1		1	1	1	1	1	1		1
Exploration Detail Result	1	1		1	1	1	1	1	1	1	
Orebody Interpretation	1	1			1	1	1	1			1
Type of Rock	1		1	1		1		1		1	
Total	4	3	1	3	3	4	3	4	2	2	2
%	13%	10%	3%	10%	10%	13%	10%	13%	6%	6%	6%

Geological Mapping

The block body of the Grasberg ore is categorized as easy and can be caved, or in other words, has the potential for positive economic value with the adopted mining method, which is through caving. Sensitivity analysis study shows that the type of block mineral still meets the economic criteria by do the adopted method of block caving at additional implementation of secondary breakage program.Effort to include fragmentation improvement meet thecurve ratio of cave abilityas previously conducted through the interpretation of rock characteristics at the orebody. In research of Grasberg orebody, potential impact into economic value is influenced by the orientation of the cave towards the block mineralsaround the HSZ zone. It mainly concerning the volume of mineral dilution since the failure of old open-pit walls, which most of parts are HSZ. Therefore, detailed exploration and geological dataexplain this condition is crucial inanalysing the grade impact, volume of ANC in plan for blending pyrites and economic value impact since this dilution issues.The concentration of sulphide rock groups, carbonates, and other types ofrocksupporting the scenario of blending operations in purpose reducing impact of pyrite in the orebody needs to map out. Geological mapping involves the competence of knowledge in the following areas:

1. Mining engineer, planning forundercutting and drawpoint production sequence at inclusion of blending scenarios
2. Geologist, geological data with mapping based on rock group types
3. Hydrologist, identify the areas with unavoidable surface water seepage and flowing into areas containing pyrites
4. Mineral economics, block mapping areas based on economic value benefit
5. Metallurgist, rock characteristics and their correlation to plant operation optimization considering the chemical composition of the rocks
6. Material Technology, adjusting material characteristics based on geological mapping of both primary and secondary minerals and other contaminating materials.
7. Environmentalist, study of geochemical aspects of rocks and potential negative environmental impacts based on geological mapping of rocks and mixing scenarios.
8. Geophysics, geophysical anomalies to complement geological mapping.
9. Law/Social, permits, legality, taxes, penalties, and documentation of other approvals regarding
10. mining area extent, production capacity, and mining age.

b. Exploration Detail Results & Ore Body Interpretation

Drilling programin obtaining the more details of exploration results within the Grasberg porphyry orebody began in December 1967. The results of the drilling through laboratory testing confirming ore body contains 30 million tons of material at an average copper content of 2.5%. Geological mapping of the rocks identified that the Grasberg orebody has sustainability for open-pit mining at an elevation of 4200m down to an elevation of 2600m below it. The transition to underground mining through the blockcavemechanism aims to excavate reserves located within the elevations of 3300m – 2600m. The upper part of the ore body has a gold content of 1 gram per ton, which decreases following the changes on orebody dimensions and composition of the rock types.Detailed studies of exploration data and interpretation of ore bodies involve knowledge competencies such as:

1. Mining engineer, planning mining operations according to determination of block mapping at consider of ore grades and composition of material to neutralize acid
2. Geologist, geological data with validation needs to detail information about the type of rock groups and proceeding the block mineral mapping
3. Hydrologist, adjustment of areas with surface water seepage conditions that cannot be avoided based on details exploration data
4. Mineral economics, mapping of economic benefits based on the block mapping and the establish production plan sequence
5. Metallurgist, the characteristics of rocks and their correlation to the optimization of plant operations considering the chemical composition of the rocks
6. Materials Engineering, the adjustment of material characteristics based on geological mapping of the rocks
7. Environmentalist, the study of the geochemical aspects of rocks and the potential negative impacts on the environment based on geological mapping on the rock types
8. Geophysics, geophysical anomalies to complement geological mapping
9. Occupational Health and Safety (OHS), health and safety aspects of mining viewed from the risks associated with the job

c. Type of Rock

The characteristics of mineral ore are categorized based on geological rock classification. This classification will determine the processing methods of each mineral associated with the Main Grasberg Skarn (MGSK), Dalam (DLM), and Heavy Sulphide Zone (HSZ) rock types, taking into account a stratigraphic study of class versions A and B as a classification of low and high recovery values. The ore processing is carried out through grinding facilities (SAG regrind) and cleaner flotation circuits that have been modified according to the geometallurgical conditions of the rocks. Additional facilities are implemented to better manage pyrite rock at the plant and store it in the deposition area.The analysis of rock types involves knowledge competencies in the form of:

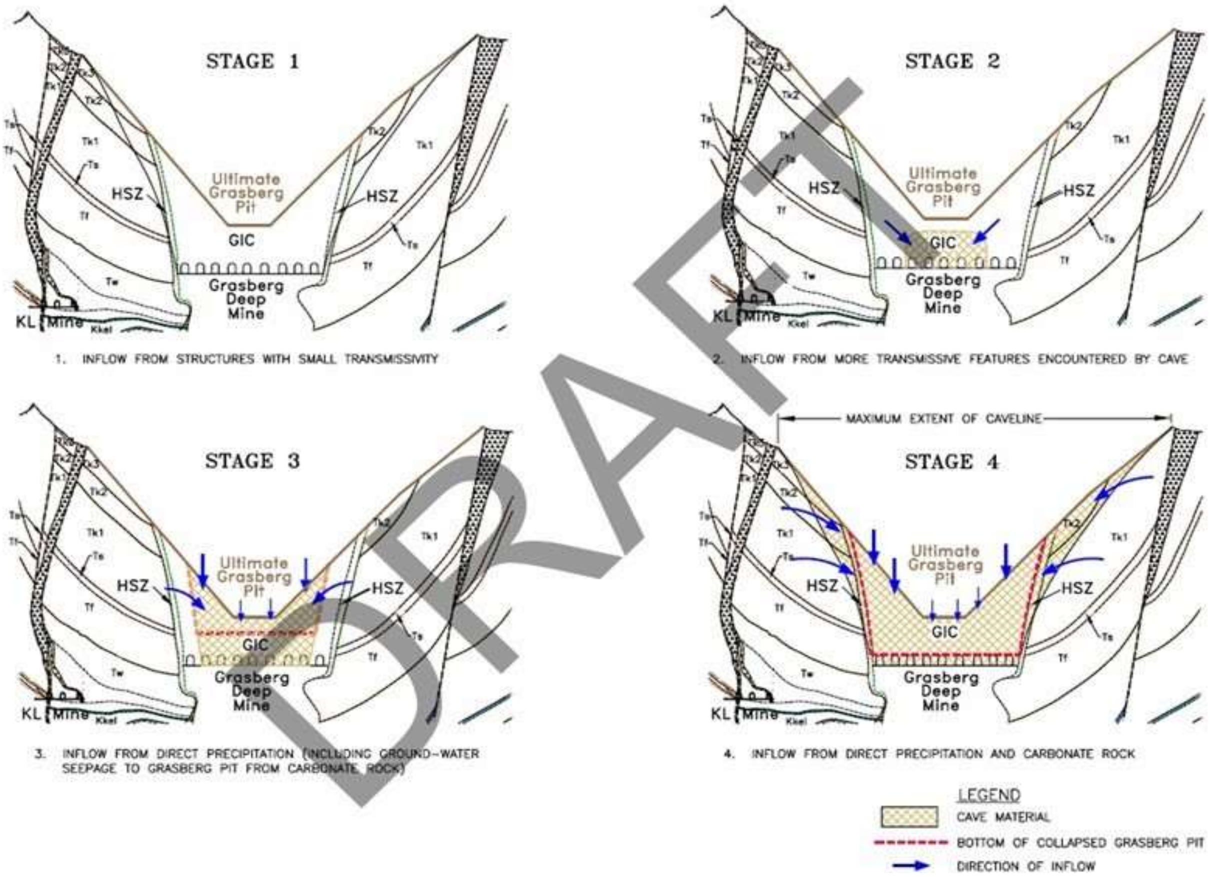
1. Mining engineer, operation planning for blending, facilities and mining infrastructure for effective and efficient fragmentation program achievements.
2. Geotech, analysis of geotechnical aspects, potential ground failures and their effects on the stabilization of openings due to inclusion of blending scenario into plan for draw orders
3. Hydrological, areas with unavoidable surface water seepage conditions
4. Metallurgical, characteristics of rocks and their correlation to optimizing plant operations considering the chemical composition of rocks in the blending operation scenario
5. Environmentalists, the target achievement of increasing the pH value of water with a mixing operation scenario.
6. Occupational health and safety (OHS), aspects of health and safety in mining are reviewed from the risks in the work.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

The activity of managing the blendingscenario between the pyriteand ANC within the research study of Grasberg orebody provides an insight into the need for a collaborative between multiple knowledge background. The output generated from the conducted assessment is a comparison of the percentage of mixture pyrite-ANC that is transported intomill-plant for further process.

3. Drainage & Dewatering System

Through effective management of the drainage system and mine dewatering, it prevents the surface water flowing into the cave as well as to the area containing the pyrite. The program of water diversion and or properly channelling the potential acid water contamination can be done through the hydrologist engineering designation. Research study of Grasberg orebody to indicate the infiltration of surface watercan be properly manages by firstly evaluate the geological structures and directing into dedicate drainage system.



The technical study from the perspective of drainage system and mine dewatering includes:

Drainage Plan

Some sources of water flow in the Grasberg mine orebody are potentially acidic due to the flow passing through geological structures that intersect the mining area and also through the caveat ore containing pyrite. Through geological mapping, it can be illustrated that passive water seepage from the surface is attributed to geological structures intersecting limestone. The present of geological structures as such fault shape of Grasberg contribute into potential access for water infiltration from surface. This analysis concludes the direction of water flow sources that require diversion planning.Another engineering solution option to investigate is with foam injection to fill the void or crack to divert water into dedicate mine dewatering areas.

b. Hydrology Engineering

The potential for water infiltration in mining, including flow from the overburden stockpiling area to the cave, is somewhat difficult to predict, especially due to the presence of old boreholes from the open-pit mining process.

Nevertheless, the significant potential for this water flow can be predicted to flow through geological rock structures. The hydrological aspect can be traced and in studiesby investigate the amount of rainfall and the increasing dischargewater flowing into the mine drainage system. As part of the drainage handling plans, the conducted study on hydrological characterization since thealteration process around the orebody can also assist to confirmpotential and predict future volume of water seepage. This analysis concludes the large volume of water that potentiallyflowing into the mine in certain period, which can serve as a reference for planning the sequence of production and water diversion.

c. Study of the geological structure of rocks

The prediction of rock fractures in the Grasberg ore body and the existence of layering structures between different types of rocks indicates the potential for water seepage into the cave and mining areas. Through hydrological measurements and surveys, it was found that the contribution of passive flow during rainfall can reach 7,400 gpm. The study of the geological structure aspects of the rocks plays an important role in determining the volume of water that will flow into the mining area from the surface.

d. Diamond Drill

Geological structure data of rocks along with the chemical composition of the rocks is obtained through drilling results from exploration activities. This data provides a reference for planning fragmentation, support systems, and the sequence of operations for extracting ore from the cave area while considering the blending activities of acidic materials with the type of rocks that can neutralize acid.

e. Geometry of the ore body

The reserve dimension is to determine area for mining operations include potential future subsidence impact which recognize as cave boundary of cavecrackline. Itis determining the needs ofpermanent ground support and become a reference for placingtheproduction support infrastructures that will remain staying over the mine lifetime. These supporting facilities to include drainage, pumping station and the other infrastructure for water diversion program.A study of the minehydrologist engineering to look intoperson who competent in this fields and mapping the activities in purpose of effectively handling the drainage and mine dewatering system. The activity study related to the engineering of drainage systems and mine dewatering system involves knowledge competencies in the form of:

1. Mining engineers, planning for execution of integration mine drainage system along with all requirement facility and infrastructures.
2. Geologiest, study of geological structure of rocks and information needs on potential impacts on volume of water seepage.
3. Geotech, interpretation of the impact of water presence and its effects on geotechnical and geochemical aspects.
4. Hydrologist, identification of runoff water volume and engineering design for handling the infiltration surface water.
5. Mineral Economics, mapping of cost investment and operating cost and its impact to economic benefits. ✈ Metallurgist, utilization of water in processing and neutralizing acid content facilities
6. Materials Engineering, characteristics of materials as influenced by the presence of water in the chemical composition of rocks
7. Environmentalists, study of the geochemical aspects of rocks and potential negative impacts on the environment
8. Geophysics, interpretation of cavities or gaps in rock structures that may increase the amount of water seepage from the surface based on geophysical anomaly studies and the application of modern equipment/sensors
9. Occupational Health and Safety (OHS), aspects of health and safety in mining viewed from the risks in handling drainage and dewatering work in mines.
10. Law/Social, permitting, legality, taxes, penalties, and other approval documentation related to the mining

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

11. operation period and compliance with government regulatory standards.

Assesment Areas	Knowledge Areas										
	Mining Engineer	Geologist	Geotech	Hydrologist	Economic Mineral	Metallurgist	Material Science	Environmentalist	Geophysics	OHS	Laws / Social
Drainage Plan	1	1	1	1				1	1		1
Hydrology Engineering		1		1			1	1		1	
Geology Structure	1	1	1	1		1	1		1		
Exploration Drill	1	1		1	1	1	1	1	1		1
Geometry Orebody	1	1			1	1	1	1	1		1
Total	4	5	2	4	2	3	4	4	4	1	3
%	11%	14%	6%	11%	6%	8%	11%	11%	11%	3%	8%

4. Orebody Interpretation

In addition to the study on the three important aspects above, the interpretation of the orebody is part of the planning activities for the blending operation of pyrite-ANC material. This is particularly concerning the impact into overall economic benefits of mining operations itself. The team collaboration between various disciplines of knowledge background as such mineral economics, metallurgist, environmentalist, and other study fields as presence in below matrix table is essence for orebody interpretation. The interpretation study of ore bodies involves knowledge competencies in the form of:

1. Mining engineer, perform an assessment, planning of effective, efficient, and environmentally friendly mining operations through evaluate the operational scenarios at inclusion of blending scenario between the sulphide and carbonate type of rock groups to neutralize acid.
2. Geological, geological data that requires validation to detail information regarding the types of rock groups.
3. Hydrological, adjustments of areas with unavoidable surface water seepage conditions based on detailed exploration drilling data.
4. Mineral economy, mapping of economic benefits with reference to detailed geological mapping data
5. Metallurgist, characteristics of rocks and their correlation to the optimization of plant operations considering the chemical composition of the rocks
6. Materials Engineering, adjusting material characteristics based on geological mapping of rocks
7. Environmentalist, study of geochemical aspects of rocks and potential negative impacts on the environment based on geological mapping of rocks
8. Geophysics, geophysical anomalies to complement geological mapping
9. Occupational health and safety (OHS), aspects of health and safety in mining from the perspective of risk activities

Assesment Areas	Knowledge Areas										
	Mining Engineer	Geologist	Geotech	Hydrologist	Economic Mineral	Metallurgist	Material Science	Environmentalist	Geophysics	OHS	Laws / Social
Mineral Economic Study	1	1			1	1	1	1	1		1
Geochemical Analysis		1			1	1	1	1		1	
Environmental Assessment	1				1	1	1	1			1
Orebody Characterization	1	1	1		1	1	1	1	1		1
Total	3	3	1	0	4	4	4	4	2	1	3
%	10%	10%	3%	0%	14%	14%	14%	14%	7%	3%	10%

RESULT AND DISCUSSION

The geological complex of the Grasberg ore body is described as a type of andesite rock in fine grain size, with the deep suspected fragmentation are in coarse grains due to the intrusions of diorite igneous rocks. The inner perimeter of orebody is a heavy sulphide zone (Heavy Sulphide Zone - HSZ) with a composition greater than 50% pyrite. The outer ring of perimeter of HSZ zone consists of folded sedimentary rocks from the limestone rock group (New Guinea limestone group). The composition of the country rock at igneous and sedimentary types provides varying levels of rock hardness and geological structures. This creates a complex study to produce a safe, productive, and effective mining operation plan while in same time requirement also extending into managing pyrite along its potential risk to generate the acid mine drainage. Geological structure presents the challenges for managing the cave sequence to meet economics criteria while minimize the environmental impact since the presence of pyrite. As of the risk nature of underground block cave mine in managing the geotechnical aspect by balance the rock pressure, additional requirement for blending the ores become another technical challenge needs to be investigated. The study provides a review in numerous geotechnical events that occur in block cave mine comparing to forecast and actual volume of pyrites transported into the mill. Tracking of geotechnical events to present the successful of managing the cave and applying the ground control system. Record events provide a recommendation in adjust the plan sequence while prevent further failure or damages in the mine. Volume comparison for pyrite between the actual and forecast to indicate the accuracy of planning and the level of successful on collaborations. As such the effectiveness of block mapping and its recommendation for the draw orders.

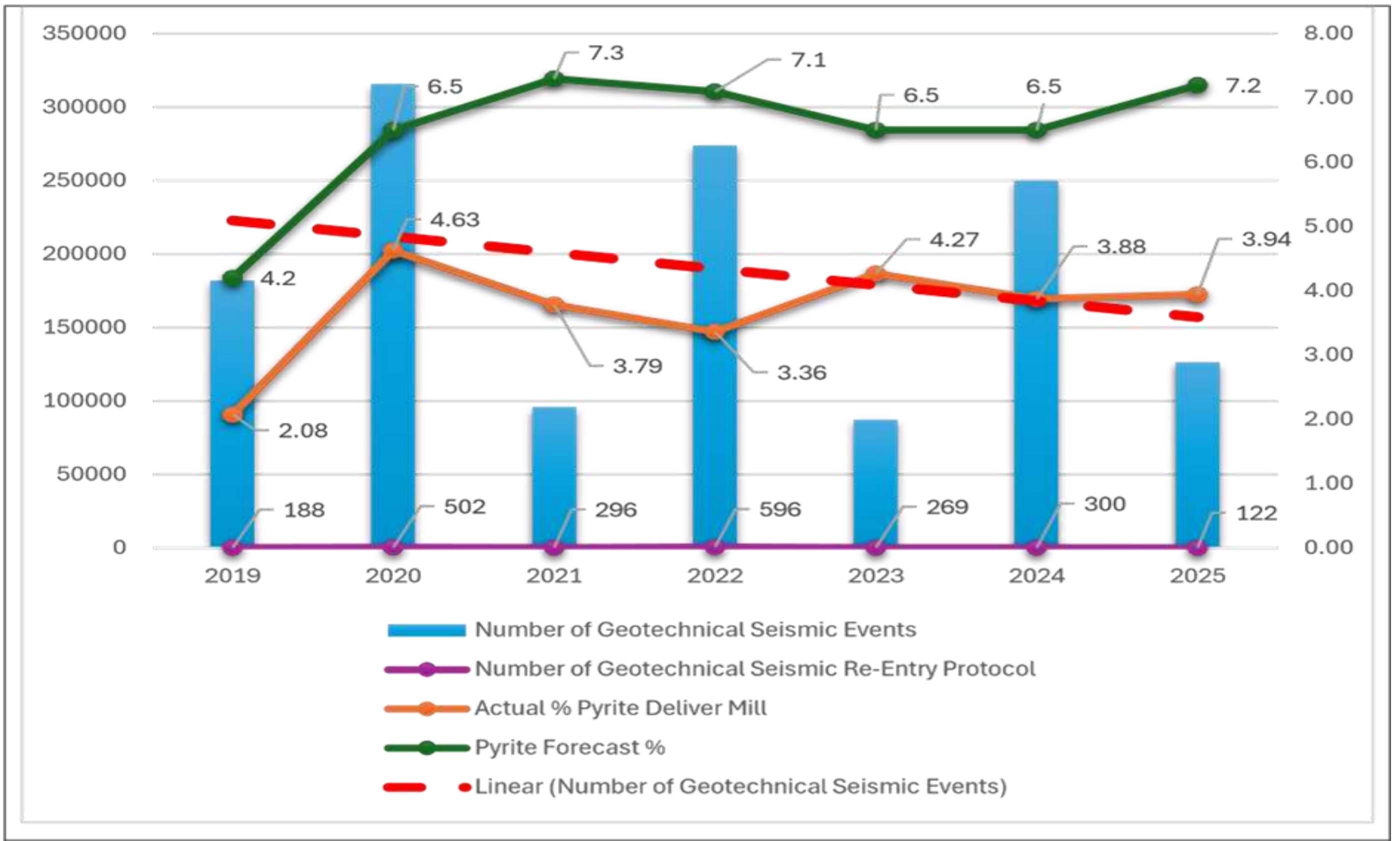


Figure 7: The trend in the composition of pyrite in the ores is lower than previously predicted, which confirms the level of effectiveness geometallurgical study. The trend of geotechnical cases shows a decline, indicating opportunities for improvement and flexibility in the scenario of draw order from the cave in consider of blending operations.

Graph depicting actual volume of pyrite deliver into mill-plant is lower than it was previously predicted. While the indication refers into the level of effectiveness join collaboration with the result of an accuracy of block mapping, it may suggest into potential impact for future strategy of managing the pyrites. The early period of mining presence the low volume of pyrite which gives another indication further increase on pyrite volume along

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

its potential risk of generation acid mine drainage happens in the later period of mine or even in post closure of mine. That means accumulation of consequences impact could happens in era of production declining which another risk into mining economic and financials. The trend of decreasing geotechnical cases indicates there is presence of improvement through the maintain balance in sequencing cave. There should no issues in perspective of geotechnical aspect while gives an early suggestion at room for improvements or re-investigate scenario of pushing ahead the blending program. Learn into the study on level involvement of the certain expertise in this collaboration review confirming it as the lack factor. The low percentage involvement of geologists, geophysicists, and process design experts in the early stages of mining engineering presenting a large of deviation between the initial volume predictions and the actual recorded data.

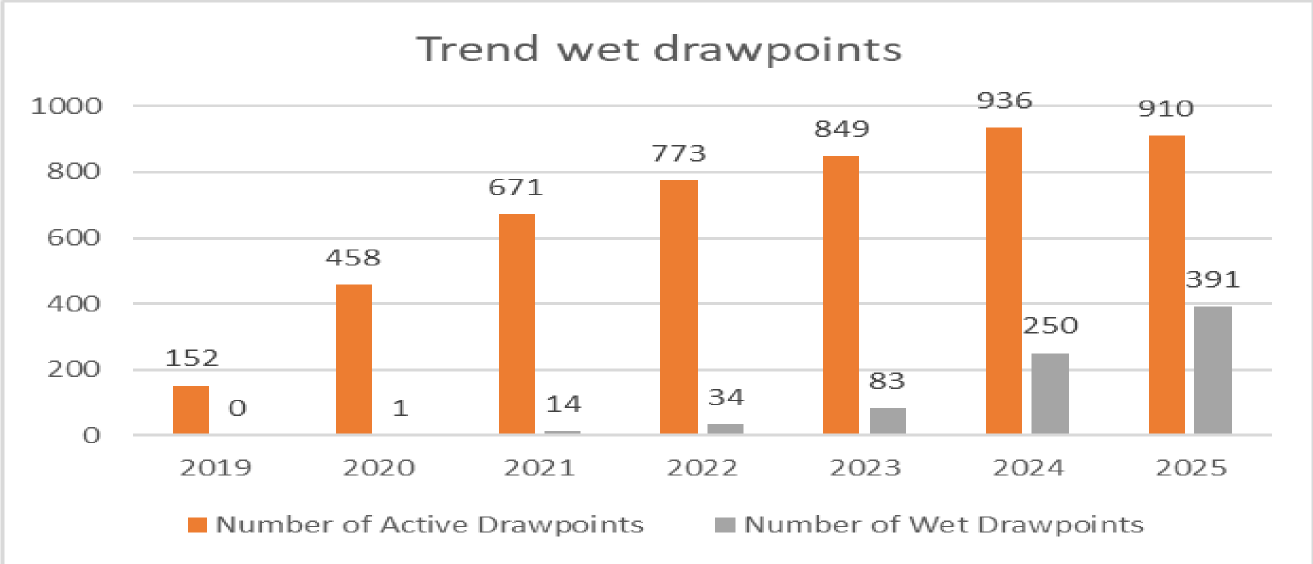


Figure 8: Trend of increasing number of wet drawpoints/extraction locations with wet conditions

The second chard depicting increases on the ratio of percentage of wet drawpoints which indicates the level effectiveness of hydrological engineering and successful design of drainage systems. Low percentage of involvement geologist, hydrologist, environmentalist and geophysics on early design study gives an indication as the leading factor into this presence of high increase on wet drawpoint.

The above chart confirms with the conclusions on level of effectiveness the join assessment at low percentage on involvement the key expert. In contrary the excessive involvement on some expert directing the improvements toward their strong fields without balance the idea into other aspects. As such on the excessive of involvement metallurgist and mineral economics lead into recommend improvements to only happens in area of processing facilities. At the combine of knowledge mapping into an international standard competency in field of Geometallurgy which commonly recognize an effective scientific group in designing the mine, it may suggest something differently.

The main functions and tasks of the geometallurgy program include:

1. General data reporting
2. Representative sampling
3. Geological characterization
4. Metallurgical characterization and environmental impact
5. Data consolidation and data quality assurance
6. Development of operational models⍰ Evaluation of operational models
7. Project optimization ✈ Reconciliation

To tabulate the tasks and level of involvement expert in the key fields of geology, mineralogy, metallurgy processes, and mining planning, preset of composition can be describe as follows:

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

KNOWLEDGE AREAS	Geometallurgy Aspect					
	Geology	Mineralogy	Metallurgical Process Development	Mine Planning	Total In Geometallurgy Program Involvement	% Scoring To Geometallurgy Assessment
Mining Engineer					49	17%
Geologist					40	14%
Geotech					18	7%
Hydrologist					17	6%
Economic Mineral					25	9%
Metallurgist					32	11%
Material Science					32	11%
Environmentalist					21	8%
Geophysics					18	7%
OHS					12	4%
Laws / Social					15	5%

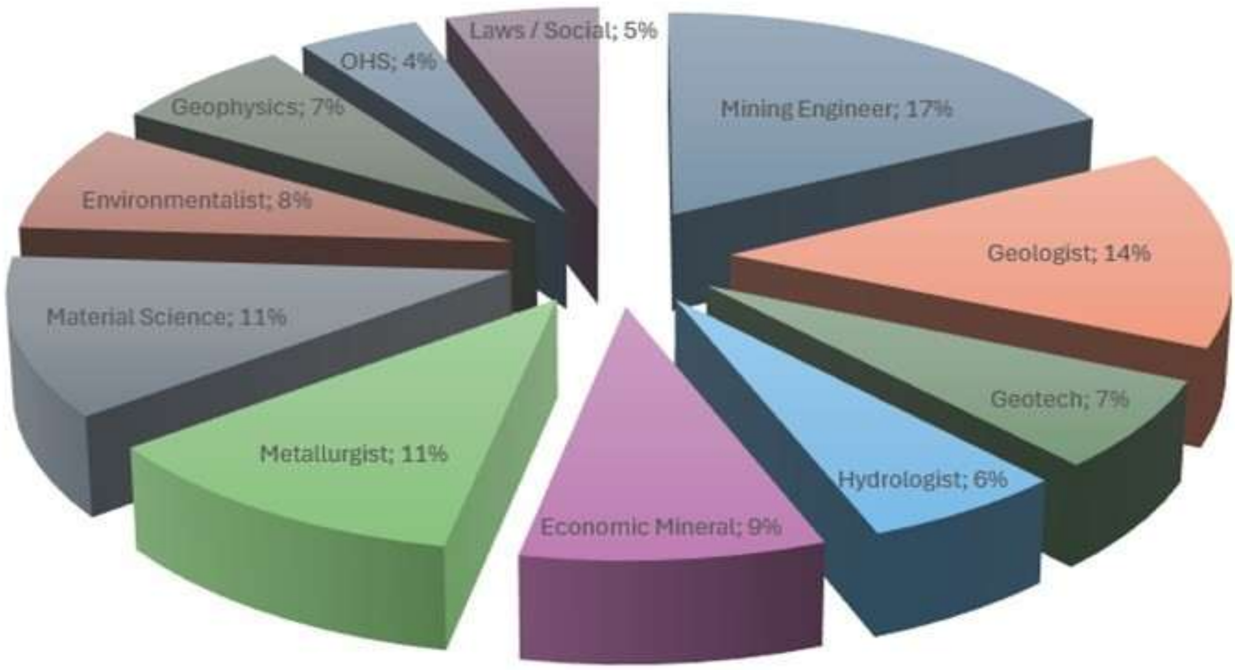


Figure 9: Percentage of involvement of different scientific disciplines in the study of Geometallurgy aspects.

The percentage composition of this involvement is expected to be in ideal portion so that can produce input for mining operation engineering in consider all aspects. The knowledge areas along with expect effective components to be delivers with the percentage of involvement can be describe in the following matrix table.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

Knowledge Areas	EFFECTIVE COMPONENTS (TO BE DELIVER)	Mining Operation Engineering-Design Requirement (% Involvement)	Geometalurgy Assessment Requirement (% Involvement)
Mining Engineer	Basic knowledge about safety, effective, efficient mining operations which provide multieffect benefits from the conducted of mining operations. Understanding well on the concept of underground block caving mining operations and being able to organize the sequence of development, undercut pattern in a balanced manner to achieve stability of openings during the production operation period. The suitability of mining operations to achieve maximum benefit targets without neglecting health, safety, and the degradation of environmental quality.	12%	17%
Geologist	Basic knowledge of geology by providing mapping data effectively and serving as a reference for planning for mining operation. Providing data on the shapes of geological rock structures that can influence the hydrological and geotechnical aspects in learn into rock characterization along with the composition of chemical elements in the rocks as considerations in environmental and metallurgical studies.	10%	14%
Geotech	Basic geotechnical knowledge of mining with the ability to study the characteristics of rocks, the orientation direction of pressure distribution due to loading, and ensure its alignment with the determination of the direction of convergence. The impact of water seepage on the occurrence of wet slurry conditions in underground mines. Providing recommendations for effective support systems.	6%	7%
Hydrologist	Basic hydrological knowledge with the ability to predict the amount of seepage or water intrusion entering the mining area based on the study of rainfall data, the geological structure of the rocks that provides the potential for water entry routes into the mine. Providing recommendations for excess water drainage routes through both the mining drainage system and other potential measures that can be taken as a step to divert surface water from entering the mining area.	8%	6%
Economic Mineral	Basic knowledge of economics and its relationship with mineral extraction. The broad economic benefits of the commodity exploitation plan to be mined. Future prospects of commodities and other associated minerals contained in the ore body, investment opportunities and risks, government permitting, and any clarifications needed regarding investment decisions.	8%	9%

Metallurgist	Basic knowledge of metallurgy with the ability to interpret the mineral composition present in the ore body along with recommending effective and efficient processing methods to achieve maximum benefits from mining. Metallurgical studies also consider other accompanying minerals found in the ore body that may have either a positive or negative financial impact on mining operations.	11%	11%
Material Science	Basic knowledge about the characteristics of mining minerals along with the chemical elements contained in rock groups and providing suitable processing recommendations to enhance the value of the benefits of extraction activities carried out. Assessment of the characteristics of minerals contained in ore bodies includes other ancillary minerals along with the contents of impurities.	11%	11%
Environmentalist	Basic knowledge about the environment and the negative impact of the composition of chemical elements in rocks on ore bodies. Providing recommendations for the handling of rocks containing acid, heavy metals and describing the negative impacts of the failure to act.	11%	8%
Geophysics	Basic knowledge of geophysics and providing reference input on natural anomalies that occur as part of mining operations being conducted. Changes in the physical properties of water and rocks due to the extraction activities carried out. An increase in water discharge due to the influence of geological structure conditions of the rocks as well as the use of other equipment/technologies deemed necessary to better identify the negative impacts of mining operations and their mitigation actions.	9%	7%
OHS	Providing studies and recommendations for the planning of mining activities in terms of health and safety aspects of mining operations.	6%	4%
Laws / Social	A study on the needs for permits and compliance with government regulations and other relevant authorities. Identification of the potential impacts of regulatory changes due to leadership succession in government officials. The impact of social disruption on community members caused by mining activities and chemical components in rocks with their potential negative consequences.	8%	5%

The comparison between the needs and available resources provides an understanding on what level of efforts in handling the pyriteand what solutions can be offering overcoming potential risk of generate acid mine drainage.The join collaboration from different background knowledge with the balance composition will ensuring effectiveness of design is achieved by taking into consideration all aspects.

	Mining Engineer	**Geologist**	**Geotech**	**Hydrologist**	**Economic Mineral**	**Metallurgist**	**Material Sci/Process Eng**	**Environmetn**	**Geophysics**	**OHS**	**Laws / Social**
Mining Operation Engineering Design Requirement	12%	10%	6%	8%	8%	11%	11%	11%	9%	6%	8%

Geometalurgy Assessment Requirement	17%	14%	7%	6%	9%	11%	11%	8%	7%	4%	5%
Actual Engagement	10%	3%	10%	5%	17%	28%	5%	2%	2%	5%	12%

In evaluate above comparison at the two standard of mining operation engineering and Geometallurgy and the actual engagement, it fairly presence ineffective of engineering design for the mine due to low involvement on few key knowledge background. This then recommend for an ideal composition of skill expertise and background knowledge be involve in join collaboration review targeting successful managing the pyrite for the underground block cave mine operation. This successful is align into meet the objective program in attain future of green and smart mining.

CONCLUSION

Government of Indonesia's mining regulations through it champing policies of implementGood Mining Practices (GMP) requires an alignment into the requirement programimproving person'sskill-knowledge. It respectively in area of engineering and design meet the future objective targetof green and smart mining. The level of maturity in the organization is influence by individual performance who work best in their expertise area for work collaboratively as a team in deliver the mine design outcomes.Geological characterization at presence of pyrite in orebody create a concern on potential risk of acid generation when having no strategy in place to manage them. The risk into environmental impact can be managed from the early stage of engineering design by incorporated all aspect intoplan scenario of block cave mine. Enable achieve this, there will be a need of expertise from multiple knowledge background to work collaboratively as a teamfor a join solution. Research study of Grasberg orebody see some deviations from the result of join review design compared to actual record happens in several year of early mine production.The unavailability of standard and regulations within thedomestic and international determining the skill levels for an effective mine design makes the objective target achievinggreen mining somewhat difficult to attain. The perform of best practices by each mining operator are limited to serve for public use. Learn from this research study of Grasberg orebody assessment hopefully can form as the basis to identify the need of some specific knowledge enable each of mining operators attain the future targetof green and smart mining. In addition to invest the people, establish the robust framework of mine engineering design at basis of risk prevention and having an agreed execution roadmap will be the right path infull implementation of Indonesian's GMP at all areas.

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REFERENCES

1. Nichola McKay et all (2016) melalui riset dan penulisan berjudul strategic and tactical geometallurgy – a systematic process to add and sustain resource value
2. Max Frenzel et.all (December 2023) melalui riset dan penulisan dengan judul Geometallurgy: Present and Future
3. Peta Chirgwin (December 2021) skill development and training of future workers in mining automation control rooms
4. Gregory Trencher et. all (2018) Evaluating core competencies development in sustainability and environmental master's programs: An empirical analysis
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