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Block Cave Mine Geometallurgy And Environmental Cost In Green Mining Strategy: A Case Study Of Analysis Using A System Dynamic Approach

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Abstract: *An orebody containing large volume of pyrites can generate acid mine drainage (ARD) upon rock-mineral is exposures due to the excavation. It goes through an oxidation process and without an in-place system enables pyrites is in properly handled could then create risk of environmental ecologist quality degradation. Many mines in today operation implement the recovery in area of mill-processing by including treatment process for ores containing pyrites along its generated acid at the mil facilities prior to release the tailing or wastewater. Activities extended into establishing the sedimentation pond for the tailing deposition area enable mine operator to properly control and measure the PH of waters along any other environmental risk-hazard. All of those happens in consideration of the solution after the fact which could contain more risk for mining operations following its less time given for mine to react and or potentially having more impact due to later spending extra cost on penalties upon fail managing the ARD. Risk possibly extends to the major discontinue of mine operation whenever reading result indicates beyond the accept level of tolerance. An effective of mining operation engineering in today's industry not only consider the way of mine can be producing the large amount of tonnage in the good grade of metal but also in the zero harm of environmental were called green mineral exploitation. Green mineral exploitation on earth can be achieved through the performing of proper-robust engineering design at all stage activities. This robust engineering design will reduce until eliminate the negative impact since the presentation of pyrites in the orebody to surrounding mine environment while reduces consequences on area of commercials-cost. The underground mine method facing the challenge on its way of achieving ore extraction in effective and in efficient manners. The method is something that cannot be avoided when the location of orebody dictates the operator to do so which simply shows challenge is somewhat present the things to deal with it. This paper addresses the challenge of managing the containing of pyrites in underground mine orebody to prevent more impact on the environmental along the consequence impact on continuity of mining operation. It's done through the structured risk assessments on each stage of mining activities, from the beginning of exploration, development-construction, production operations, processing in mill and refining facilities up until the last stage of mine closure. Multiple scenarios are developed using of the principles of system dynamics (SD) in oversee the possible negative impacts caused by mineral-chemical composition in the orebody along with the potential amount of environmental impact cost. Study research covers the analysis of gaps on current as-is process of mining engineering designation versus the ideal or to be process using the case of Grasberg district orebody complex. The current as-is process describes to extract the ores follows the production design capacities and mainly deferring mill-processing facility handling the pyrites. The to be considered of incorporate the planning of handling the pyrites as part of the underground blockcave mining operation scenario and reduce the load in area of mill-processing facility.*
Keywords: *Green Mining, Environmental Risk, Acid Mine Drainage, Geometalurgy, Block Cave Mine Engineering.*

1. INTRODUCTION

The mining industry has a large impact on the country's economy and cannot be avoided in today's human lives due to the needs of metal. On the other hand, environmental impact since mining activities remains negative views for the public and civilization. There will be a need to continue campaigning the green mining by continuing exercise engineering design process to meet environmentally friendly concepts. Research and studies in purpose of balancing people's needs on metal commodities and limiting down the disruption for surrounding environment must happen at all stages of mining processes. Mining practices in the past took into consideration profitability only at least of environmental management aspect following some negative beliefs where it could increase spending and reduce profits. Therefore, it is necessary to conduct a study on the effectiveness of mining process at the inclusion of environmental management aspect. Extended components are critical for sustainable development review to include economic, social and environmental factors. They are playing an important role for decision-making process from early stages of feasibility studies, planning and mining operations scenario developments. To be success in sustainable development, several methods could be used in examining the factors that can influence the results. Under the basic principle of mining operations achieving maximum benefit while optimizing the resource usage, the impact on area of environmental must also be part of key in examination process. It is especially under study requirement of mining facilities and infrastructure supporting the green mining concept during the process investigating of orebody along its geometallurgical aspect consideration. Something that does not happen much in the past of mining practices when investigating current understanding where environmental issues tend to increase costs and decrease profit margins. For the underground mining methods where high on its capital and operating spending compared to the surface mining, challenge for optimizing cost become the essential concern. To balance these needs, an economic study of green mining implementation strategies and their impact on production operating costs becomes very important. Research must conduct considering environmentally friendly mining strategies for the purpose of achieving sustainable development by firstly evaluating any impact on the environment. As such there should be any effect on the standard quality of ecological life along with their cost consequences that potentially arise since decisions do or do not do the strategy mitigation. The expected results in this research area provide an early understanding to all mining stakeholders in both sides of outcomes and requirement effort for strategically attaining the green mining target from the initial stage of mining development. Targeting minimum impacts into mining operations from geometallurgical stand point, several questions can form into the basis for investigation and modeling the assessment. They are; what are the advantages in incorporating EC (Environmental Cost) into the case study of environmental issues?, can the implementation of EC technically and economically achieve the main target of sustainable development?, what are the decision influence in targeting green mining strategies supporting sustainable development program?, can these questions be answered by considering the main ideas of EC in reducing overall operational costs. Exercising all these questions through every single cycle of mining process could lead to the need of extra effort due to its complexity of assessments. However, this complexity of assessment can be simplified through the using system dynamic (SD) methods to analyze the impact costs in whole process-activities. The best result and answer on above questions can be concluded throughout a study involving criteria for decisions that happen in multidimensional (Multi-Criteria Decision-Making/MCDM). The research study is conducted by using a system dynamic method through modeling and formulating the question involve of the cause-and-effect relationships and analyzing the importance of EC aspects in mining operations attaining green mining concept.

The system dynamic (SD) method has several advantages including the ability to analyze complex systems, integrate visions into all existing issues, evaluate the impact between criteria that affect one to another and the entire system process, presenting a complex problem with a simple but accurate analysis and make a rapid assessment of the impact of each component of the problem on the entire system process. This research evaluates the effectiveness of a green mining implementation strategy by using a world-class underground mining case reference for modelling the cost structure and cause-and-effect relationships in the established system process concept. Study simulations using system dynamics (SD) modeling will summarize all scenarios that will be viewed as the most attractive solutions at main consideration of impact into overall cost since the presence of EC factors. Effective study attaining green mining or environmentally friendly mining program provides an opportunity for the underground mine managers to adopt the most appropriate scenarios. The SD method involves mathematical formulations which also can solve various issues related to the economic and financial consideration aspects. The analysis in this area of economic and financial considerations due to the EC aspect creates a prolong study following its complexity of exercise. In using this EC method, economic and financial value assessment can be found to be more accurate and realistically achievable. The structure of this study was carried out by investigating all literature that had been previously conducted in the field of environmental cost estimation in underground mining and the application of the SD method in the mining industry. Grasberg orebody along its complexity geometalurgy and adopted method of underground block cave mining will be the exact case research area in assessing the effectiveness solution attain green mining strategy. The written paper is defining the concept and method and conducting a case study review from results of mine scenario simulation which conducted by using the SD method. The final part of the conducted study is to conclude with the results and provide recommendations.

2. LITERATURE REVIEW

This section discusses several other studies that have been previously conducted regarding EC using a variety of methods to disclose total mining costs at inclusion environmental management aspects. In second to the literature study is to apply the system dynamic methods for a decision-making process for the engineering design activities and management of strategic decisions.

Financial study on mining operations will differ from one place to the other and can vary depending on the characterization of the orebody. In the past model, most of the study is performed at efforts of operating costs reduction and then seek into separately allocate the costs in provision of environmental impact remediation. It has changed in recent decades by starting to include environmental risk assessment as part of study the mining operation. This section will highlight some of the research that has been conducted in this area of environmental cost impact. Respectively due to the influence of rock chemical in the orebody and its potential impact on the environment. Izabella Joneh, The Silesian University of Technology. 2017. Through conducted study research and technical paper writing entitled Environmental Cost of Mining Production in The Perspective of the Mine Lifecycle to highlight environmental cost for mining production on each phase cycle. Its beliefs the identification of environmental cost for surface mine operations under strategic program of sustainable development consider the following two of main things:

- Comparison of environmental cost present in theory compared to what practices that have generally occurred in the field
- Exploring the key factors in determining environmental cost on each cycle of mining operation activities

The study of the two above main points is found important as reference in conducting the risk analysis at recommendation results become the control actions on each cycle of mining. Ravi K Jain, Zengdi Cui, Jeremy K Domen. 2016, perform a research study and journal writing in subject of Environmental Impact on Mining and Mineral Processing: Management, Monitoring and Auditing Strategies stressed the essence of putting a strategy of monitoring and properly conduct audit in measure the effectiveness of mitigation control. Tuija Mononen, University of Eastern Finland. May 2022, through its results of study research entitled Social and Environmental Impact on Mining Activities indicates some improvements in area of regulations to minimize the environmental impact. Research study is evaluating the effectiveness of laws and regulations in the mining operations to reduce negative impacts from side of environmental for future of mining operations. Naser Badakhshan, Kourosh Shahriar, Sajjad Afraei and Ezzeddin Bakhtavar through their research study and technical written entitled Determining the environmental costs of mining project: A comprehensive quantitative assessment to highlight the EC in the mining activities. Research focuses on the impacts to the profitability of mining projects with therefore pointing essential of understanding the way in calculating the cost. This research study also compares the impact of EC costs on the two different mining methods, surface open pit mine and underground block caving. The research study also formulates empirical mathematical calculating EC in both mining method of open pit and underground block caving options. F.Testaye Firdu, P. Tarkines – Espoo 2010, through his research on subject of Sulfide Mineralogy – Literature Review to highlights the optimization process and refining sulfide minerals through the study of thermodynamic data (heat energy changes) which predict happens under the constant reactions. It is further found that properly managing the mineral processing is beneficial for the orebodies that have a complex chemical composition. It is even for an orebody with a low level of purity and low-grade material. Madison Lianna Goldberg, April 2021, Harvard College through its research at the theme consideration of effective control acid mine drainage can be done through the way of increasing sulfate formation. This suggests an effective way of handling the acid by reducing the influence or exposure of oxidation material such as pyrite content through blending with the carbonate materials. It was documented through a technical writing entitled Pyrite Oxidation in Acid Mine Drainage Systems. Alireza Javadi, Lulea Technical University. 2013 discussed the composition of mixing several types of rock under different formation groups (Pyrite-Chalcopyrite, Pyrite-Galena, Pyrite Sphalerite) which can affect the acidity level. The pH value of water is influenced by the composition of hydrogen peroxide formation who create a high pH. It then underlies study of effective engineering design for or processing facilities. Research study was then documented on technical paper entitled Sulphide Mineral Flotation – A New Insight into Oxidation Mechanism. Simon C Dominy and Louisa O Connor, 2018 on their written paper entittled Geometallurgy, A route to more resilient Mine operation, highlights the importance of geometallurgical studies to the success of evaluating mining projects. Through the 3D modeling, it finds possible in optimizing NPV value and effectively managing the exploitation of orebodies, reducing technical and operational risks. The effectiveness and efficiency of the mine can be measured by evaluating the optimum cost that can be attained through the setup process. As such geometallurgy consideration supporting the concept of sustainability mining can be incorporated into whole stages of operations in combining the review aspect of technical, environmental and social impacts. Giovanni Grieco, Agim Sinojmeri, August 27, 2021, on his written paper entitled Environmental impacts of copper ore overburden disposal in Fushe Arrez: Benefits of pyrite separation during the flotation process arguing the essence of include gangue segregation program into ore dressing process. It is stressing the segregation of Pyrite in mineral mines and mill processing activities playing a critical role in achieve the green mining concept to prevent any release of hazardous waste. In addition to environmental risk, this segregation can further create an opportunity as an added value by make pyrite as another marketable commodity. Pyrite separation during the flotation process makes mine more viable in achieving the target of an environmentally friendly mine. It happens through the program of reduction the acidity level and the amount of metal content in the water column that passes through the disposal facility. This research is conducted more to discuss the issue of geometallurgy along with the environmental impact and the need for engineering design capabilities in addressing the issues. However, the assessment has not been fully elaborated into perspective of cost assessment and its measurable effectiveness value. Especially whether it can be effectively implemented for the underground mining methods (block caving) in aiming achieve green mining concept within the optimum cost wise.

The use of the system dynamic (SD) method can solve the complexity issues involve the needs of strategic decision-making for planning and engineering design purposes. Under the green mining concept with an optimum cost spending brings into one of big challenges when mine meets an orebody with the complexity of geometallurgical conditions which requires an integrated study-simulation. SD method can simplify the complexity of assessment and allows for simulations to be carried out in analyzing economic characteristics and behavior, biological modeling, energy optimization, environmental issues, transportation efficiency and many others. In principle, the SD method can demonstrate the ability to simulate and analyze complex problems with an acceptable level of confidence. The research and study have been conducted by researchers in the following literatures describes the effectiveness of system dynamic methods exercising any complexity issues, especially in the mining industry. Amir Jafarpour, Siamak Khatami. July 16, 2021, through their research and technical writing on subject Analysis of Environmental Cost in Green Mining Strategy Using a System Dynamic Approach: A Case Study has distinguished the green mining strategy under concept of less environmental harm can be carried out through a better of do the ore processing assessment in the concentrating plant. Research results presence a significant impact on the cost to mining operations. Dante H. Montaldo, through his research and writing entitled A system dynamic model of an underground metal mine, demonstrates the structure and characteristics of tool who can be considered to use for mining operators in exercise the complexity issues. The use of the method is found useful in application supporting mine feasibility study from the initial stage project concerning the fluctuations of metal commodity prices in the market. Zikra, Listriyana and Rosyid on their research at the subject a system dynamic modelling in examine smelter development policy at Situbondo, Indonesia – 2018 describe the modeling decision on properly select nickel smelter through the engineering design study to be based on the environmental impact considerations. Webby Banda, 2023 on paper writing entitled A system dynamics models for assessing the impact of fiscal regimes at the mining project introduce the model development at inclusion of technical aspects and economic parameters in the mining operation projects. This providing model has the potential use for the government in formulating the policy and regulations achieving an effective mine strategy from the fiscal regimes side. It happens through including the tax aspects and non-tax elements into assessment who have a great impact on the economic value of mining operations. Bernadette O'Regan and Richard Moles, 2006, using system dynamics in modelling the interaction between environmental and economic factors for the mining industry. Study simulation illustrates the way in optimizing the mining operations cost under the complex and uncertain issues related to mine planning, mine design, cut-off grade and NPV value improvement. The availability of facilities and its impact on capital investment side in addition to other aspects related to the period of project completion, regulations concerning the environment and human resource productivity which can directly affect and burden capital spending. Various studies that have been conducted in consideration of capability use of system dynamic (SD) evaluating the complex issues bring into conclusion on effectiveness of method who can also be extended applying for strategic planning meet the objective target of green mining concept at remain wisely on cost spending. Research that has been done previously using this system dynamic method has included the aspects of EC (environmental cost) but not specifically studied the impact due to the metallurgy or the negative chemical impacts since the characterization of orebody. As such the composition of various minerals, gangue, waste in the orebody along its rock chemical characterization who can generate environmental risk and their influence into exploitation and ore recovery process cost under adopted underground mining method. The research studies that have been previously conducted compared to this proposed research can be outlined into the following matrix table:

Table I. Previous Conducted Research

Researchers	Year	Underground Mine Cost	Environmental Cost	Geometallurgical Aspect	Application of Systematic Dynamic Method
F.Testaye Firdu dan P. Tarkines	2010		X	X	
Alireza Javadi	2013			X	
Ravi K Jain, Zengdi Cui dan Jeremy K Domen	2016		X		
Izabella Joneh	2017		X		
Simon C Dominy dan Louisa O Connor	2018	X	X	X	
Zikra, Listriyana dan Rosyid	2018		X		X
Madison Lianna Goldberg	2021		X		
Giovanni Grieco dan Agim Sinojmeri	2021		X	X	
Amir Jafarpour dan Siamak Khatami.	2021		X		X

Researchers	Year	Underground Mine Cost	Environmental Cost	Geometallurgical Aspect	Application of Systematic Dynamic Method
Tuija Mononen	2022		X		
Dante H. Montaldo	-	X			X
Webby Banda	2023		X		X
Naser Badakhshan, Kourosh Shahriar, Sajjad Afraei dan Ezzeddin Bakhtavar	2023	X	X		
Bernadette O'Regan dan Richard Moles	2026		X		X

Limitation on past study information and availability of reference in evaluating the area of geometallurgical aspects for the underground block cave mine with the objective target achieved green mining concept in optimum cost lead into this new research and study investigation. Simon C Dominy and Louisa O Connor have conducted research and evaluation which find closes into this objectivity but have not truly deeply exploring EC (Environmental Cost) aspect from the side of rock-chemical composition in orebody and the potential risk impact to the environment. Their previous study and scenario simulation also conducted in manual methods and are not fully integrated among the others mine process at further questioning the level of accuracy. It certainly can be different under study-exercise at using of the system dynamic method (SD) who can integrate all aspects and better quantify the effectiveness of solution even under complexity assessment process.

3. METHOD

This section discusses research studies conducted for the underground block caving mining operations, ore-concentrate processing and its activity related due to the impact of cost since presenting a great volume of pyrite inside of orebody. Commence with identifying and mapping all activities related to the adopted mine method of underground block caving and cost activities. This mapping activities to further evaluate the ineffective task which contributes to high spending on ore treatment in processing facilities due to the presence of pyrite and its potential risk to generate acid mine drainage. Its beliefs of having control mitigation through the engineering of block cave mine can improve the effectiveness of pyrite handling and further optimizing the total mining cost. As such load reduction and further processing cost for mill-plant on treating the contaminant ore-pyrites at improvement of handling activities in the underground mine.

A. Mining Operations and Cost Activities

Mining activities are one of the initial sources that generate acid mine water following the orebody containing pyrites, exposure and mixed into a run water who will then affect environment by improperly handling them. An initial mapping for underground mining operations is performed in understanding the cost impact following presentation of acid mine water who led to environmental quality degradation. As the nature of underground block cave, mine, activity begins with opening an access tunnel to the ore body location, developing the cave areas, constructing mining facilities and infrastructure, progressing the cave and then drawing the ores from the caving. The broken ore is then transported into crushing and mill processing facility in enable to separate ore with the gangue or waste material. In general, the underground block cave mine to describe in the following step activities:

- Opening of tunnel access
- Development of the cave boundary area
- Construction of mining operation facilities and equipment
- Progressing undercut and caving development.
- Drawing ores from the cave

- Transportation of ores to processing facilities

Mining engineers must consider geometallurgical aspects from the initial stage of mine design process for better planning the underground block cave mine, especially with the rock-chemical composition presence in orebody and its potential negative impact into overall of mining process. Environmental impact due to the creation of acid mine water on presence of pyrite material in the ore body will require a proper management system from the early stage of engineering design. Poor in managing the mine from this stage of engineering design will then increase cost spending for the development and construction due to the additional requirements of facilities such as wastewater and tailing treatment, development of tailing dams, and potential of extra payment of fines or penalties at smelting facilities as result of supplies metal concentrate containing other negative elements. Some facts show that the environmental quality degradation could create much greater on handling costs due to the happening of pollution, major risk can be extended into failure to sell final product due to the damage of company reputation. Managing the potential of domino effect is an important part that needs to be evaluated, not only aiming to prevent greater consequences but also to find a way in optimizing the mining cost. It shall become an essential part of engineering design strategy to be able to best manage the underground mining operation. Plans for funding an environmental cost (EC) can be evaluated and considered value will be spent on having no action or no engineering design control in place to mitigate the risk. It therefore the value of impact will become a reference in comparing to engineering value effort as part of program for risk mitigation. As such with the level of effort needed for mine along with an establish plan in better way of handling the potential environmental issues. This research study is conducted by focusing on EC and its impact on the cost of spending underground block cave mine operations due to the geometallurgical or geochemical aspect at presentation of sulfide-pyrites rock in the orebody who can generate the acid mine drainage.

In addition to the study of engineering operations, economic factors and potential financial disruptions which are the keys and an important factor in mining projects, maximizing the benefits by having an early identification of challenge and opportunity will be another factor for mining operator to investigate. Some various ways which the mining operators can do in map-out their plan spending to meet target of maximizing benefit through the conducted of mining project. On the common practices, mining operators is to sub-divide their plan spending into capital investment budget or cost, operating cost, general and administrative cost. Capital cost represents an initial investment which is needed for building the mines and processing facilities during the stage of development and construction. Operating cost relates to the spending on production and maintenance activities that happen in the mine which are calculated in cost per ton. General and administrative cost cover spending any indirect of my activities since requirement of compliance, legality, annual report, and other supporting documentation. Environmental cost (EC) must be included in all these four categories due to the impact potentially occurs at all stages of mine activities. Having this said, scenario simulations must be carried out under the cause-and-effect relationships which present the complexity of issues along with a proposed solid recommendation to action. This is where evaluation studies need to happen in robust simulation tools such as the system dynamic (SD) method.

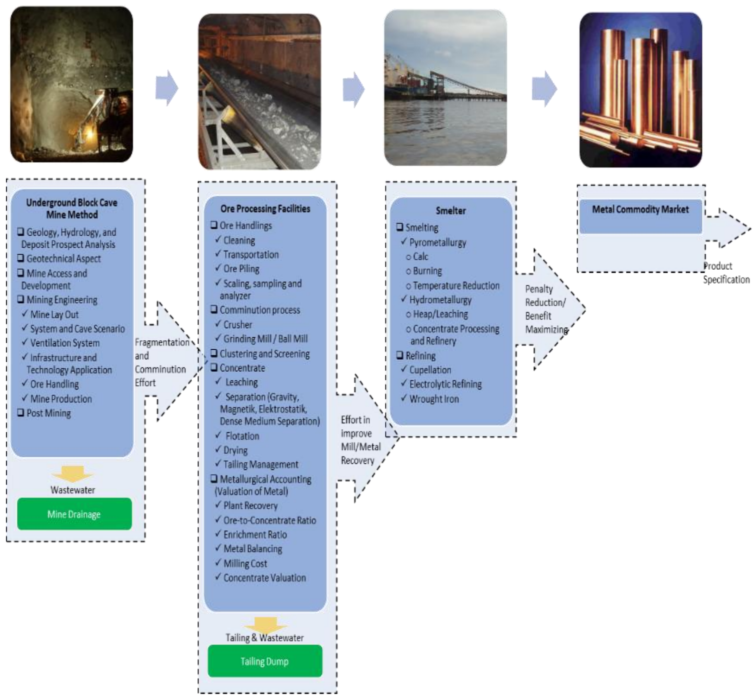

Fig. 1 Schematic Operation Underground Mine and its linked to ore processing facility, smelters and market of final metal product.

B. System Dynamic Application

The system dynamic (SD) method first introduced by Forrester in 1950 and since then has been used widely in structuring system for identifying solutions under complex problem issues by beginning to understand characteristics of its fluid and dynamic issues. Through this SD method, modelling and simulation could be done effectively under the complexity issues of economic and social which leads into improving organization strategic policy and or call for right decisions. Analytical problems commence by understanding of its characteristic issues which are formed under several variables with more than one scenario simulation. Scenario simulation along the observation is made more possible to be visualized through mathematical formulations presenting under the graphical format. It then becomes more visible, informative and creates reference for decision making. The basic principles of the SD method can be explained simply through the following water faucet diagram philosophy.

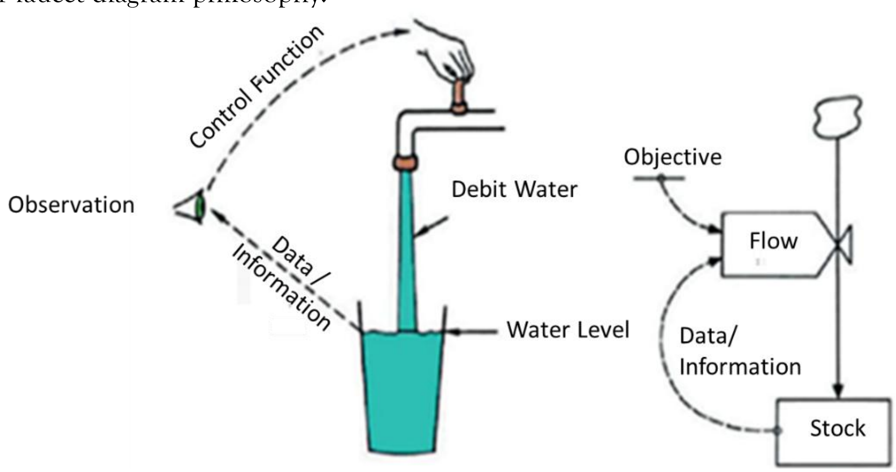

Fig. 2 Early Concept of System Dynamic develop by Forrester in 1950

As is present in the water faucet philosophy diagram, SD method evaluates how to fill water into a glass. Forrester stresses that filling water into a glass is not only about how the water flows into the glass. The problem is more about how to control the volume of water flowing into the glass. The control happens through providing instructions when looking into water level in the glass and then adjusting the flow rate through changing direction of the faucet rotation. This system encourages the function of observing water level and the function of hands for turning the faucet. The illustration diagram also depicts two symbols of stock and flow. Stock contains the accumulation of flow collected in storage while flow functions present a variable which could change stock. Flow provides a statement of how the volume of flow can be controlled compared to the setting target. This concept can be applied in solving a complex issue with there will only be 2 types of variable areas that require improvement or reference for decision making. They are stock and our flow. This then becomes the basic principle in applying system dynamics through performing the following steps:

- identify and define the problem: in this step, the main problem is identified, variables causing the problem and define the things that create the problem.
- Determination of problem characteristic: a study is performed by connecting the variables from an early reference of knowledge or previous research to an expected result of research that tends to be carried out.
- Explaining relationships of variables and the cause-and-effect descriptions using flow accumulation diagrams: All assumptions are defined as an initial estimate which can describe the characteristics of system. Hypotheses, variables, knowledge references, previous research and other data are then connected forming an accumulation of stock and in connecting flow diagrams.
- Development and implementation of simulation models: stock accumulation and flow diagrams that have been previously described presenting the dynamic hypotheses which become a problem to be observed. By doing it, an initial value of variable and the modeled parameters begin to be identified. The implementation of simulations and model studies happens under an extreme condition; the expected ideal characteristics can be compared to the actual observed situation. Likewise, with comparisons to knowledge references, previous research and previous conditions to validate the model. Finally, testing the hypothesized structure with the observed system characteristics through the results of the scenario simulation study becomes a tenable proposition.

There are several software packages that can be used for modeling and simulating system dynamics. Through this research, Vensim software is using which one of the effective tools for simulation, model testing, engineering solution design and reviewing several scenarios with complex systems. Underground block cave mine operation, processing facility operational concept and the environmental impact can be mapped along with the cost estimate for further evaluation and simulation using the system dynamic method. Activity cost mapping can be presented in the following diagram.

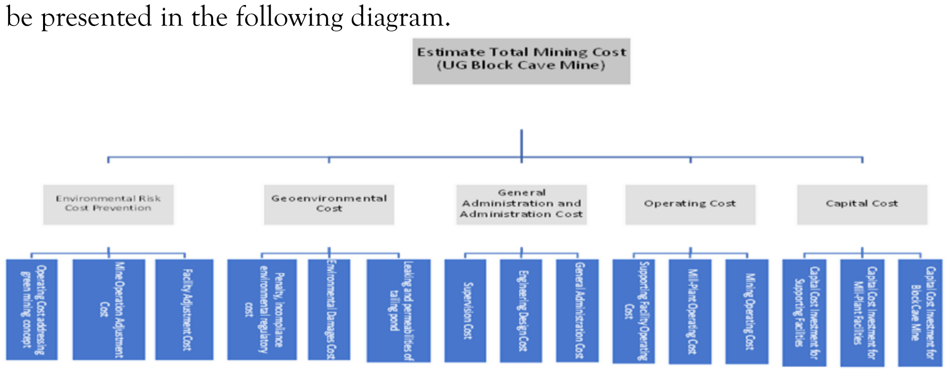

Fig. 3 Environmental cost mapping for the underground block cave mines happens through identification of all various activities on each stage of operation along its potential cost impact in strategically planning of the green mining concept

4. Simulation Results and Discussion

This section discusses all data and information related to this investigation conducted for the block cave underground mining operation as initially presented under the research theme. The next step is to describe the dynamic system (SD) model and then present with the analytical study through simulation model and generate a best-spoken solution in overcome the issues.

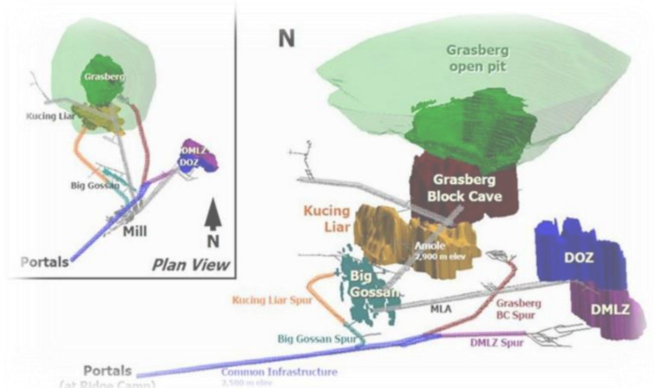

Fig. 4 Underground Grasberg Block Cave Mine in 3D model. Presents a complexity of Geometallurgy aspect who need the technical evaluation on best way managing the risk of acid mine drainage since the presence of Pyrites in the orebody.

A. Case Study Analysis

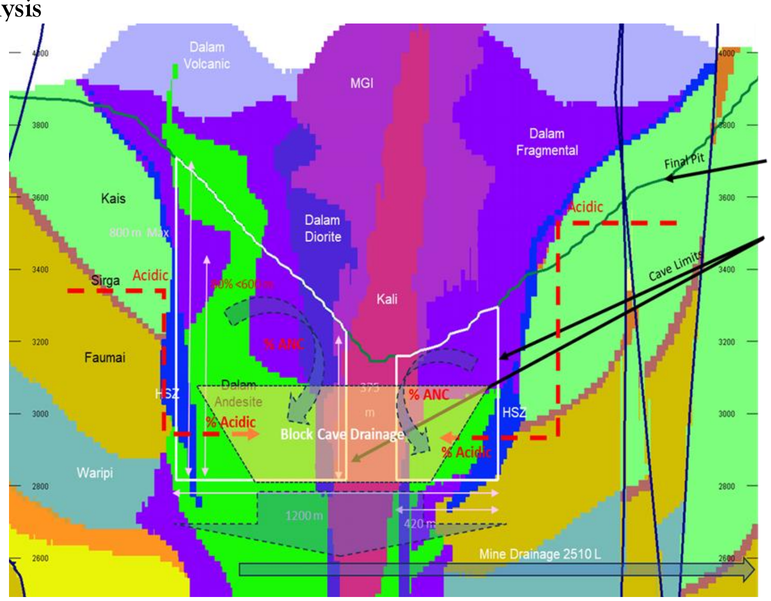

Fig. 5 Geological cross section on the orebody indicates location of HSZ (High Sulphur Zone) who is potentially source of acidity and the carbonate's host rock where is considered as the ANC (Acid Neutralizer Capacity) materials. Scenario of blending as part of criteria designing the block cave mine could potentially reduce until eliminate the acid water hazard.

The case study is using an underground block caving mining operation with the ore body that has complex geometallurgical conditions and rock chemistry issues who can potentially create the acid mine drainage with a large of value impact into the surrounding environment. The case study observes of the practices of mining operations at PT. Freeport Indonesia located in Tembagapura District, Mimika Regency, Central Papua Province - Indonesia. The impact value assessment will align to previous research study which has been conducted by Naser Badakhshan, Kourosh Shahriar, Sajjad Afraei and Ezzeddin Bakhtavar through their written paper entitles Determining the environmental costs of mining projects: A comprehensive quantitative assessment using environmental impact factor values based on the type of mining operation with the blockcaving method. The impact of mining operations to the surrounding environment can be classified as potentially significant in terms of positive and negative impacts based on the scale of mining operations and other criteria that have previously been defined and developed by Naser Badakhsan, Kourosh Shariar, Sajjad Afraei and Ezzeddin Bakhtavar. The Grasberg district of ore body complex is described as a combination of gold-copper porphyry and some other type of skarn geological formation with current production operations producing copper, gold and silver minerals. The total deposit reserves reach 989 million tons with an average content of 1.02% copper, 0.77g / t gold and 3.54g / t Ag silver. The additional life period based on government approval for the granting of a Special Mining Business Permit (IUPK) for 40 years with mining has been under operation for 13 years. Using data is based on technical and economic documentation from PT Freeport Indonesia and several other reports who previously published explaining the mining operations. Some other data is also taken from official reports issued by the Company to the government.

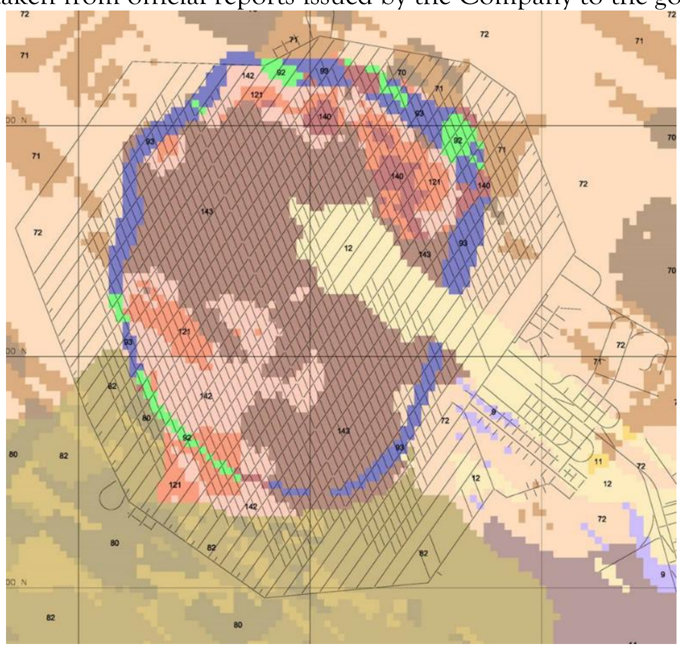

Fig. 6 The Grasberg Block Cave Mine lay out at shows of production grid. Critical design factors in applying for the block cave mine method shall be integrated with requirement for properly managing the pyrite. A complex of study evaluation who can be simplified at using of system dynamic method in objective of obtaining strategic decisions.

B. Model Description

As an initial reference for study, modeling is performed through assessing the relationships to factors that are considered effective in applying the system dynamic (SD) method. Simulation with a computerized system will be carried out through Vensim software. The results achieved under the simulation-scenario will be presented in the following section of this written research study results. The simulation is developed considering several options presented in the following scenarios:

- Scenario 1 is defined as a standard or initial condition when the mining operational engineering runs as is without considering any requirement environmental mitigation solutions. The cost of impact is indicated on presenting of rock acid which generates by the excavation of large volume of rock containing high pyrite in the ore body. Scenario 1 includes elements of consideration of environmental cost impacts as consequence of decision performing the mining without any available mitigation solutions.
- Scenario 2 investigates reduction of mining area, and the production capacity considers no excavation in the locations containing high pyrite. Mining production area under classification high pyrite is if they are containing greater than 40% pyrite.

- Scenario 3 investigates conducting effective current engineering control in boundary of underground block cave mining activities with a maximum scale of production or mining to include excavating rock in areas containing high pyrite. The intended engineering control measures covers all need of efforts in eliminate the formation of acid mine drainage through the designing of an effectiveness drainage and mine dewatering system, proper sequencing the mine consider blending pyrite with the other type of rocks which can neutralize the acid, improving ventilation system and properly managing the progressive of caving and prevent any intrusive of surface water into the cave.
- Scenario 4 investigates a full scale of production operations with no adjustment into the mining operation area in exception only do the modifications to exist processing facilities in anticipating impact of mineral containing pyrite. Namely this scenario is assuming that the block cave mining continues expanded into entire areas, no changes into the mining scenario with only modifying the concentrating plant anticipating contamination pyrite in supplying ores who can generate acid into the tailing or wastewater. Plant modifications include the additional grinding facilities, separation, and cleaning of minerals from contaminating ores, power plants and other requirement supporting facilities.
- Scenario 5 investigates a full scale of production operations with modifications to processing facilities and sedimentation ponds in anticipating residual impacts of present acid in wastewater or tailing due to the pyrite content in processing ores. Scenario 6 represents the option of reduction production capacity in avoiding excavation of high pyrite areas and the modification of processing plants include settling ponds before the final discharge of wastewater.
- Scenario 6 happens by making simultaneous adjustments on the mining operations area with the facility modification happening at the processing facilities only.
- Scenario 7 presents the option of simultaneously performing the adjustments at entire areas of engineering, the mining operations, processing facilities and the sedimentation pond to better anticipate the impact of processing ores containing pyrite.

The simulation of the above scenario can then be tabulated as follows:

Table II. Mining Production Simulation Scenario

Simulation-Scenario	Description	Formulation Mathematic
Scenario 1/Basic Scenario	System Dynamic simulation study without developing engineering design solution following environmental impact into overall mining system	Simulation of Production Capacity of 160k tons per day with full impact of environmental consequences at no engineering-design solutions.
Scenario 2	System Dynamic study simulation by reduction of area and production, i.e. without exploitation activities under the area containing high pyrites.	Reduction of capacity to 115KTPD/exclude of high pyrite area
Scenario 3	System Dynamic study simulation of mining operations with full exploitation capacity and perform robust Engineering Design of Block Cave Mine to deal with high containing pyrite in orebody	Full Capacity 160KTPD with only Handling of pyrite in the direct mine/excavation area (without modification of ore processing plant and or sedimentation pond)
Scenario 4	System Dynamic study simulation with full production in mining operations, without scenario Pyrite Handling Capacity 160KTPD with Modification of processing facilities land and only Adjustment to facilities processing (engineering design ore processing facility complex)	Full Capacity 160KTPD with Modification of processing facilities complex only (with no modification sedimentation pond)

Simulation-Scenario	Description	Formulation Mathematic
Scenario 5	System Dynamic study simulation at reduction of underground block cave production capacity (exclusion of high pyrite areas) with additional modification of ore processing facility and sedimentation pond in overcoming pyrite contamination issues.	Capacity reduction of 115KTPD with modification of processing facilities and sedimentation pond
Scenario 6	System Dynamic study simulation by doing simultaneous adjustments into engineering of mining operations and ore processing facilities. Without considering modification of tailing sedimentation pond	Reduction of production capacity at 115KTPD with mining engineering and ore processing facilities only.
Scenario 7	System Dynamic study simulation by simultaneously adjusting the engineering of mining operations, processing facilities and deposition areas (design engineering) under scenario of full production capacity at 160KTPD.	Full Production Operation 160KTPD with modification of processing facility and deposition or tailing sedimentation facility

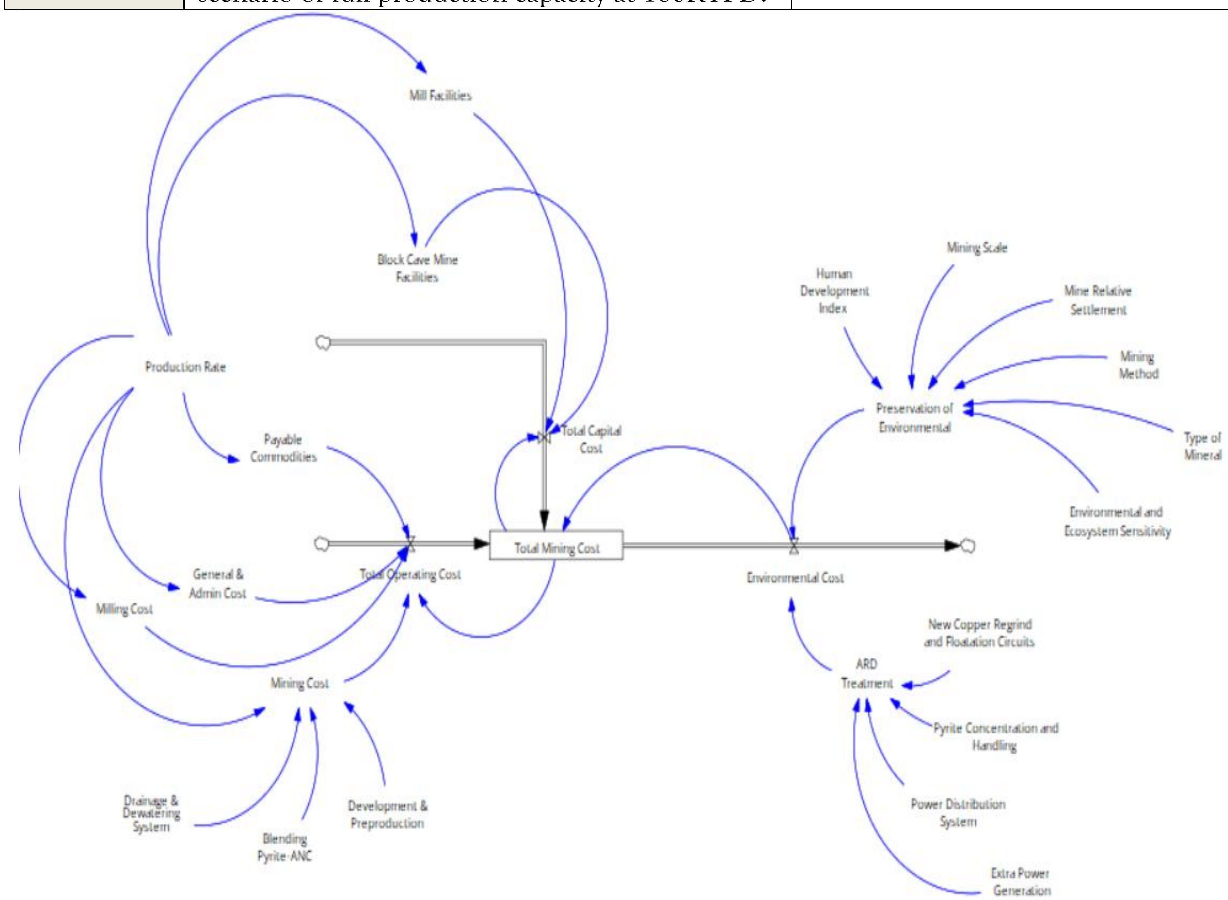

Fig. 7 Study simulation under different engineering-design scenario of mine at some possible improvement effort happens for block cave mine in optimize the total mining cost. Consideration has included the environmental concern and cost provision in managing the ARD

Study simulation on each of operation engineering scenarios is performed by considering the following parameter values:

- Production Rate (Expected production capacity at optional 115KTPD or 160KTPD)
- Mining Cost (Engineering control carried out for the mining itself with regard the activity needs in overcoming presentation of acid in mine wastewater following the contain of pyrite in orebody. Provision covers activity of design and implementation drainage & dewatering system, Pyrite-ANC Blending, Development and progressing the cave to better managing pyrite-ore contamination.
- ARD Treatment (Control engineering carried out at the mill-plant or ore processing facilities, New Copper Regrind and Floatation Circuit, Pyrite Concentration and Handling, tailing sedimentation pond, Power Distribution System and Dual Power Generation)

The values generated through scenario simulation on Vensim are as follows:

Table III. Sumulation Values Result and Coefficient

Simulation-Scenario	Values	Coefficient
Scenario 1 / Basic Mode	1,57E+23	0 or 1
Scenario 2	-513095	-3,27E-18
Scenario 3	9,83E+05	6,27E-18
Scenario 4	-708059	-4,52E-18
Scenario 5	-513095	-3,27319E-18
Scenario 6	-541546	-3,45468E-18
Scenario 7	-736510	-4,69842E-18

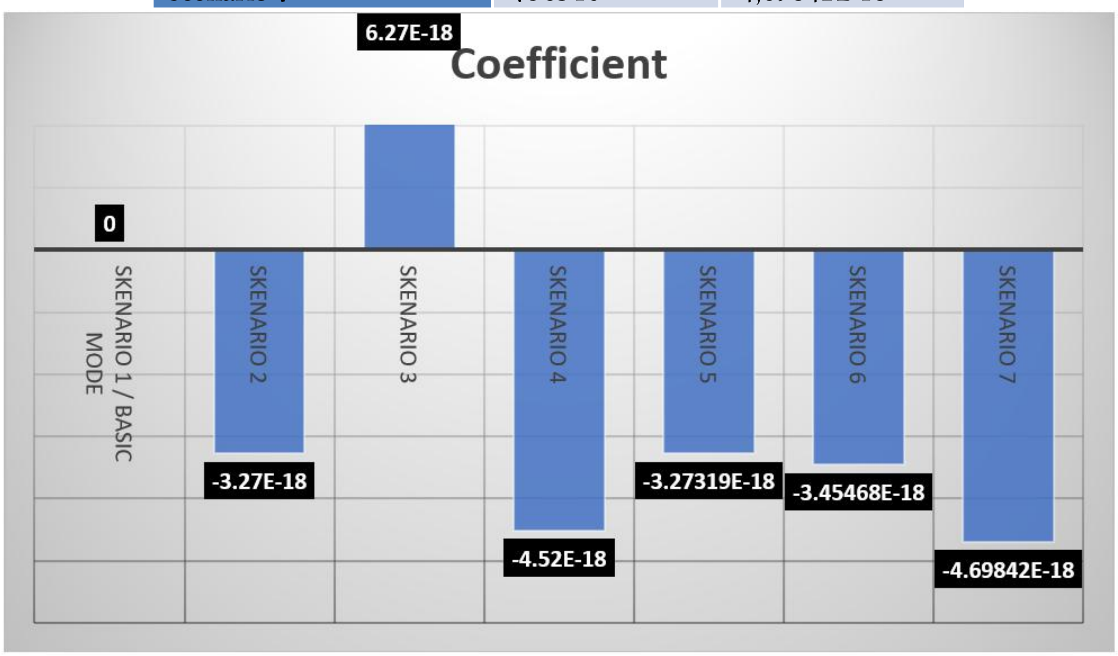

Fig. 8 Scenario Coefficient Chart

Possibility is also open for the Mine operators who want to apply more strategies in determining with the most effective scenario options. It depends on objectives of strategy assessment and the complexity of mining process itself. The conducted simulation scenario in this research determines impact from side of cost to the engineering design solutions that are implemented under one operational location (only in the mining operation area or ore processing facility) as well as a combination of engineering solutions that will be implemented in both areas (mining and mill-plant facility). The result of this simulation aims to provide guidance for the decision-makers who can have a great influence on strategically planning for mining operations. On a simple mining operation perspective, each simulation-scenario intend to find the best operational scenario for cost reduction or optimizing the resource spending of the mining operation. Simulation scenario on the other side also in consideration providing views at the needs of mining operations achieving an optimum cost with low of environmental impacts. Under scenario 1 or basic mode, there is no consideration of the direct impact of EC (Environmental Cost) into production operations. But by investigating the later consequence in the activity of selling or marketing the product- commodities, it can present a greater impact on the operational cost due to obligation fulfill environmental regulation compliance where there a needs of mining operator spend an extra bill for something not in properly planned upfront. As example paying penalty and or other requirement of an administration fee following the happens of contract dispute. Scenario 1 to become a reference for model validation in respectively understand value impact by not doing any engineering design control. Formulation of mathematics can be developed and used in better structuring the cause-and-effect relationship under system dynamic model with expect result to learn into present graphical trending. Formulation of mathematics can be described as follows:

TMC = (TCC + TOC) – MEC (1)

Total Mining Cost = Total Capital Cost + Total Operating Cost – Mining Environmental Cost

TOC = (MNC + MLC + GAC) / PYB (2)

Total Operating Cost = Mining Cost + Milling Cost + General Admin Cost / Payable Commodities

TCC = BFC + MLF (3)

Total Capital Cost = Block Caving Facility Cost + Mill Facility Cost

MNC = DPC + BPC + DSC (4)

Mining Cost = Development-Preproduction Cost + Blending Pyrite Cost + Dewatering System Cost

MEC = PEC – ATC (5)

Mining Environmental Cost = Preservation of Environmental – ARD Treatment Cost

PEC = HDI + MCC + MRS + MDC + TOM + EES (6)

Preservation of Environmental Cost = Human Development Index + Mining Scale Cost + Mining Relative Settlement + Mining Method + Type Of Mineral + Environmental and Ecosystem Sensitivity

ATC = NCR + PCH + PDS + EPG (7)

ARD Treatment Cost = New Copper Regrind and Floatation Circuit + Pyrite Concentration Handling + Power Distribution System + Extra Power Generation

Above mathematical formulation presents the input into Vensim software who then produce results at considering various factors which have already been included in this system dynamic modeling. This study involves economic exercise (mining costs and environmental activities cost), correlation between these factors presenting an indication of the cost magnitude since the effect of adopting engineering-design solution option. It provides a linear diagram as result of study due to the increase or decrease cost towards the ending period of mining operations. As part of the conclusion on understanding the value impact, the result of each different simulation is converted into coefficient number (α) who will then be used in analyzing the level of impact into environmental. Value of impact then provides an indication at effectiveness of engineering design control on each of the studied scenarios. Further into the effectiveness of engineering-design solutions, it shall also be expected to be reduced until we eliminate any potential additional residual risks presented into mine. This residual risk could show as their potential of leakages at the tailing sedimentation area, thus the effectiveness of management of acid from upstream mining will then become very important. It then makes this research study differ and most important as the current engineering design only tends to look adjust the ore processing facility and work out tailing sedimentation pond or build of tailing dam to treat residual risk. Residual risk presenting by continuing this practice is the potential leakage of tailing dam. The potential additional impacts following the needs in anticipating residual risk can be calculated through the following mathematical formulations:

LTD = (PYC x α) + CCR)

Where.

LTD, Leakage of Tailing Dam

PYC, Pyrite Cost ($386,449,000) which is the total estimate cost of efforts in associated to the needs for handling the pyrites.
α, Coefficient value from each different scenario simulation
CCR, Closure Cost ($1,021,949,000) which is the total cost on plan to be spent for mining closure.
Leakage of tailing dam (LTD) is likely to be another quantifying potential of cost impact due to improperly handling the pyrites at the upstream mining process.

The result of calculation is presented at the following diagram chart.

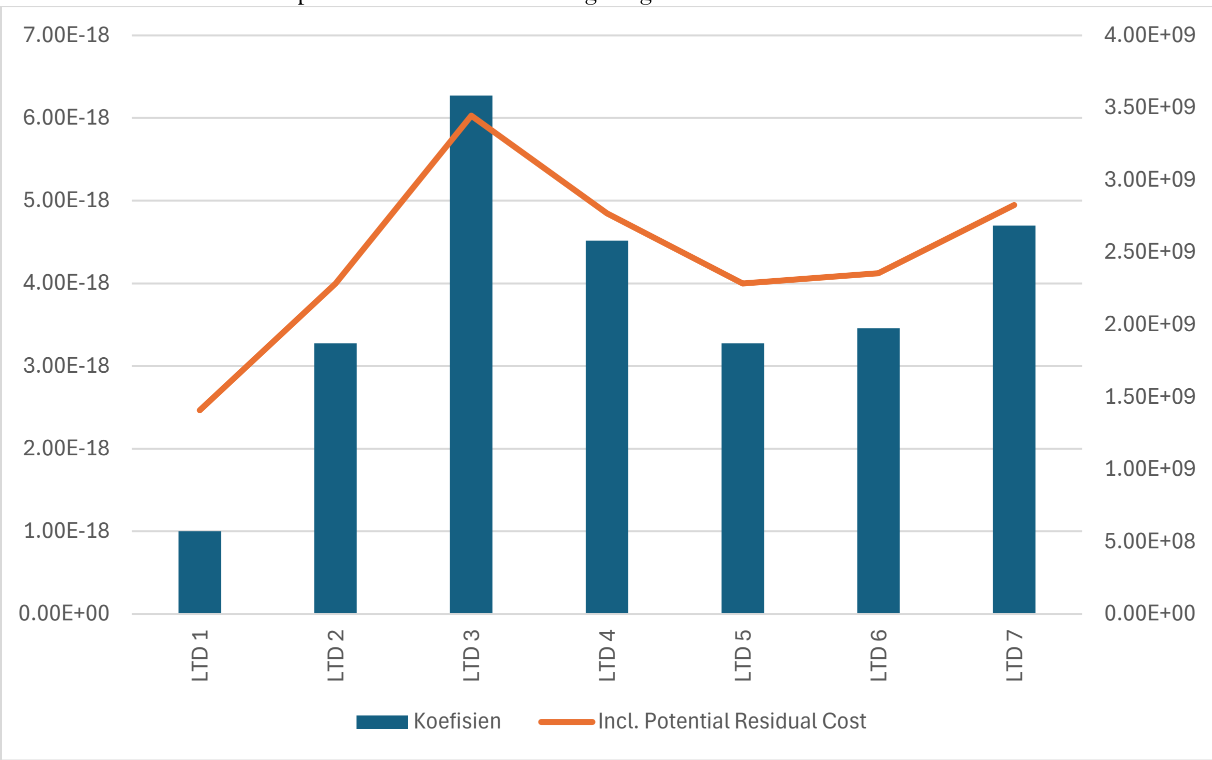

Fig. 9 Coefficient and Potential Future Residual Cost

The determination on the effectiveness of engineering control happens by investigating the impact of each solution on the total mining cost. It then set the criteria target for this SD model to find an optimum value in between mining operational cost and environmental cost since the negative effect of rock chemical in the ore body. Recommendation of strategy implementation aiming reduction of environmental cost on the later stage of mining with have something fix at upstream underground block cave mine design. It was achieved throughout the complex study of simulation scenario under the system dynamic method. The strategy development to consider any potential future impacts such as such social issues, regulatory changes, incentives for pollution or contamination and other risks associated to environmental quality degradation. The effective solution on each scenario option can be recognized through the presenting result of coefficient value from this simultaneous of scenario simulation. This simulation scenarios under the case studies of mine operations for PT. Freeport Indonesia to represents conditions in the real world of mining.

C. Scenario Analysis and Simulation Results

In this section, the results of system dynamic modeling will be deep for discussion. The following diagram chart depicts the effectiveness of solution from each develop scenario option that is simulate under the Vensim software.

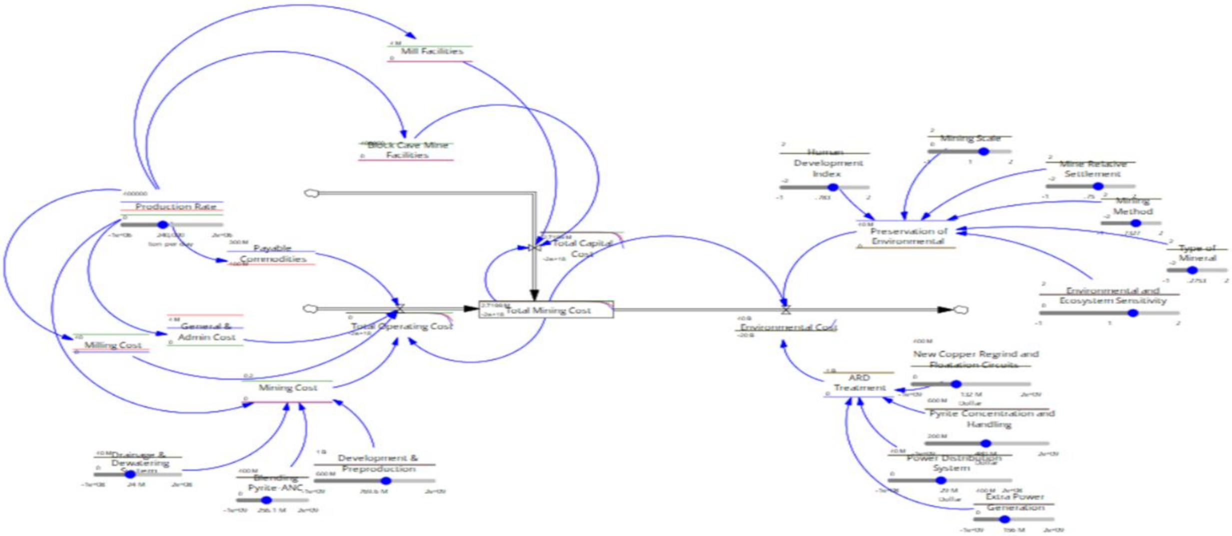

Fig. 10 Presence scenario simulation using system dynamic which can directly shows the impact into total mining cost by do the adjustment on the critical activity.

This simulation assessment underlaying impact into total mining cost at the three major option of "do nothing", "do minimum" and "do something". The do-nothing option (not making countermeasures efforts) presents as creating conditions for paying the consequences at decision for staying as-is and having no engineering design solution. The consequence includes unnecessary spending associated with fulfilling environmental obligations which happens due to the additional cost for managing the issues, fines or penalties payment, increase on complexity process for permit and licensing because of incompliance to regulation. The do minimum option represent scenario on reduction of production volume since the exclusion of exploitation area who containing the high pyrite (scenario 2 – 115ktpd production operation). This do minimum option does not provide any significant benefits while it tends to leave a residual risk that may require an additional effort to handle it in the later stage of mining. Doing something provides several options with a good scale of benefits and presents reduction on risk for environmental along its cost impact for future.

Skenario 1 – Basic Mode, Production 160KTPD at no CAPEX for ACID treatment

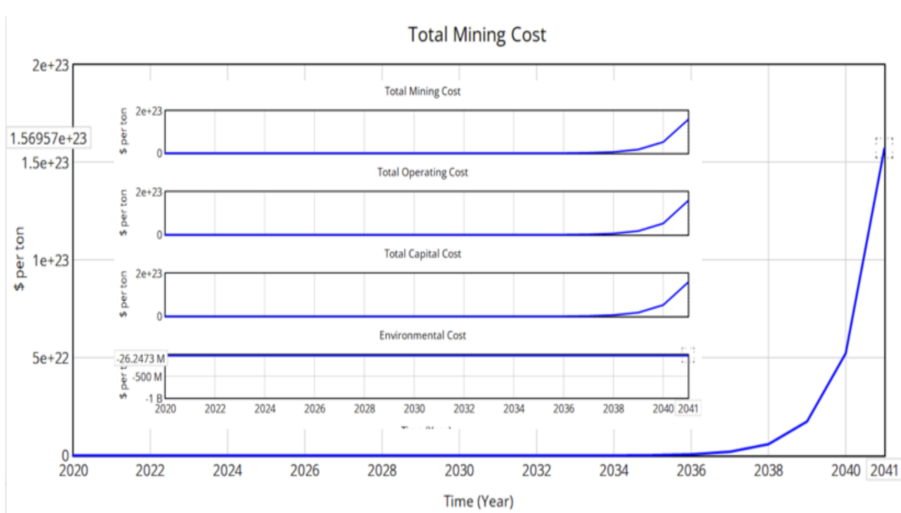

Fig. 11 Scenario 1 or Basic Mode simulation results. System Dynamic simulation study without developing engineering design solution following environmental impact into overall mining system

This scenario 1 presents trends on increase of total mining cost toward the stage of mine closure (near the end of mining). Environmental costs are constant during the period of mining. Trending on increases of environmental cost towards the end period of mining to also indicate increase of cost will continue in period of post-mining.

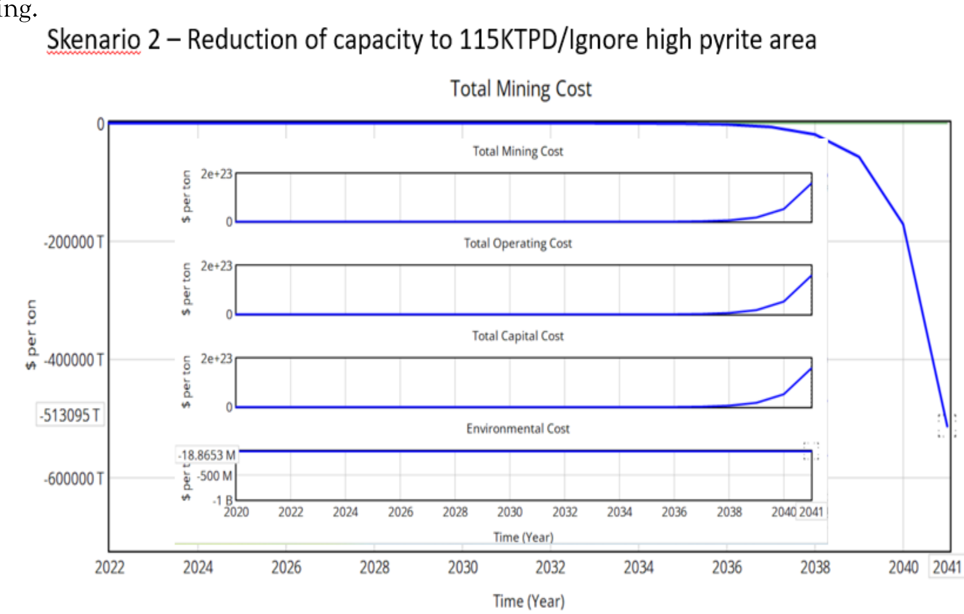

Fig. 12 Scenario 2 simulation results. System Dynamic study simulation by reduction of area and production, i.e. without exploitation activities under the area containing high pyrites.

Scenario 2 presenting the trend on decreasing of total mining cost towards the end period of mining. The operating and capital cost trending increase which indicated there is an impact since exploitation activity have reached into the high pyrite area. Potential of residual risk requires additional control if this scenario option is selected. Environmental cost (EC) shows a constant but in lesser values compared to the scenario 1 – basic mode.

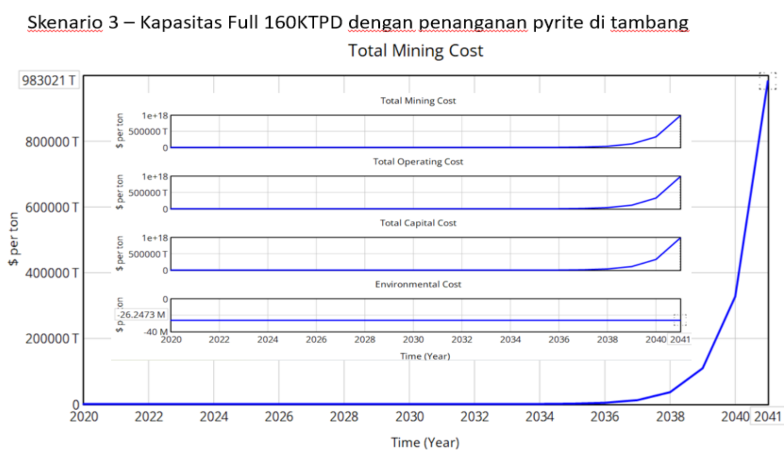

Fig. 13 Scenario simulation 3 results. System Dynamic study simulation of mining operations with full exploitation capacity and perform robust Engineering Design of Block Cave Mine to deal with high containing pyrite in orebody

Scenario 3 presents a trend of increase on total mining cost respectively close to ending period of mine. This trend indicates ineffectiveness of mining engineering solutions, or it has not been fully implemented. Environmental cost (EC) presents a trend of constant up until the end period of mining. Same value of impact to scenario 1 or basic mode option fairly indicates ineffectiveness of current practices of the engineering control.

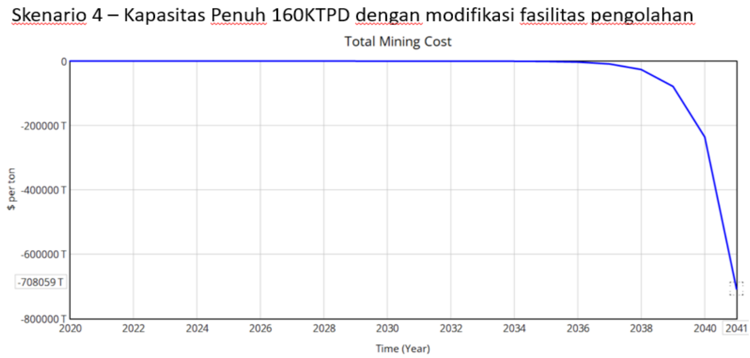

Fig. 14 Scenario simulation 4 results. System Dynamic study simulation with full production in mining operations, without scenario Pyrite Handling Capacity 160KTPD with Modification of processing facilities land and only Adjustment to facilities processing (engineering design ore processing facility complex)

Scenario 4 presents a trend on decline of total mining cost respectively near the ending period of mine. The impact value is even large compared to scenario 2.

Fig. 15 Scenario simulation 5 results. System Dynamic study simulation at reduction of underground block cave production capacity (exclusion of high pyrite areas) with additional modification of ore processing facility and sedimentation pond in overcoming pyrite contamination issues.

Scenario 5 presenting trend decline in total mining cost at lesser value compared to scenario 4.

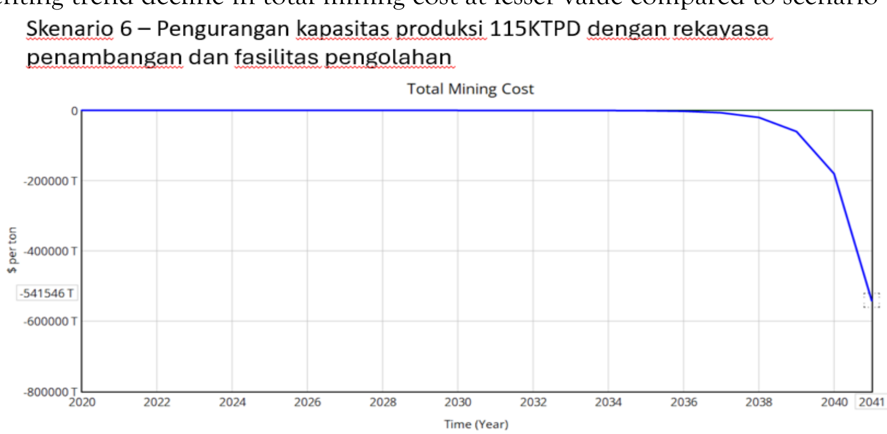

Fig. 16 Scenario simulation 6 results. System Dynamic study simulation by doing simultaneous adjustments into engineering of mining operations and ore processing facilities. Without considering modification of tailing sedimentation pond

Scenario 6 presents a trendy decline on total mining cost with a better value compared to scenarios 4 and 5.

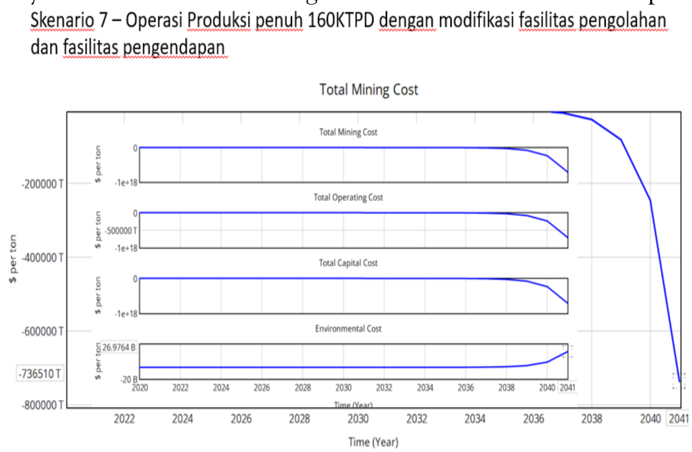

Fig. 17 Scenario simulation 7 results. System Dynamic study simulation by simultaneously adjusting the engineering of mining operations, processing facilities and deposition areas (design engineering) under scenario of full production capacity at 160KTPD.

Scenario 7 presents a trendy decline in total mining cost at better value in comparison to scenarios 4, 5 and 6. Nevertheless, environmental cost (EC) presents trends of increase close to the end period of mine. Same indication happens for previous scenarios 4,5 and 6 on trend of environmental cost. This requires an evaluation study of additional engineering controls for reduction until eliminating any negative impact on residual risk since the present of acid in tailing or wastewater.

The overall simulations conclude with the trend of decreases in total mining cost in exception of scenario 3. This shows the ineffectiveness of existing engineering controls for the underground block cave mines to deal with the ores containing pyrites. On the other hand, engineering controls for ore processing facilities remain presenting residual risk with the containing acid in tailing and wastewater which require adjustment into existing sedimentation pond or tailing dam.

5. CONCLUSION

The value of coefficient resulted under simulation scenario 3 illustrates significant increase on total mining cost since ineffective engineering control for the underground block cave mine in overcoming the issue of ore containing pyrites. Large reduction on total mining cost present under simulation scenario 7 requires extra control to reduce until eliminate any residual risks that potentially arise since the present of acid in the tailing or wastewater. This research generates a conclusion that there is requirement of more engineering design control shall happen at the upstream of underground mining area. The gap identified through the simulation shows the large increase in total mining cost if control mitigation is only happening in mining operation areas at as-is implementation method. That means to become focus area of investigation for improvements. The value of cost under scenario simulation 7 can also be aligned into this value simulation happens for scenario 3. As such the residual risk present under scenario simulation 7 can be eliminated by solving the issues present under ineffectiveness of scenario simulation 3. In investigated scenario simulation 3, it further can be indicated that there are things that have not been done effectively. The deviation value between these two scenario options becomes an important reference for the level of needs at effort for handling the pyrites in underground mining area which also will eliminate remaining residual risk which may arise at the ore processing facility. Improvement of the engineering control for an underground block cave mine operation will cover:

- Properly designing the mine drainage and dewatering system
- Consider operational blending Pyrite & ANC into scenario of block cave mine

- Robust plan and scheduling the mine on properly sequencing of development & preproduction-caving activities.

There will be a further need of process mapping on the requirement of engineering control for underground block cave mine to be effectively handling the pyrites along with the needs for collaboration from different disciplines and knowledge background. To be in the next focus of research study and written journal.

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