THESIS

EVALUATION OF FAILURE IN LIMESTONE PRODUCTION AT PT SEMEN TONASA, PANGKEP REGENCY, SOUTH SULAWESI

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LEMBAR PENGESAHAN

EVALUATION OF FAILURE IN LIMESTONE PRODUCTION AT PT SEMEN TONASA, PANGKEP REGENCY, SOUTH SULAWESI

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ABSTRACT

ANGELIE SANTOSA. *Evaluation of Failure in Limestone Production at PT Semen Tonasa, Pangkep Regency, South Sulawesi* (supervised by Aryanti Virtanti Anas and Rini Novrianti Sutardjo Tui)

The implementation of sustainable mining should be emphasised that sustainable development is, in any case, a continuous handle, and not a transitory under-taking. An effective management strategy requires failure management in order to identify and minimize the effect of the failure. PT Semen Tonasa produces cement made of raw materials such as limestone and clay. Limestone mining in PT Semen Tonasa is done through process such as drilling, blasting, loading, hauling, and crushing. Limestone production report of November 2022 shows that actual production reached 613,809.37 tonnes with production target 645,460 tonnes. This number shows that actual production did not reach the target of November 2022. Detailed evaluation in the mining process is needed to identify failures which responsible to the unattainability of production target. Each of the mining process is simulated using dynamic modelling, in order to predict if the production would reach the target, using current parameters that applies in the field. Simulation results shows that limestone productivity tend to fluctuate for each day, but mostly did not reach the target instead. In order to identify failures, Failure Mode Effect Analysis (FMEA) is done for each mining process in PT Semen Tonasa. This analysis resulted in Risk Priority Number (RPN) that shows which process of mining should be prioritized for improvement. RPN ranking shows that hauling process should be prioritized. Therefore, the improvement plans are calculating optimum number of equipment using the match factor theory, and road geometry planning based on AASHO 1965 standard.

Keywords: limestone mining, dynamic modelling, failure mode, FMEA, RPN

ABSTRAK

ANGELIE SANTOSA. *Evaluasi Kegagalan Produksi Batukapur di PT Semen Tonasa, Kabupaten Pangkep, Sulawesi Selatan* (*dibimbing oleh* Aryanti Virtanti Anas *dan* Rini Novrianti Sutardjo Tui)

Implementasi penambangan berkelanjutan harus menekankan bahwa pembangunan berkelanjutan, dalam kasus apapun, merupakan tanggungan berkelanjutan, dan bukan kegiatan sementara. Sebuah strategi manajemen yang efektif membutuhkan manajemen kegagalan untuk mengidentifikasi dan mengurangi dampak dari kegagalan. PT Semen Tonasa *memproduksi semen yang terbuat dari bahan mentah berupa batukapur dan tanah liat. Penambangan batukapur di* PT Semen Tonasa *dilakukan melalui proses berupa pengeboran, peledakan, pengangkutan, dan kominusi. Laporan produksi batukapur* November *2022 menunjukkan bahwa produksi actual mencapai 613.809,37 ton dengan target produksi berjumlah 645.460 ton. Angka ini menunjukkan bahwa produksi actual tidak mencapai target* November *2022. Evaluasi mendetal terhadap proses penambangan perlu dilakukan untuk mengidentifikasi kegagalan yang menyebabkan ketidaktercapaian target produksi. Setiap proses penambangan disimulasikan menggunakan pemodelan dinamis, guna mem prediksi apakah produksi akan mencapai target, menggunakan parameter terkini yang berlaku di lapangan. Hasil simulasi menunjukkan bahwa produktivitas batukapur cenderung berfluktuasi untuk setiap harinya, tetapi Sebagian besar tidak mencapai target. Untuk mengidentifikasi kegagalan, dilakukan* Failure Mode Effect Analysis (FMEA) *untuk setiap tahapan penambangan di* PT Semen Tonasa. *Analisis ini menghasilkan nilai* Risk Priority Number (RPN) *yang menunjukkan proses penambangan yang harus diprioritaskan untuk pengembangan. Pengurutan RPN menunjukkan bahwa proses pengangkutan harus diprioritaskan. Oleh karena itu, rencana pengembangan berupa perhitungan jumlah alat optimal menggunakan teori* match factor, *dan perencanaan geometri jalan berdasarkan standar AASHO 1965.*

Kata Kunci: penambangan batukapur, pemodelan dinamis, failure mode, FMEA, RPN

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LIST OF ACRONYMS AND SYMBOL DESCRIPTION

Acronym	Description
NGO	Non-Governmental Organization
CLD	Causal Loop Diagram
SFD	Stock-Flow Diagram
FMEA	Failure Mode Effect Analysis
RPN	Risk Potential Number
BCM	Bank Cubic Meter
LCM	Loose Cubic Meter
MA	Mechanical Availability
PA	Physical Availability
MF	Match Factor
DT	Dump Truck
BFF	Bucket Fill Factor
Eff	Effectivity
SF	Swell factor
JSA	Job Safety Analysis
SOP	Standard Operation Procedure
COGS	Cost of Goods Sold
CTL	Cycle Time Loader
CTH	Cycle time Hauler
DpT	Digging Time
SLT	Swing Loaded Time
DDT	Dumping Time
SET	Swing Empty Time
NPV	Net Present Value
AASHO	American Association of State Highway Officials

Symbol	Description
T_A	Average time
Q_L	Productivity
Kb	Bucket capacity
T_c	Cycle time
W	Width of running surface (m)
L	Number of lane(s)
X	Vehicle width
$\overline{T_L}$	Average loader cycle time
$T_L n$	Loader cycle time per cycle
$\overline{T_H}$	Average hauler cycle time
$T_H n$	Hauler cycle time per cycle
n_L	Loader amount
n_H	Hauler amount

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The dynamics in the activities and preparation of this report found no significant obstacles. Therefore, I would like to express respect and gratitude to Dr. Aryanti Virtanti Anas, S.T., MT. as Head of the Department of Mining Engineering as well as thesis supervisor, along with Dr. Eng. Rini Novrianti Sutardjo Tui, S.T., MT., MBA who has taught, guided, and briefed so that the thesis composing took place smoothly. I would also express my gratitude to Hikmania Ayu Febrianti, S. Psi as Manager of Training and KM Officer PT Semen Tonasa for her guidance during 6 months of internship, and Hariyono Gunawan, S.T. as Senior Manager of Mining PT Semen Tonasa as well as field supervisor for motivating, giving moral support, and guiding during the internship for 6 months.

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I apologized if there were any miswords in the preparation of this report, because I realized perfection belongs only to the Creator. Hopefully in the future this thesis can be useful for everyone, both practically and scientifically.

Gowa, 26th January 2024

Angelie Santosa

CHAPTER I
INTRODUCTION

1.1 Background

Mining and processing of limestone are one of the utilizations of natural resources in order to maintain development at either central or district areas. Increase of usage and requirement of technology in development results in increase of demand in raw materials. Production stage includes processing from raw materials to finished goods which are ready to use (Juniardi and Adiansyah, 2020).

Limestone constitutes a group of raw materials commonly referred to as carbonate rock. It is considered as non-metal minerals based on UU No. 3 *Tahun* 2020. Limestone is widely spread among Indonesia and commonly mined due to its various usage in industries. Limestone mining are done massively in Indonesia with high production target (Kogel, et al., 2006).

PT Semen Tonasa produces the largest amount of cement in eastern region of Indonesia, which located in 715-hectare area of Biringere Village, Bungoro District, Pangkep Regency, about 68 kilometers from Makassar city. This company is capable of producing up to 5,980,000 tonnes of cement per year and equipped with four units of factories, namely Tonasa II, III, IV, and V.

PT Semen Tonasa produces cement made of raw materials such as limestone and clay. These materials are mined from five location for clay mines and one location for limestone mine. The limestone quarry of PT Semen Tonasa is located in the area of Bulu Jota. WIUP (*Wilayah Izin Usaha Pertambangan*) or Legalized Mine Area of limestone quarry was legalized under 95/I.03/PTSP/2018. Limestones are mined through quarry mining method with daily production target up to 30.000 tonnes.

Limestone mining in PT Semen Tonasa is done through process such as drilling, blasting, loading, hauling, and crushing. PT Semen Tonasa hired 4 vendors to conduct the limestone production through loading and hauling process. Further processing is done through four units of cement factory in the plant site area which adjoined with WIUP of limestone quarry. Limestone production target for each vendor is set by PT Semen Tonasa and are reported daily to the Mine Planning and Evaluation Section of PT Semen Tonasa.

Limestone production report of November 2022 shows that actual production reached 613,809.37 tonnes with production target 645,460 tonnes. This number shows that actual production did not reach the target of November 2022. Detailed evaluation in the mining process is needed to identify failures which responsible to the unattainability of production target.

The most significant factor in economical development in the mining industry is production which is proned to failures (Kumar and Kumar, 2018). Production failures can be caused by equipment, environment, and mining method. Many losses happen because of unidentified failures and low control of failures. Risk analysis can be used as a procedure to identify failures that occurs during mining process and measure its level of effect to the limestone production. A qualitative and quantitative analysis method is needed in order to conduct the risk analysis (Subiantoro, 2007).

In order to identify failure potential, a simulation is needed to predict the deviation between target and actual production with current parameters that are used in the field. This simulation can be done through dynamic modelling. Dynamic modelling can be used to learn the flexible behavior of a complex system, as well as the mining system. Limestone production can be modelled to predict whether the production will increase or decrease, using current parameters that applies in the field. Decrease of production in the future indicates a failure has occurs in the mining system. However, further analysis is needed to identify detailed cause of failure and its level of effect to the system.

Failure identification can be done through FMEA (Failure Mode Effect Analysis). is a systematic technique of identifying, analyzing and preventing product and process problems before they occur (Balaraju, et al., 2019). The output of this method is RPN (Risk Priority Number). The RPN is a reference to provide recommendations to be used as a focus of maintenance and improvement from the biggest types of risk occurred based on its priorities (Suryoputro, et al., 2019).

Dynamic modelling and FMEA are a good combination for detailed risk analysis. Dynamic modelling can be used as simulation method meanwhile FMEA can be used to identify failure potentials in mining process. However, in order to complete the FMEA process, an optimation is needed based on the failure modes. The optimation will be done based on the highest RPN number during FMEA analysis. This concludes the topic of this research will be evaluation of production failure in limestone production.

1.2 Research Problem

Evaluation of failure potentials is important in production management. In order to maintain effective management in production, failures should be calculated and reduced. Failure identification could be done through simulation with dynamic modelling and calculated with FMEA method. By doing so, it is expected that failures could be handled based on its priority, in order to maintain best solution in small amount of time. Therefore, this research questions are:

1. What factors possibly make limestone production failed at PT Semen Tonasa.
2. How does the significance of each factor in causing limestone production failure.
3. What is the improvement plan to prevent and/ or detect limestone production failure.

1.3 Research Purpose

Based on research problem above, aims of this research are:

1. To identify and determine failure mode that causes limestone production failure.
2. To classify failure factors based on their priority
3. To compose the improvement plan that can prevent and/ or detect the limestone production failure.

1.4 Research Advantages

Advantages from this research are research development about risk identification using dynamic modelling and FMEA method, as well with identification of the potential limestone production failure from the company.

1.5 Research Scope

This research includes dynamic simulation and risk analysis of production in limestone mine. Production process is modelled to simulate whether the production rate will increase or decrease, using current production parameters that applies in the field. Simulation results will be used to determine whether risk analysis should be conducted or not. Risk analysis is conducted through root-cause analysis and FMEA. Risk analysis results in RPN based on identified failure modes. Improvement planning is arranged based on failure mode with highest RPN.

CHAPTER II
LITERATURE STUDY

2.1 Sustainable Mining

Sustainable mining is an objective as well as an apparatus for adjusting financial, social, and natural contemplations (Masloboev and Pettersson, 2015). Sustainability index of mining management comprise of social, financial, natural and regulation measurement (Anas et al., 2015). Sustainability science has gotten dynamically more noteworthy consideration around the world, given the developing natural concerns and financial imbalance, both generally coming about from a winning worldwide financial demonstrate that has prioritized benefits. It is presently broadly recognized that mankind ought to receive measures to alter the right now unsustainable generation and consumption patterns (Segura-salazar and Tavarez, 2018).

The implementation of sustainable mining should be emphasised that sustainable development is, in any case, a continuous handle, and not a transitory under-taking. It has clearly characterized objectives and implies of accomplishing them, in all of the over said key ranges. It is expected that these zones are of rise to significance.Hence, the emphasison one area usually leads to a crisis across the entire area of mining activity. Economic growth implies accomplishing long-term sustainability both in regards to planned production volumes, and in accomplishing desires of clients, as well as accomplishing economic efficiency based from the deal of the uncovered mineral. Protection of natural resources and of the environment means concern for the bed and the protection of its resources by its rational acquisition, which is characterised by savings in its depletion. This also means taking measures that minimise the negative impact of the different processes related to the extraction of mineral resources on the various forms of the geological environment and natural environment on the surface (Dubiński, 2013).

There are 11 research agendas that should be maintained in order to investigate pathways of sustainability in mining. This research will prior 2 of these agendas. The first one is investigating of the NGOs perceptions of reality in mining and their involvement in partnerships with mining companies. The role of NGOs in the mining industry is critical; their perceptions of sustainability of the mining industry and their involvement in working together with the mining industry through partnerships require further investigation and analysis. The second one is potential gains for various aspects of sustainability by formally including more of the metals and energy value chains. A number of the papers used the context of value chain and some atrial value chain analyses, particularly broad scale material flow analysis. However, the models to support explicit, formal research for dramatic improvements in material and energy demands in production from ore bodies to commodity reuse and recycling remain elusive. This includes a lack of formal linking of new geological ore body properties to downstream improvements (Moran et al, 2014).

2.2 Quality Management

Quality indicates the capability of all components of an entity to satisfy the stated and implied needs, that a quality item will perform satisfactorily in service, and is suitable for its intended purpose. In any case, to achieve satisfactory quality, we must be concerned with all three stages of the product or service cycle which include (Kiran, 2017):

a. The definition of needs.
b. The product design and conformance.
c. The product support throughout its lifetime.

Quality management like innovation is also a broadly defined topic. Most research, however, agree that the main goal of quality management is to improve and meet stakeholder needs by removing deficiencies including error and rework. While a vast majority of studies view quality management practices as a single variable e.g., quality management on manufacturing capabilities from contries with different cultures (Kull and Wacker, 2010).

The quality management is devided into two different dimensions: social and technical practices. Technical quality management refers to the mechanical methods used by employees of an organization. It is generally defined as practices with a focus on controlling processes and products through tools for the purpose of conforming to and satisfying established requirements. Previous literature defines technical quality management in a variety of ways including process management, preventative maintenance and housekeeping (Schniederjans and Schniederjans, 2015).

Cause and effect diagrams are a problem solving technique developed in 1943 by Ishikawa 'in Japan as a result of workers being confused by the number of factors which influence a process and thus finding it difficult to solve process-related problems. The diagram is developed after brainstorming, by identifying a problem to be solved i.e. effect and the likely causes (Zairi, 1991). This method can be used on any type of problem, and can be tailored by the user to fit the circumstances. Use of this tool has several benefits to process improvement teams (Kiran, 2017):

a. Straightforward and easy to learn visual tool.
b. Involves the workforce in problem resolution—preparation of the fishbone diagram provides an education to the whole team.
c. Organizes discussion to stay focused on the current issues.
d. Promotes "System Thinking" through visual linkages.
e. Prioritizes further analysis and corrective actions.

The main motive of application of the tool is to disembark the various sources/causes that contribute most extensively toward the problem under examination. These causes are then taken for initiating improvement actions. The method also portrays the interactions among the wide range of potential causes of the effect. Figure 1 presents cause and effect analysis. The diagram shows six possible causes, i.e., cause 1, cause 2, cause 3, cause 4, cause 5, cause 6 to a particular event or problem on hand. These causes are connected to a horizontal line which on right-hand side connects to a problem (Sharma, 2021).

After identification of main causes, the subcauses are added to the bones on the main bone represented by the horizontal line. The fundamental notion in the cause and effect analysis is that the "basic problem" of concern is entered at the right side of the diagram at the end. The major possible causes of the problem (known as the effects) are listed on the horizontal line (Sharma, 2021).

The guidelines to construct Cause and Effect diagram (Sharma, 2021):

1. Define the problem or the effect that needs to be studied or examined.

2. Formulate the team of individuals to carry out the analysis. Often, the teams will discover the probable cause through brainstorming.
3. Draw the effect box on right-hand side and the center line.
4. Identify the probable cause categories and join them as boxes connected to the centre line.
5. Identify the probable cause and classify them into the categories and create new subcategories, if necessary.
6. Ranks order these possible causes in order to recognize those that seem almost certainly to affect the problem.
7. Initiate the remedial actions.

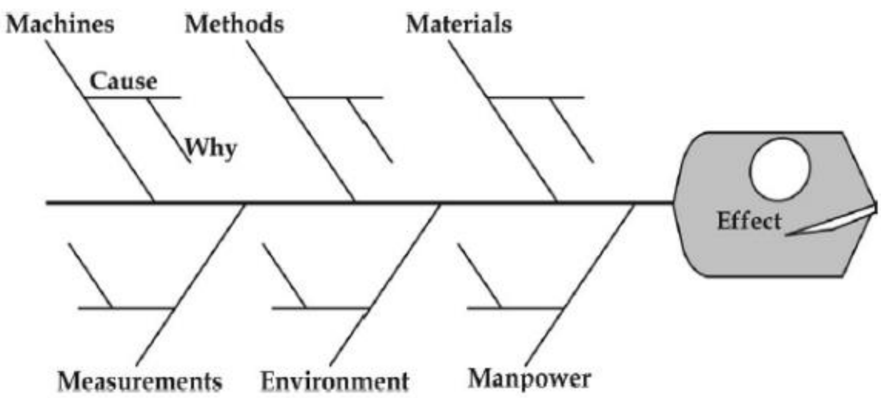

Figure 1 Fishbone diagram (Kiran, 2017)

2.3 Dynamic Modelling

2.3.1 System Dynamics

Simulation is defined as an activity in which the reviewer can draw conclusions about the behavior of a system through the study of harmonious model behavior in which the causal relationship is the same as or as that of the actual system (Eriyatno, 1998). The tool used is SFD as a central concept in dynamical systems theory. Simulations with a wide range of values can offer insight into the behavior of a system. Changes in parameter values can identify parameters whose specific values can significantly affect system behavior (Anas et al, 2017).

The behavior of a system dynamics model is determined by the uniqueness of the model structure that can be understood from the results of model simulation. Simulations are obtained from behavioral analysis and forecasting of behavior, symptoms or processes in the future. Simulation is carried out by incorporating policy factors/policy interventions (according to the desired scenario) into the model that has been built. Simulation is one of the activities in system analysis which broadly includes three activities:

1. Formulate a model that describes the system and the processes occurring in it.
2. Conduct experiments.
3. Use models and data to solve problems.

The starting point of modeling with simulation is to simplify the real system that only pays attention to a few main parts or properties that have a causal relationship of the real system. Simulation is the process of designing a model of a real system and conducting experiments on the model with the aim of understanding the state of the system and or evaluating various operating strategies in the system. Simulation as a system model in which its components are presented by arithmetic processes and logic that are run on computers to estimate the dynamic properties of the system. Simulation involves the generation of processes as well as observations of the process to draw conclusions from the represented system (Suryadi and Ramdhani, 2002). Simulation is an activity to draw the behavior of a system by studying the behavior of models that have similarities with the system (Gottfried, 1984).

Modelling system dynamics requires several steps. These steps should answer questions below (Sterman, 2000):

1. Problem articulation (boundary selection)
   a. Theme selection: what is a problem? Why is it a problem?
   b. Key variables: what are the key variables and concepts we must consider?
   c. Time horizon: how far in the future should we consider? How far back in the past lie the roots of the problem?
   d. Dynamic problem definition (reference modes): what is the historical behavior of the key concepts and variables? What might their behavior be in the future?

2. Formulation of dynamic hypothesis
    a. Initial hypothesis generation: what are the current theories of the problematic behavior?
    b. Endogeneous focus: formulate a dynamic hypothesis that explains the dynamics as endogeneous consequences of the feedback structure.
    c. Mapping: develop maps of causal structure based on initial hypotheses, key variables, reference modes, and other available data, using tools such as
        1) Model boundary diagrams
        2) Subsystem diagrams
        3) Causal loop diagrams
        4) Stock and flow diagrams
        5) Other facilitation tools
3. Formulation of a simulation model
    a. Specification of structure, decision rules
    b. Estimation of parameters, behavioral relationships, and initial conditions
    c. Tests for consistency with the purpose and boundary
4. Testing
    a. Comparison to reference modes: does the model reproduce the problem behavior adequately for the purpose?
    b. Robustness under extreme conditions: does the model behave realistically when stressed by extreme conditions?
    c. Sensitivity: how does the model behave given uncertainty in parameters, initial conditions, model boundary, and aggregation?
5. Policy design and evaluation
    a. Scenario specification: what environmental conditions might arise?
    b. Policy design: what new decision rules, strategies, and structures might be applied in the real world? How can they be presented in the models?
    c. Effect analysis for the possible policy
    d. Sensitivity analysis: how robust are the policy recommendations under different scenarios and given uncertainties?

e. Interaction policyes: Do the policies interact? Are there synergies or compensatory responses?

2.3.2 Causal Loop Diagram (CLD)

Dynamic conditions that cause a risk of continuous failure in the production process can be illustrated by the relationship of variables in the production process which is a system of interrelationships between variables in the form of a variable relationship diagram (causal loop diagram) (Suwandi, et al., 2020).

Majority of system dynamics modelling is discovering and representing the feedback processes, which, along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of a system. The most complex behaviors usually arise from the interactions (feedbacks) among the components of the system (Sterman, 2000).

All dynamics rise from the interaction of just two types of feedback loops, positive and negative. Positive loops are the self-reinforcing part of the system. Negative loops are the self-correcting loops. Positive loops tend to reinforce or amplify conditions in the systems. Negative loops counteract and oppose change. These loops describe processes that tend to be self-limiting. Combination of these loops will lead to equilibrium in the system. The dynamics arise from the interaction of these loops (Sterman, 2000).

In the term of stock flow process, there are inflow and outflow that controls the stock amount. Inflows tend to reinforce or adding the amount of the stock. Increase of inflow will result in increase of stock, and vice versa. Outflow tend to lower the amount of stock. Increase of outflow will result in decrease of stock. Decrease of outflow will result in increase of stock. A simple causal loop is modelled by figure below (Sterman, 2000).

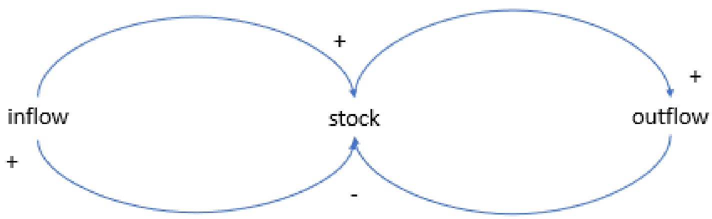

Figure 2 simple causal loop (Sterman, 2000)

2.3.3 Stock Flow Diagram (SFD)

SFD is a central concept in System dynamicss theory. Stock is the accumulation or collection and characteristics of system conditions and information producers, which form the basis of actions and decisions. Stocks are combined with rate or flow as information flow, so that stock becomes a source of dynamic imbalance in the system (Sterman, 2000). Model formulation is the process of translating the concept of a qualitative model into a quantitative model. The simulation model in order to run must be complete with correct mathematical equations, parameters and determination of the initial value conditions into the SFD (Suwandi, et al., 2020).

Stock represents the accumulation or collection and characteristics of the state of systems and information generators on which actions and decisions are based. This stock is combined with rate or flow as a flow of information, so that stock becomes a source of dynamic imbalance in the system. The basis for determining the value of stock and flow is based on integral and differential mathematical equations. This stock is combined with rate or flow as a flow of information, so that stock becomes a source of dynamic imbalance in the system. The basis for determining the value of stock and flow is based on integral and differential mathematical equations. Mathematical equation are explained using converters (Sterman, 2000).

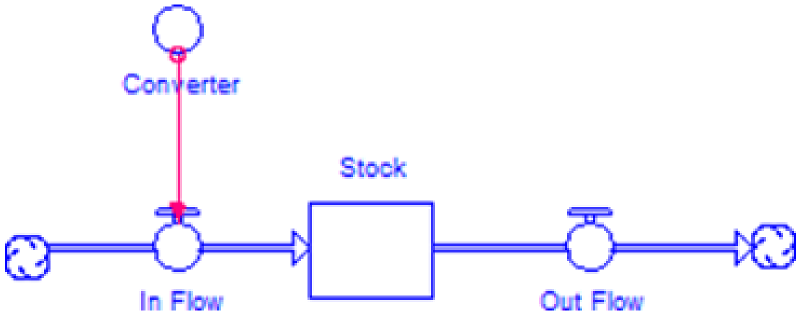

Figure 3 Stock flow diagram (Subiantoro, 2007)

2.4 Productivity Rate

2.4.1 Cycle Time

The average time (T_A) required for a mining shovel to complete one cycle includes loading the dipper, hoisting and swinging, dumping, and returning time. If the time to perform one shovel cycle has been determined, it is possible to calculate that which is really desired, the ideal cycles per shift. With this information and the load per cycle one can calculate the production per shovel shift (Hustrulid, et al., 2013).

2.4.2 Mine Productivity

Rising productivity, alongside exploration, is the principal means by which mining can combat resource depletion. Over the past one hundred and fifty years, the mining industry has been remarkably successful in growing its productivity. However, since 2000, there are signs of a slowdown. Some aspects of this are clearly cyclical but there are increasing concerns that some of the underlying, longer term, factors which have kept productivity growing in the past are losing their force (Humphreys, 2020).

Equipment productivity is the ability of loading equipment to carry out excavation/ loading production in units of BCM/ LCM/ Tonnage per unit (Fiscalaga, Difa et al., 2019). The amount of material unloaded, loaded, and transported by each tool is expressed in terms of the amount of production that can be known using the following equation (Siregar, 2022):

1. Loading Equipment Production

   Loading tools are generally used for material loading work on conveyances and others. Calculations for the production of loaders can be formulated as follows:

$$Q_L = Kb \times \frac{3600}{T_c} \times \text{BFF} \times \text{Eff} \times \text{SF} \quad (1)$$

   Where,

   Q_L = Loading equipment production (BCM/h)

   Kb = Bucket capacity (m^2)

   T_c = Cycle time (seconds)

   BFF = Bucket Fill Factor (%)

   Eff = Efficiency (%)

   SF = Swell Factor (%)

2. Hauling Equipment Production

Transport equipment operations include *loading*, *hauling*, *dumping*, *returning*. To calculate the production of the conveyance, it is related to the amount of filling of the loading equipment and can be calculated using the following equation:

$$Q_H = \frac{3600}{T_c} \times (Kb \times BFF) \times Eff \times SF \quad (2)$$

Where,

Q_H = Hauler production (BCM/hour)

Kb = Bucket capacity (m^3)

BFF = Bucket Fill Factor (%)

T_c = Cycle time (seconds)

Eff = Efficiency (%)

SF = Swell Factor (%)

Going hand in hand with the increasing size and quality of equipment has been an increase in the size of mines. This permitted the deployment of larger and more productive equipment as well as helping to reduce unit costs of production by helping to spread fixed costs over larger tonnages. Scale in mining is, in effect, the equivalent of mass production in manufacturing (Humphreys, 2020). Mining productivity is caused by many factors, such as:

1. Physical properties of material

   The physical properties of rock play significant role in optimization of loading machinery. As the physical properties of rocks are uncontrollable parameters but by knowing them, can design the proper and sustainable method of drilling and blasting in open pit and underground mines (Rezaye, 2019).

2. Front condition

   The dimension and condition of the mining front affect the performance of loading and hauling equipment. Wide mining front dimensions and dry conditions can increase the productivity of loading and hauling equipment.

3. Climate

   Weather is very influential to the working area of mechanical equipment because it will be used to estimate how many days in a year there is rain, so mechanical equipment is not very effective to work when it rains with heavy intensity. This is because the road in the work area becomes muddy and when the dry season causes a lot of dust that makes the work that occurs as a result of direct contact with the outside air in the mining (Arief, 2016).

4. Working efficiency

   The value of a job's success is complicated to determine precisely because it includes several factors such as human factors, machinery and working conditions. The success value of a job is influenced by time efficiency, working efficiency or tool availability to operate and operator efficiency (Arief, 2016).

5. Equipment availability

   The availability of equipments is a key management parameter to be predicted and controlled (Modgil and Sharma, 2016). State that the only way to ensure minimum maintenance costs and a minimal probability of failure is to routinely monitor equipment condition and failures, and to make predictions on the basis of current conditions and historical equipment maintenance and operations (Kothamasu et al., 2006). Equipment availability consists of:

   a. Physical Availability (PA)

      Physical availability (PA) is the proportion of time in which a machine is in an operational conditions. PA is determined by considering stand-by time of equipment. It is defined by the following equation:

$$PA = \frac{Up\ time}{Up\ time + Down\ time} \quad (3)$$

$$Up\ time = operating\ time + stand\ by\ time \quad (4)$$

b. Mechanical Availability (MA)

Obtained by subtracting the stand-by hours from the denominator and numerator in the equation defining operational availablity. It is defined by the following equation (Hustrulid, et al., 2013):

$$MA = \frac{Operating\ hours}{Operating\ hours + Down\ time} \quad (5)$$

6. Match Factor

The match factor itself provides a measure of productivity of the fleet. The ratio is so called because it can be used to match the truck arrival rate to loader service rate. This ratio removes itself from equipment capacities, and in this sense, potential productivity, by also including the loading times in the truck cycle times (Burt and Caccetta, 2018).

A harmonious working relationship between loading equipment and transportation equipment is obtained by managing the productivity of the loading equipment must be in accordance with the productivity of the means of transportation. The working relationship between two or more tools is said to be harmonious if the production of the equipment that serves is the same as the production of the equipment served. The *match factor* calculation formula is as follows (Fiscalaga, et a*l*., 2019):

$$\text{MF} = \text{Na x CTL} / \text{Nm x CTH} \quad (6)$$

Where,

MF = Match Factor

Na = Loader amount (unit)

CTL = Loading cycle time (seconds)

Nm = Hauler amount (unit)

CTH = Hauling cycle time (seconds)

Based on this equation, there are three possible match factor number, namely:

1) MF< 1, The production capability of the loading equipment is greater than the ability of the hauling equipment, so there is a waiting time for the loading equipment
2) MF= 1, The production capability of loading tools is the same as the production capability of hauling equipment, so there is no waiting time

3) MF> 1, The production capability of the means of transportation is greater than the production capability of the means of loading, so there is a waiting time for the hauling equipment.

7. Haul road

   Haul road greatly affects the productivity of loading equipment and its match with hauling equipment (DT). Velocity is authoritative on the cycle time of hauler; therefore the velocity has also been designed in accordance with the design of the haul road (Saputra et al., 2017). Furthermore, haul road geometry will be explained in the next sub-chapter.

2.5 Haul Road Geometry

Haul road width, quite understandably, increased with the increase in the truck size. The haul roads are designed to be 3.5 to 4 times the width of the largest truck using the road. This rule of thumb is intended to provide adequate passing clearance between trucks. More recently, there has been discussion about establishing criteria for what constitutes a safe passing distance. It has been suggested that a fixed minimum clearance distance between trucks is needed because the distance should not be only a function of truck width. Other elements of haul road geometry such as slope of sides, ditch depth, and lift thickness have remained more or less constant over the years (Tannant and Regensburg, 2001).

Various classifications for haul roads exist. Primary or permanent roads are used for longer than six months or are intended for an approved post-mining land use. Ancillary or temporary roads are roads not classified as primary and may be used for exploration access, for in-pit haulage, and for pit access. Other definitions refer to three classes of roads: longer-lived haul roads, pit access roads, and in-pit roads. Mine design involves determination of road parameters such as grade, traffic layout, curves, intersections, and switchbacks. The choice of grade may affect access to the ore body, exposing more minerals for extraction and affecting stripping ratios (Tannant and Regensburg, 2001).

Road planning involved several factors that should be considered. These factors should be considered as it will affect machine performance and productivity rate. These factors are as follows (Tannant and Regensburg, 2001):

a. Stopping Distances

Stopping distances must be calculated for each vehicle and the alignment of the road adjusted to the vehicle with the longest stopping distance.

b. Sight Distances

The sight distance that a driver has must be equal to or greater than the stopping distance of the vehicle. Both horizontal and vertical curves must be planned with this criterion.

c. Road Widths and Cross Slopes

The width of the travelled portion of a haul road is usually calculated as a multiple of the width of the widest vehicle that regularly travels it. On corners, the width will usually be designed wider than the straight stretch to allow for overhang of vehicle on the corner. Cross slopes should be approximately 1:25 to ensure proper drainage off the road.

d. Curves and Super-elevation

Horizontal curves should be designed to ensure that all the vehicles can safely negotiate the curve at a given speed, taking into account sight distance and minimum turning radius. Super-elevation of the curve is required to reduce the centrifugal forces on the truck when it negotiates the corner.

e. Super-elevation Runout

When approaching a super-elevation corner from a straight stretch, there must be a gradual change from level to super-elevation to allow the driver to safely maneuver the truck through the curve.

f. Maximum and Sustained Grade

Grade (steepness) of roads is a function of safety and economics. In most cases, grades will vary between 0 and 12% on long hauls and may approach 20% on short hauls. However, most haul road grades in mines will have a grade between 6% and 10%. It is usually best to design haulage with a long-sustained grade rather than a combination of steeper and flatter sections.

g. Intersections

Intersections should be made as flat as possible and should be avoided at the top of a ramp.

2.5.1 Road Width

The width of haul roads on both straight and curved sections must be adequate to permit safe vehicle manoeuvrability and maintain road continuity. Since the size of equipment that travels on haul roads varies significantly from mine to mine, vehicle size rather than vehicle type or gross vehicle weight are best used to define road width requirements. In the past, for straight road segments, it was recommended that each lane of travel should provide clearance on each side of the vehicle equal to one-half of the width of the widest vehicle in use (AASHO, 1965).

Roads that are too narrow can drastically reduce tire life by forcing the truck operator to run on the berm when passing another vehicle. This results in sidewall damage, uneven wear, and cuts. This is a particular problem when an operator adds new larger trucks to an existing fleet but does not change the road layout to accommodate the wider trucks (Tannant & Regensburg, 2001).

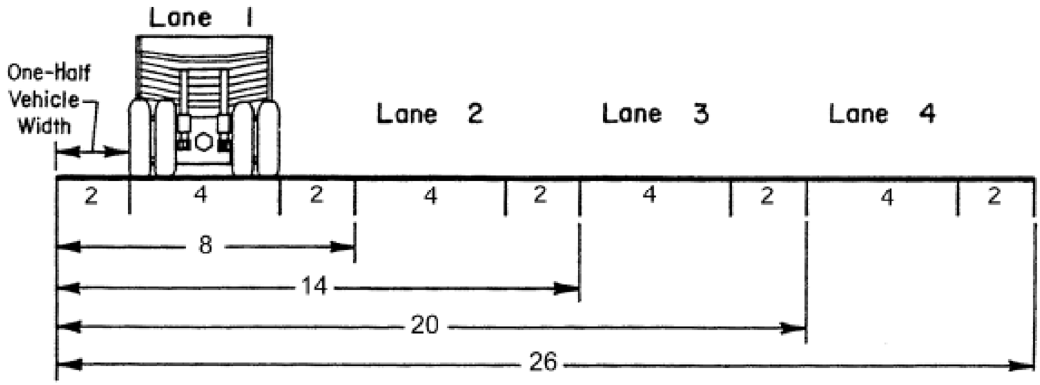

Figure 4 Relation between road width and number of traffic lanes with distances in metres (Tannant & Regensburg, 2001)

The minimum width of running surface for the straight sections of single and multi-lane roads can thus be determined from the following expression (Tannant and Regensburg, 2001):

$$W = (1.5L + 0.5) + X \quad (7)$$

Where,

W = width of running surface (m)

L = number of lanes

X = vehicle width (m)

Additional road width in excess of the minimum determined from Equation (7) might be required locally along the road alignment, for example (Tannant and Regensburg, 2001):

a. To accommodate equipment larger than the primary road users, such as shovels or draglines,
b. To allow sufficient room for vehicles to pass on single lane roads, and
c. If, on single lane roads, the sight distance is less than the stopping distance, sufficient space must be provided for moving vehicles to avoid collision with stalled or slow-moving vehicles.

2.5.2 Curves

Switchbacks or other areas on haul roads requiring sharp curves must be designed to take into consideration the minimum turning radius of the haul trucks. A wider road is required on curves to account for the overhang occurring at the vehicle front and rear. The procedure for determining road width on curves to account for vehicle overhang, lateral clearance between passing haul trucks and extra width allowance to accommodate difficult driving conditions on curves is shown on the following equation (Tannant and Regensburg, 2001).

$$Wt = 2(I + Fa + Fb + Z) + C \quad (8)$$

$$C = Z = \frac{U + Fa + Fb}{2} \quad (9)$$

Where,

Wt = Curve width (m)

U = Track width of vehicle (center-to-center tires)

Fa= width of front overhang

Fb = width of rear overhang

C = Total lateral clearance

Z = extra width allowance due to difficulty of driving curves

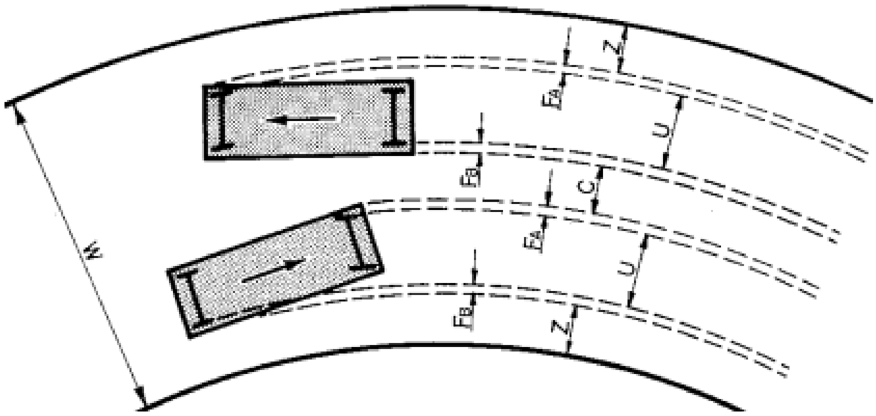

Figure 5 Curve design (Tannant and Regensburg, 2001)

Horizontal haul road alignment addresses the required width and super-elevation of the road to enable vehicles to safely negotiate around curves at a given speed taking into account sight distance and minimum vehicle turning radius. The cost implications of physical constraints to construction, such as quantity of rock excavation necessary, must also be considered in laying out the curve (Tannant and Regensburg, 2001).

Curve and switchback design should include consideration of truck performance. Haul roads designed for constant speed will allow trucks to perform to their potential. The truck performance may have a greater influence on mining costs than the initial road construction costs. Poorly designed curves that slow the cycle time can add thousands of dollars in haulage cost each day (Tannant and Regensburg, 2001).

The maximum potential speed of the truck is a function of the grade plus rolling resistance. For curves on roads where the grade is greater than zero, design the curve radius for the fastest truck, which is usually the truck going downhill. Therefore, curve radius can be calculated using following equation (Tannant and Regensburg, 2001).

$$R = \frac{V^2}{127(e+f)} \qquad (10)$$

Where,

R = curve radius (m)

V = vehicle speed (km/hr)

e = super-elevation (m/m)

f = coefficient of friction between tires and road surface

2.5.3 Super-elevation

Negotiating curves can generate high lateral tire forces. These forces contribute to high tire wear and ply separation. Super-elevating the curve helps eliminate these forces. Ideally, tire wear would be reduced and steering would be effortless if road super-elevation was just equal to the vehicle weight component. There is a practical limit to which a road can be super elevated since high cross-slopes around curves can, for slow moving vehicles, cause higher loads on the inside wheels, increased tire wear, potential bending stresses in the vehicle frame and, on ice covered surfaces, vehicle sliding down the cross-slope (Tannant and Regensburg, 2001).

Super-elevated curves present a danger when the road surface is slippery. Unless the proper speed is maintained, a vehicle may slide off of the lower edge of the roadway. For this reason, super-elevation over 10% should not be used. Super-elevated curves should be maintained in good tractive conditions. Choosing the ideal super-elevation is guided through the following table (Tannant and Regensburg, 2001).

Table 1 Super-elevation based on vehicle speed

Turn	Vehicle Speed							
Radius (m)	10 mph	15 mph	20 mph	25 mph	30 mph	35 mph	40 mph	45 mph
15.2	13%	-	-	-	-	-	-	-
30.5	7%	15%	-	-	-	-	-	-
45.7	4%	10%	-	-	-	-	-	-
61	3%	8%	13%	-	-	-	-	-
91.5	2%	5%	9%	14%	-	-	-	-
152.4	1%	3%	5%	8%	12%	16%	-	-
213.4	1%	2%	4%	6%	9%	9%	15%	-
304.9	1%	2%	3%	4%	6%	8%	11%	14%

Source: Tannant and Regensburg (2001)

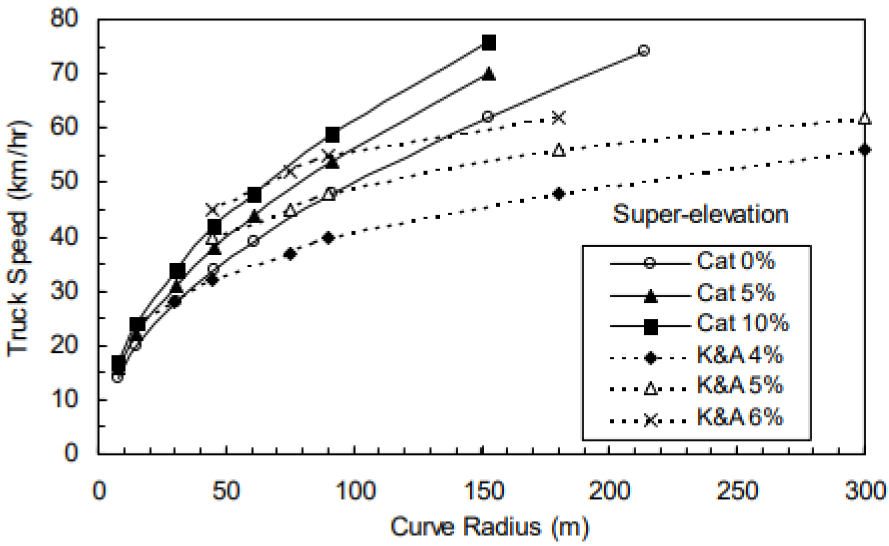

Figure 6 Curve of super-elevation versus vehicle speed (Tannant and Regensburg, 2001)

2.6 Risk Analysis

Sustainability Opportunity and Threat Analysis is another simple operational tool addressing the social, economic, and environmental dimensions of the issues under consideration and it can be applied to evaluate the viability of a mining operation and its ability to contribute to sustainable development objectives. An impact-based model of sustainable mine development is shown in Figure 2.2. This analysis involves constructing inventory of sources of impacts and following key steps including (Chattopadhyay and Chattopadhyay, 2012):

1. Scoping (addressing the reasons for the mining process and the environment, and agreeing to the scope of the exercise).
2. Information gathering (to emphasize the importance of collecting and organizing relevant information into a suitable framework).
3. Identifying risks (systematically reviewing impact areas under consideration, and identifying opportunities or threats).
4. Analyzing and evaluating the risks (qualitative scales of likelihood and consequence can be assigned to identify opportunity or threat to create overall risk rating and prioritized list).
5. Treating risks (control measures to address opportunities or threats considered high priority).

6. Reporting and reviewing to represent a broad, scanning exercise that can be picked up by existing business planning and monitoring processes. It also provides an opportunity for subsequent evaluation of relevant metrics for the issues identified by the process, allowing operations to measure both impacts and progress toward agreed objectives.

Risks are determined in terms of the likelihood that an uncontrolled event will occur and the consequences of that event occurring. The above relationship is used in both qualitative and quantitative risk analysis methods. A quantitative risk analysis method is a probabilistic estimation of risk where risk is calculated as a continuous series from high to low. A qualitative risk analysis method is a basic estimation where risks are typically ranked from high to low. Risk assessment and analysis techniques and tools consist of a systematic, logical set of actions used to identify hazards, assess risk, and implement controls to mitigate high-risk conditions. These techniques and tools can be described by their levels of formality, the types of analysis performed, and the work processes they are attempting to address (Ostrom and Wilhelmsen, 2012).

The most fundamental risk assessment activity, called an informal risk assessment, occurs when workers are asked to think about the hazards in the workplace before work commences, determine what could go wrong, and report or fix the hazards. More formal risk management activities require structured procedures, often focusing on work processes that involve multiple levels of an organization. These activities are practiced at some mines and are typically organized by an operations safety official and developed with the help of individuals familiar with the work practice in question. Higher level risk management activities focus on major mining hazards or on major changes in the mining operations involving the entire organization, such as reopening a mine, moving to a new location within the mine, and utilizing a new mining technique or process (Ostrom and Wilhelmsen, 2012).

There are several categories of risk analysis, such as (Ostrom and Wilhelmsen, 2012):

1. Informal Risk Assessment Techniques

   Most informal risk assessment techniques consist of multiple steps where the worker is asked to look for hazards, determine the significance of the hazard, and take some action to mitigate the risk. Many systems have been proposed and are widely used in mining.

2. Basic-Formal Risk Assessment Techniques

   Basic-formal risk assessment techniques are characterized by the requirement to follow a structured process that occurs prior to performing specific higher risk work activities. These techniques also require documentation that allows management to monitor and audit individual risk assessment activities. The most commonly used basic-formal risk assessment technique is the Job Safety Analysis (JSA). A JSA typically leads to development of Standard Operating Procedures (SOP) that define how to best approach a task considering the hazards identified in the JSA. An SOP is a set of instructions that act as a directive, covering those features of operations that lend themselves to a standardized procedure. An SOP is typically a set of instructions or steps a worker follows to complete a job safely and in a way that maximizes operational and production requirements. SOPs can be written for work processes by the individual or group performing the activity, by someone with expertise in the work process, or by the person who supervises the work process.

3. Advanced-Formal

   Advanced-formal risk assessment techniques require the use of a structured approach that incorporates one or more risk analysis tools and produces a documented assessment of the risk associated with unwanted events.

One of the basic-formal assessment method is Failure Mode and Effect Analysis (FMEA). Example of the application of the FMEA approach where the risks to the environment, workers and the public associated with the closure of a mine were identified. This was accomplished by developing a FMEA worksheet for potential unwanted events post-closure of the mine (Ostrom and Wilhelmsen, 2012).

2.7 Failure Mode Effect Analysis (FMEA)

FMEA (Failure Mode and Effect Analysis) is a systematic method of identifying and preventing product and process problems before they occur. FMEAs are focused on preventing defects, enhancing safety, and increasing customer satisfaction. Ideally, 17 FMEAs are conducted in the product design or process development stages, although conducting an FMEA on existing products and processes can also yield substantial benefits (McDermott, et al., 2009)

Unlike many quality improvement tools, FMEAs do not require complicated statistics, yet they can yield significant savings for a company while at the same time reducing the potential costly liability of a process or product that does not perform as promised. FMEAs do take time and people resources. Because FMEAs are team based, several people need to be involved in the process. The foundation of FMEAs is the FMEA team members and their input during the FMEA process. Companies must be prepared to allow the team enough time to do a thorough job. Effective FMEAs cannot be done by one person alone sitting in an office filling out the FMEA forms. Automotive customers and ISO auditors today can easily spot an FMEA that was done just to appease the customer and fulfill standards requirements (McDermott, et al., 2009).

The FMEA process is a way to identify the failures, effects, and risks within a process or product, and then eliminate or reduce them. The relative risk of a failure and its effects is determined by three factors (McDermott, et al., 2009):

a. Severity is the consequence of the failure should it occur.
b. Occurrence is the probability or frequency of the failure occurring.
c. Detection is the probability of the failure being detected before the impact of the effect is realized.

Using the data and knowledge of the process or product, each potential failure mode and effect is rated in each of these three factors on a scale ranging from 1 to 10, low to high, a risk priority number (RPN) will be determined for each potential failure mode and effect. The risk priority number (which will range from 1 to 1,000 for each failure mode) is used to rank the need for corrective actions to eliminate or reduce the potential failure modes. Those failure modes with the highest RPNs should be attended to first, although special attention should be given when the severity ranking is high (9 or 10) regardless of the RPN factors (McDermott, et al., 2009).

$$\text{RPN} = \text{severity} \times \text{occurence} \times \text{detection} \tag{11}$$

Improvement of productivity has become an important goal for mining industries in order to meet the expected targets of production and increased price competitiveness. Productivity can be improved in different ways. The effective utilization of men and machinery is one such way. Equipment is prone to numerous unexpected potential failures during its operation. Failure Mode and Effect Analysis (FMEA) is one of the suitable techniques of reliability modeling used to investigate the failure behavior of a complex system (Balaraju et al., 2019).

2.7.1 Failure Modes

Failures are not limited to problems with the product. Because failures also can occur when the user makes a mistake, those types of failures should also be included in the FMEA. Anything that can be done to ensure the product works correctly, regardless of how the user operates it, will move the product closer to 100% total customer satisfaction. Ways in which a product or process can fail are called failure modes. Each failure mode has a potential effect, and some effects are more likely to occur than others. In addition, each potential effect has a relative risk associated with it. The FMEA process is a way to identify the failures, effects, and risks within a process or product, and then eliminate or reduce them (McDermott, et al., 2009).

Identifying the failure modes was described as one of the main challenges for conducting an FMEA. Identified problems include a lack of information on the actual or 21 potential asset failure, which in turn lead to difficulties in making detailed distinctions between failure modes and identifying possible causes (Braaksma et al., 2013).

Failure modes are investigated at the system's sub-component level, according to the desired level of depth in the analysis. For each failure mode a severity (S), occurrence (O) and detection (D) rating is defined and rated according to subjectively defined scales, based on available information and supported by expert opinion and evaluation. The rating system involves expert opinion and a level of subjectivity which is typical of rating systems based on a scale defined by the user (Colli, 2015).

Use of dynamic modelling takes part as qualitative phase in an analytical process. In the qualitative phase, it starts with the observation of the systems under consideration before identifying the model objectives. Then, systems approach and analysis are applied to the observed systems by selecting properly all relevant entities and variables to the objectives in order to have a simplified and well-defined system. In the next step, a causal loop diagram is developed which is then transformed into a stock and flow diagram. During the quantitative phase, the stock and flow diagram is translated to a simulation program using SD software for developing dynamic models. Once the initial models are gathered, they are iteratively verified and validated to obtain sufficient models (Rasjidin, et al., 2014).

2.7.2 FMEA Procedure

An FMEA (Failure Mode and Effect Analysis) is a systematic method of identifying and preventing product and process problems before they occur. FMEAs are focused on preventing defects, enhancing safety, and increasing customer satisfaction. Ideally, FMEAs are conducted in the product design or process development stages, although conducting an FMEA on existing products and processes can also yield substantial benefits (McDermott, et al., 2009).

Purpose of an FMEA is preventing process and product problems before they occur is the purpose of Failure Mode and Effect Analysis (FMEA). Used in both the design and manufacturing processes, they substantially reduce costs by identifying product and process improvements early in the develop process when changes are relatively easy and inexpensive to make. The result is a more robust process because the need for after-the-fact corrective action and late change crises are reduced or eliminated (McDermott, et al., 2009).

A formal FMEA process should be a part of a comprehensive quality system. While FMEAs can be effectively used alone, a company will not get maximum benefit without systems to support conducting FMEAs and implementing improvements that are a result of the FMEAs. For example, one element of a comprehensive quality system is effective use of data and information.

Without reliable product or process data the FMEA becomes a guessing game based on opinions rather than actual facts. The result may be that the FMEA team focuses on the wrong failure modes, missing significant opportunities to improve the failure modes that are the biggest problems. Another example that supports the need for a comprehensive quality system is documentation of procedures (McDermott, et al., 2009).

The objective of an FMEA is to look for all of the ways a process or product can fail. A product failure occurs when the product does not function as it should or when it malfunctions in some way. Failures are not limited to problems with the product. Because failures also can occur when the user makes a mistake, those types of failures should also be included in the FMEA. Anything that can be done to ensure the product works correctly, regardless of how the user operates it, will move the product closer to 100 percent total customer satisfaction (McDermott, et al., 2009).

The relative risk of a failure and its effects is determined by three factors (McDermott, et al., 2009):

a. Severity - the consequence of the failure should it occur
b. Occurrence - the probability or frequency of the failure occurring
c. Detection - the probability of the failure being detected before the impact of the effect is realized

Using the data and knowledge of the process or product, each potential failure mode and effect is rated in each of these three factors on a scale ranging from 1 to 10, low to high. By multiplying the ranking for the three factors a risk priority number (RPN) will be determined for each potential failure mode and effect. The risk priority number (which will range from 1 to 1,000 for each failure mode) is used to rank the need for corrective actions to eliminate or reduce the potential failure modes. Those failure modes with the highest RPNs should be attended to first, although special attention should be given when the severity ranking is high (9 or 10) regardless of the RPN. Therefore, calculating RPN can be done using Equation 4 (McDermott, et al., 2009). The valuation for severity, occurrence, and detection is as shown in Table () (Stamatis, 2019).

Table 2 Severity valuation

Effect	Description	Rate
None	No effect noticed by customer. The failure will not have any effect on the customer	1
Very minor	Very minor disruption to production line. A very small portion of the product may have to be reworked. Defect noticed by discriminating customers	2
Minor	Minor disruption to production line. A small portion (<5%) of product may have to be reworked online. Process up but minor annoyances	3
Very low	Very low disruption to production line. A moderate portion (<10%) of very low product may have to be reworked online. Process up but minor annoyances.	4
Low	Low disruption to production line. A moderate portion (<15%) of product may have to be reworked online. Process up but some minor annoyances.	5
Moderate	Moderate disruption to production line. A moderate portion (>20%) of product may have to be scrapped. Process up but some inconveniences.	6
High	Major disruption to production line. A portion (>30%) of product may have to be scrapped. Process may be stopped. Customer dissatisfied.	7
Very high	Major disruption to production line. Close to 100% of product may have to be scrapped. Process unreliable. Customer very dissatisfied.	8
Hazard with warning	May endanger operator or equipment. Severely affects safe process operation and/or involves noncompliance with government regulations. Failure will occur with warning.	9
Hazard with no warning	May endanger operator or equipment. Severely affects safe process operation and/or involves noncompliance with government regulations. Failure occurs without warning.	10

Source: Stamatis, 2019

Table 3 Occurrence valuation

Occurrence	Description	Frequency	Rate
Remote	Failure is very unlikely, no failures associated to similar processes	<1 in 1,500,000	1

Occurrence	Description	Frequency	Rate
Low	Few failures. Isolated failures associated with like processes	1 in 150,000	2
		1 in 15,000	3
		1 in 2000	4

Moderate	Occasional failures associated with similar processes, but not in major proportions.	1 in 400	5
		1 in 80	6
High	Repeated failures. Similar processes have often failed.	1 in 20	7
		1 in 8	8
Very high	Process failure is almost inevitable.	1 in 3	9
		>1 in 2	10

Source: Stamatis, 2019

Table 4 Detection valuation

Detection	Description	Rate
Almost certain	Process control will almost certainly detect or prevent the potential cause of subsequent failure mode	1
Very high	Very high chance process control will detect or prevent the potential cause of subsequent failure mode	2
High	High chance the process control will detect or prevent the potential cause of subsequent failure mode.	3
Moderate high	Moderately high chance the process control will detect or prevent the potential cause of subsequent failure mode.	4
Moderate	Moderate chance the process control will detect or prevent the potential cause of subsequent failure mode.	5
Low	Low chance the process control will detect or prevent the potential cause of subsequent failure mode	6
Very low	Very low chance the process control will detect or prevent the potential cause of subsequent failure mode	7
Remote	Remote chance the process control will detect or prevent the potential cause of subsequent failure mode	8
Very remote	Very remote chance the process control will detect or prevent the potential cause of subsequent failure mode	9
Very uncertain	There is no process control or the control will not or cannot detect the potential cause of subsequent failure mode	10

Source: Stamatis, 2019

Once corrective action has been taken, a new RPN for the failure is determined by reevaluating the severity, occurrence, and detection rankings. This new RPN is called the “resulting RPN.” Improvement and corrective action must continue until the resulting RPN is at an acceptable level for all potential failure modes (McDermott, et al., 2009).

There are 10 steps that should be fulfilled for an FMEA, those are (McDermott, et al., 2009):

1. Review the process or product
2. Brainstorm potential failure modes
3. List potential effect of each failure modes
4. Assign a severity ranking for each effect
5. Assign an occurrence ranking for each failure modes
6. Assign a detection ranking for each failure modes
7. Calculate the RPN number for each effect
8. Prioritize the failure modes for action
9. Take action to eliminate or reduce the high-risk failure modes
10. Calculate the resulting RPN as the failure modes are reduced or eliminated

The FMEA process should be documented using an FMEA worksheet. This form captures all of the important information about the FMEA and serves as an excellent communication tool. Some organizations have their own format for the FMEA worksheet. Others will adapt this form to meet their needs. A numbering system to track and access FMEA previously conducted projects is helpful. The numbering system should enable cross-referencing to similar FMEAs as well as other improvement activities dealing with the same product or process (McDermott, et al., 2009).