Volume 4, No. 5 May 2025
p-ISSN 2980-4868 | e-ISSN 2980-4841
https://ajesh.ph/index.php/gp

Strategy to Improve Coal Mining Operation Productivity In Weak Material Challenge Using Dmaic and Lean Six Sigma Method: A Case Study Of Warukin Formation At South Borneo, Indonesia

Firda Tubagus Ismail[1], Gatot Yudoko[2]
Institut Teknologi Bandung, Indonesia
Emails: Firda_ismail@sbm-itb.ac.id[1], gatot@sbm-itb.ac.id[2]

ABSTRACT
Prepared working area, downtime, limited actual hauler had significant increase in equipment waiting time which has an impact on the less than optimal productivity of the 200-ton class excavator with the potential impact of lost sales revenue opportunities each year of up to USD 13.6 million. Geological conditions with the Warukin Formation & Alluvium Deposits have challenges related to limited working areas, material strength conditions, road formations, and sustainability of operations. This study discusses the improvement strategies needed to increase excavator productivity and optimize the performance of its supporting unit equipment so that it can achieve production targets precisely and accurately. The method used is the DMAIC (Define, Measure, Analyze, Improve & Control) and LSS (Lean Six Sigma) methods to determine a systematic framework to increase the productivity of Coal Mining Equipment and encourage sustainable Mining Operational practices. There are 12 root causes based on observations of the 3 aspects that most affect the productivity of equipment performance, namely management of material, technical, and supervision. The actual productivity of 200-ton excavator is 665/hour with a Sigma Level value of 1.9 and Cpk value of 0.14. The achievement of the productivity of 200-ton excavator has a significant correlation and have incremental impact with Speed 45.45%, Match Factor 40.43%, and Condition Material 10.56%. Multivariate regression analysis has been carried out on the actual condition of loader productivity and is known to have an R-sq value of 81.36% to explain the condition of actual process in the field. Based on the implementation of improve geometry of hauling road overburden, it can increase the achievement of the productivity target by >700 bcm/hour, increase in the CpK value to 0.89 and Sigma Level to 3.37. Further improvement activities are still needed in accordance with the improvement scenario matrix of the 3 factors so that mining operations on soft materials can still achieve optimal and appropriate productivity.

Keywords: Mining Equipment Productivity, Improvement Strategy, Lean Six Sigma, SMART Analysis.

INTRODUCTION

PT. Borneo Indobara is a coal mining industry with an open pit mining method that is gradually increasing its annual production target each year to optimize the coal reserves needed for the development of the national and global industry. The company has been uses 50 units of

200-ton class excavators and 390 units of 100-ton haulers. The future challenge is that PT. Borneo Indobara will be faced with many problems with the availability of disposal areas and mining road conditions. Changes in the position and morphological conditions of sequence mining activities will directly impact the high level of mining road formation. The limited material with good strength is an obstacle that must be faced and managed so that mining activities continue to run optimally. The increasing population of mining equipment will create new risks, both the risk of road density, the risk of the number of road intersections, the risk of road durability, the risk of unattainable production and even risks to operational safety (Figure 1).

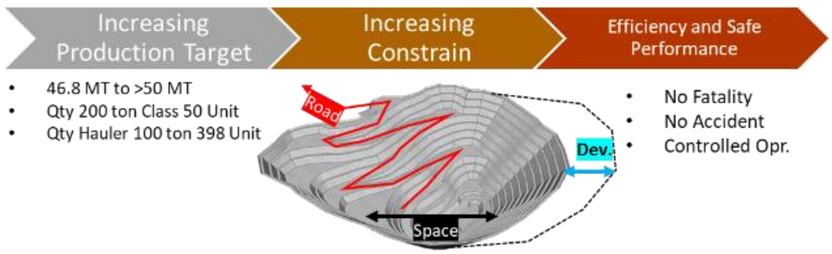


Figure 1. Overview Challenge Coal Open Pit Mine based on the risk of working space and road density

The use of 200-ton class excavator heavy equipment is expected to be able to achieve the monthly and annual targets that have been set while maintaining the population of the number of heavy equipment working in the mining area. Based on record productivity data from Pit GRB on period January – July 2024 show that the average of productivity was occurred at 665 bcm/h. The productivity results of the loader are very much a concern so efforts are needed to be able to increase its productivity capacity from 665 bcm/h increase up to reaching >700 bcm/day (Figure 2). If these productivity issues continue until the end of the year, there is a potential deviation in performance and production failure that could reach 1.35 million bcm, equivalent to the potential for coal extraction work of 260 thousand tons in 2024. Financially, this could result in the company losing potential sales revenue of up to USD 13,626,600 annually, assuming a coal price of $52.41 per ton.

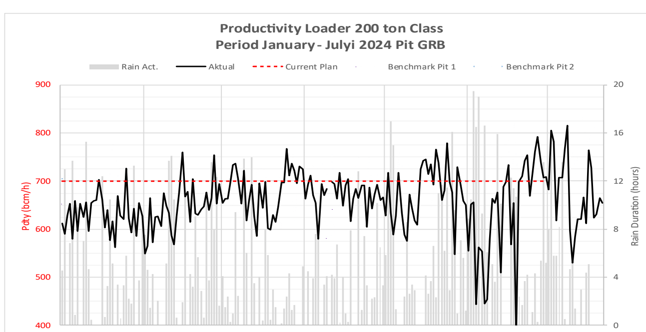


Figure 2. The Record of Productivity Loader 200 ton Class at PT. Borneo Indobara

This is a serious challenge for PT. Borneo Indobara to optimize the performance of heavy equipment to achieve the company's annual targets that increase every year, reduce risk from population and make the production efficient. Mining equipment productivity is a crucial research area, encompassing technical, financial, and even non-technical evaluations (Edy C.H.S et al., 2024). Edy et al. (2024) highlight hauling overburden, loading overburden, and hauling coal as the largest fuel consumers, impacting financials and the environment. I Nyoman D.K. (2024) studied that road condition analysis (qualitative and quantitative) enables real-time data evaluation and targeted analysis, emphasizing adherence to the match factor plan for optimal productivity. Dabbagh et al. (2019) showed that optimizing the match factor (loader/hauler availability) via linear programming can increase production by 10.6%. Ramadan et al. (2024) researched standardizing mining roads based on hauler units. Optimizing hauler cycle time and support equipment involvement can improve excavator performance. Further research using Lean Six Sigma can identify waste and lag time impacting equipment performance.

RESEARCH METHOD

Research Design

This study applies the DMAIC (Define, Measure, Analyze, Improve, Control) methodology, a structured approach widely used to solve problems and enhance business processes. The method was used to address productivity issues with a 200-ton excavator, as outlined in Figure 3. DMAIC was chosen for its ability to systematically identify problems, analyze root causes, and implement effective solutions. According to Jacob et al. (2018), DMAIC focuses on clearly defining and improving problems to meet specific targets. In contrast, Lean Six Sigma emphasizes minimizing data variation, or precision. Each phase of DMAIC serves a distinct purpose and employs various analytical tools to support process improvement. The following sections detail each stage as applied in this study.

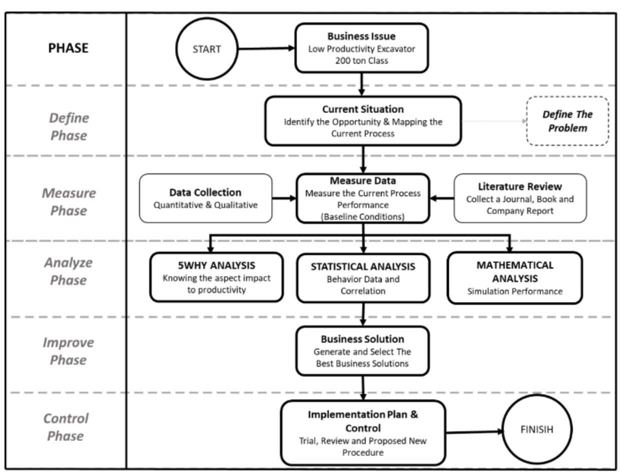


Figure 3. DMAIC & Lean Six Sigma Research Design (Author, 2024)

Define Phase

In this phase, the analysis is conducted to determine the limitations, objectives and scope of discussion of the root causes that occur in the case of 200-ton digging equipment productivity. Collecting and mapping of secondary data recording related to the work activities of 200-ton class loader equipment were carried out such as data of production, data speed of hauler, data availability units, data hour repair units and actual loss time data recording. The data explains how the relationship between the recorded data is related to time constraints and additional time that affects the productivity of the equipment.

Measure Phase

In the Measure phase, measurements of actual productivity of loader, actual speed of hauler, actual measurement of road quality, actual productivity of dozer and actual matching factor fleet and hauler, were obtained to be correlated with other secondary data. Capability analysis was conducted to determine the actual condition before the improvement.

Measurement Productivity of Hauler

Cycle Time is defined as the time required by any equipment to complete one operating cycle. Wait time, delays and operator efficiency all impact cycle time. Total cycle time is the combination of fixed time and travel time. Fixed time occurs in unit manoeuvring activities, material filling time, and material dumping time. In accordance with Samwel Victotmanyele (2017) the total cycle time for the truck was appointed as per Equation :

$$T_{ct} = T_q + T_{sp} + T_{ld} + T_{fh} + T_{dp} + T_{hg} + T_{eh} \quad (1)$$

Where T_{ct} : Total Truck Cycle Time, T_q : queuing time at the excavator, T_{sp} : spotting time, T_{ld} : loading time, T_{fh} : full haul time, T_{dp} : dumping time, T_{hg} : hanging time and T_{eh} : empty haul time.

So to determine the hauler productivity value, it is calculated using the following equation:

$$Q_H = \left(\frac{60}{T_{ct}}\right) x \text{ Payload} \quad (2)$$

where Q_H is bcm/hours, T_{ct} is Total Truck Cycle Time (s), Payload is Total Vessel Capacity based on Result Survey Sampling Measurement (bcm).

Measurement Productivity of Loader

In assessing the productivity of the loader unit in material excavation activities, it is necessary to know the definition of the difference between Bank and loose properties. Hastrulid (2013) explains that the assessment of swell properties, percent swell and swell factor can be known by the following formula:

$$Swell = \frac{bank\frac{weight}{unit}volume}{loose\frac{weight}{unit}volume} \quad (3)$$

$$Swell\ Factor\ = \frac{1}{swell} = \frac{loose\frac{weight}{unit}volume}{bank\frac{weight}{unit}volume} \quad (4)$$

In one cycle of the excavator work, the time calculation is done starting from when the bucket does digging, hoisting and swinging, dumping and returning until lowering is ready for digging (T cycle). To estimate the productivity of digging in a unit of time, it is calculated using the following equation:

$$\textbf{Bank Volume/ hour} = \boldsymbol{Q_{cl}\ x\ \left(\frac{3600}{T_{cl}}\right) x\ Job\ Efficiency} \quad (5)$$

Where, Q_{cl} is Bucket Capacity (bcm), Where, $\boldsymbol{T_{cl}}$: Cycle Time of Loader(s), Job Efficiency : Mechanical Availability x Utilities Availability.

Measurement Productivity of Dozer

Dozer productivity is determined by various factors including material conditions, operator ability, pushing speed, pushing distance and the capacity of the blade used (Klanfar & Kujundžić, 2014). The listed influences are not measured, and they can also vary significantly from case to case.

$$T_{cd}\ =\ l_c\left(\frac{1}{Vt} + \frac{1}{Vo}\right) +\ 2\ t_m \quad (6)$$

Where, T_{cd} : Cycle Time Dozer (s), Vt : speed forward (m/s), Vo : speed backward (m/s), l_c : length of dozing (m), t_m : time of change speed/gear (s).

$$Q_d = \frac{3600\ x\ V}{T_{cd}} \text{ x Material Condition} \quad (7)$$

Where, Q_d : Productivity Dozer (Bcm/h), T_{cd} : Cycle Time Dozer (s), V : Volume of Blade (m^3), Material Condition is Qualification of material condition of saturation that impact to Blade Fill Factor (Table 1).

Table 1. Blade fill Factor based on Surface Material Condition

Work Condition	Surface Material Condition	Blade Fill Factor
Easy	Full blade of soil can be dozed as completely loosened soil. Low water contented, no-compacted sandy soil, general soil, stockpile material	1.10 - 0.90
Average	Soil is loose, but impossible to doze full blade of soil. Soil with gravel, sand, fine crushed rock	0.90 - 0.70
Rather Difficult	High water content and sticky clay, sand with cobbles, hard dry clay and natural ground	0.70 - 0.60
Difficult	Blasted rock, or large pieces of rock	0.60 - 0.50

Analyze Phase

Primary data was obtained from theoretical calculations related to the specifications of the main and supporting equipment currently used in the mining area of PT. Borneo Indobara. For secondary data obtained from data recording loss gain productivity, the data was processed using Statistical Analysis to determine the relationship between parameters. The 5Why and Pareto methods are used to quantify aspects that have an influence on the productivity of the 200-ton class loader. Forum Group Discussion (FGD) were conducted with several parties with the aim of finding out important aspects that need to be considered by field personnel so that the improvements made can be known as the focus of each party. The participants in this data collection are Operation Manager, Operation Supervisor, Engineering Manager, Trainer & Plant Manager.

Data Analysis Methods

Data analysis was carried out on several aspects related to the productivity of 200-ton class equipment. The initial step taken was to conduct data analysis on data recording in the period January - July 2024. From these data, further analysis will be carried out in the form of a comparison with theoretical calculations related to the adequacy of supporting equipment. Data analysis related to the recording of the speed of the transport unit against the road geometry is carried out to determine the characteristics of the operator in increasing or decreasing its speed. The combination of these analyzes will later look for relationships and opportunities for improvement that can be carried out with existing resource conditions.

Statistical Data Analysis

At this stage, all data from the analysis results are considered and a correlation analysis is made between variables. The correlation is expected to be able to answer the relationship between mining work productivity and the constraint factors that cause loss time. Multivariate analysis is carried out to determine the relationship of various improvements applied depending on the challenges faced. The results of this statistical analysis are expected to be able to provide a better and more efficient mining management forecast. So that mine planners can determine the optimal mine management strategy and mining sequence adjusted to the availability and capabilities of units in the mining area.

Improve Phase

In the improve phase, possible solutions that can support the increase in productivity of the 200-ton loader will be processed and selected. The data will be tested and verified related to the advantages, disadvantages, threats and opportunities that can be formed from each option. The results of the test will be submitted to be applied in a small project so that the impact on increasing productivity can be known.

Comparative Production Calculation Result for truck match with loader is done by Mathematical Simulation so that the productivity impact that will be obtained can be known. Simulation of the use of support tool ratio, determination of hauler model and cycle time improvement is done to achieve the most optimal improvement option. Improvement investment is calculated and simulated against the financial benefits that will be obtained by the company by making improvements.

Control Phase

In the control phase, primary and secondary data collection is still carried out to determine the impact of implementing solutions on increasing the productivity of 200-ton class loader equipment. The results can be monitored in the form of dashboard reports and standard operating procedure updates that can be documented and their consistency is known to be applied comprehensively to 200-ton productivity in the PT. Borneo Indobara area.

RESULT AND DISCUSSION

Identify the Opportunity of Improvement

Loss-time recording is divided into loss-time recording due to scheduled and unscheduled events. The focus of this study is to determine the loss-time that occurs in the schedule event which has an impact on decreasing the productivity of mining equipment. The results of data recording in the period January - July 2024, it is known that the performance unit experienced many complex obstacles so that there was a failure to achieve production operations. The following is the proportion of production loss time that has occurred in the GRB Pit work area of PT. Borneo Indobara (Figure 4).

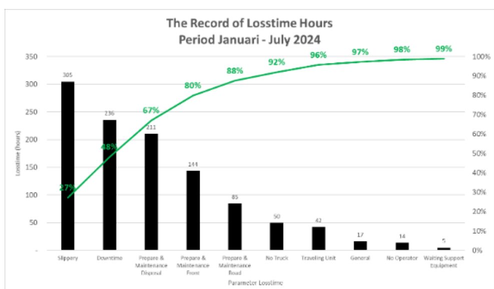


Figure 4. Pareto Analysis Loss-time Hours Activities of Loader

Table 2. The deviation actual and budget time plan of losstime parameter

No	Parameter	Plan Budget Time (h)	Actual Time (h)	Deviation Actual vs Plan	
				Time (h)	%
1	Prepare & Maintenance Disposal	42	244	202	581%
2	Prepare & Maintenance Road	24	85	61	354%
3	Prepare & Maintenance Front	42	144	102	343%
4	Slippery	291	305	14	105%
5	Downtime	486	236	-250	49%

If we see the total time accumulation at top 5 activity, the problem of work area preparation is the main problem that falls into the category of controllable problems. The deviation between actual losstime compared to the budget losstime in planning at the 5 biggest factors causing losstime, it is known that Prepared Disposal has a deviation of up to 5x greater and Prepared & Maintenance Road has a deviation of 4x higher than the planned losstime that has been planned as Standard Parameter Operational (Table 2). Both of these things are the topic of this study to find out the root of the problem that can be fixed so that it can provide optimal productivity achievement.

Define Phase

This study examines the productivity of a 200-ton class excavator in an overburden pit. and the research seeks to improve productivity up to the point of exposed coal. The study is limited to solutions applicable by the mining contractor within the soft material strength pit area. Pre- and post-stripping activities (land clearing, un-topsoiling, coal getting, hauling, and shipping) are excluded (Figure 7).

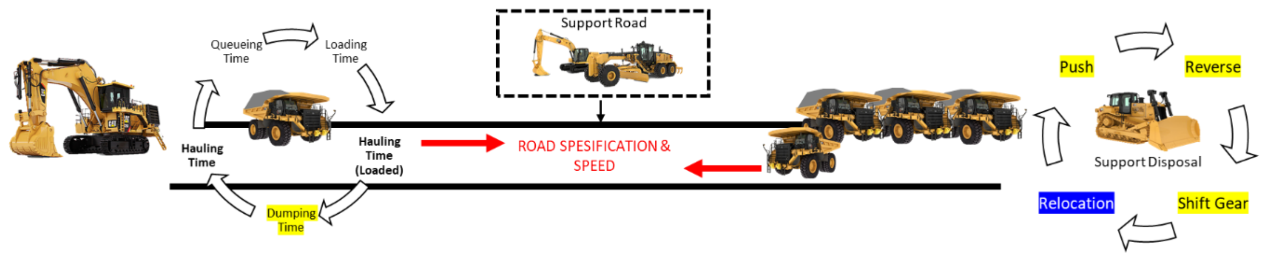


Figure 6. Scope of Study

So that in order to focus on improving the aspects of the mining operational process that will be carried out, then the limitations of the discussion of this study are as follows:

Table 3. Scope of Work of Study

Parameter	In Scope	Out of Scope
Working Area	PT. Borneo Indobara Mining Area (Pit GRB) with Characteristic Warukin Formation & Alluvium Material	Other Mining Area and Mining Contractor in PT. Borneo Indobara.
Operational Business Process	Stripping Overburden Activities from digging material, material transportation, dumping activity until readiness exposed coal getting area	Before and after stripping overburden activity such as Land Clearing, Untopsoiling, Coal Getting, Coal Hauling and Coal Shipping
Discussion Boundary	Focus on the purposed solution to improve the overburden productivity on Loader 200 ton class	Other discussion outside of Overburden Performance Problem

Measure Phase

In the measurement phase, measurements were taken on the productivity parameters of loader, hauler and dozer equipment. The objective of this phase is to know and to understand parameter that affects performance, measure phase cover Measurement System Analysis like as Table 3 below.

Table 3. Measurement System Analysis

Determine Measurement Parameter	The metrics would be measured for this project were productivity loader, productivity hauler, and productivity dozer.
Determine Measurement System	Project use data weekly plan and review report. Type Data: Measurement Objective: Analyze Data
Data collection & Determined Baseline	a. Weekly Observation Data from Monitoring Deck on Period January – July 2024. b. Upper Specific Limit (USL) Productivity Loader was set 700 Better for company, and Lower Specific Limit (LSL) was determined 650 as the minimum productivity. c. USL Match Factor was set 1 Better for company, and LSL was determined 0.95 as the minimum tolerance for impact to productivity. d. USL Speed was set 20 Better for company, and LSL was determined 17 as the minimum tolerance for impact to productivity.

Capability Process Productivity of Loader & Hauler

The actual average productivity of the loader reaches 665 bcm/hour and on average is still above the LSL. For the target of achieving productivity of 700 bcm/hour, the loader performance process has a Process Capability value with a Cpk Value of 0.14 (<1.13) which indicates that the productivity of the loader activity is still not optimal and there are still poor processes. Based on the DPMO value, it shows that the loader work process still has 366.667 ppm defects or is at the sigma level of 1.8 (Figure 6). In the work cycle of the loading equipment, various factors that need to be considered in knowing the productivity planning of the loading equipment are distance, vessel capacity, unit speed and unit spotting and dumping time. Control in monitoring the productivity of the transport equipment is consistency related to the speed of the equipment applied. The following are the results of observations of hauler speed in the period January - July 2024 with a target speed of 20 km / hour. The consistency of the hauler unit speed can be seen from the Cpk value of 0.20 with DPMO value of 433.333 or is at sigma level 1.7 (Figure 7).

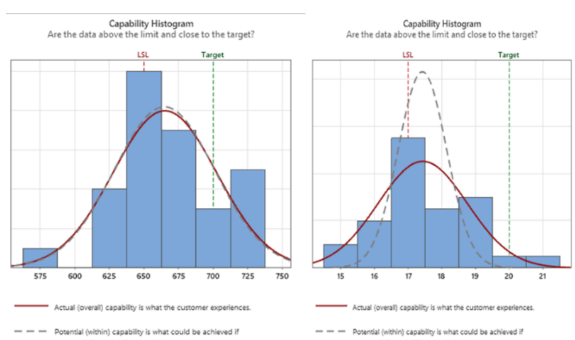


Figure 6. Capability Process of Productivity Loader (Left) & Hauler (Right)

The following is attached the results of observations of the productivity recording of the 100-ton hauler which is a partner of the 200-ton loader against the Mining Activity Distance (Figure 7).

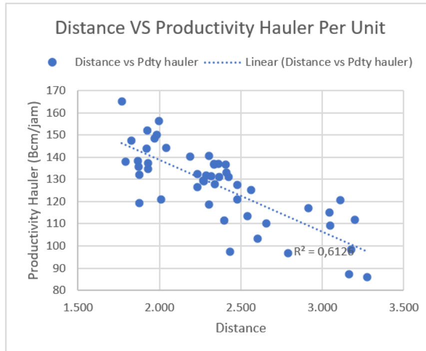


Figure 7. The Graph Correlation Pdty. Hauler and Hauling Distance of Hauler 100 ton Class

Therefore, the calculation and analysis of the compatibility of the unit is known as the calculation of the match factor (MF). Based on observations of actual observation data on actual loader productivity, actual speed, actual payload, and actual loss-time that occurs, the MF recording can be seen in the Figure 8 below:

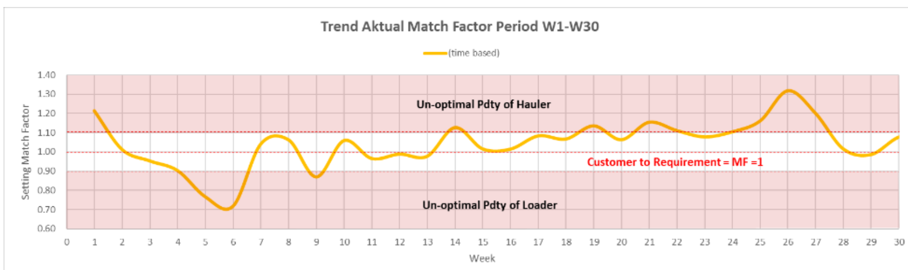


Figure 8. Weekly Trend of Match Factor Actual

The calculation of the unit compatibility requirement is carried out to ensure that the arrangement of the hauler unit requirement can meet the loader unit requirement in a balanced manner with an MF value of 1. MF>1 indicates the potential for excess haulers which has an impact on the existence of truck queues to wait for the part in the process of filling the overburden material load. Therefore, the baseline condition before the improvement related to loader productivity, match factor and hauler speed has a Mean, Cpk value and sigma level which can be seen in Table 4.

Table 4. Capability Process at Actual Condition period January – July 2024

Capability Process	Before Improvement					Remark
	Mean	% Out of Spec	DPMO	Cpk	Sigma Level	
Productivity Loader	665	34	343,597	0.14	1.90	Poor Control/ Not Acceptable
Match Factor	0.94	21	207,792	0.43	2.31	Poor Control/ Not Acceptable
Speed	17.4	37	372,382	0.20	1.83	Poor Control/ Not Acceptable

Productivity of Dozer

Dozer productivity is greatly influenced by various factors including push distance, blade size, push speed and shifting gear, and the condition of the material being pushed. The condition of the material being pushed affects the blade fill factor, so that dozer productivity will be corrected along with changes and differences in the type of material. Based on theoretically and field observations, it was known that the dozer unit used in the research area has the following capabilities as Figure 9. The dozer cycle time is greatly influenced by the type of material it is pushing. When the dozer cycle time requires a pushing time of >2.2 minutes for one pile of material. Then the condition of the material is indicated as soft material and/or there is an increase in water saturation in the material.

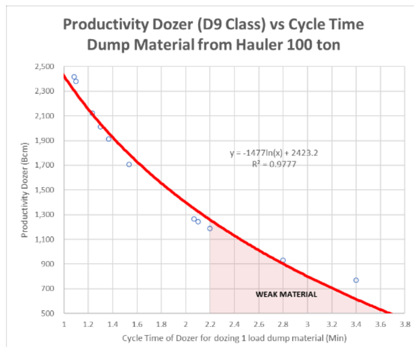


Figure 9. Correlation Productivity and Cycle Time of Dozer D9 from hauler 100 ton.

Based on the type of unit specifications, the dozer production capacity of various units in the research area can be seen in the table 5 below.

Table 5. Observation Dozer Capacity

No.	Type Unit Dozer	Ground Pressure (kPa)	Productivity Dozer (bcm/h)
1	D10	145.3	1215
2	D9	115.8	832
3	D8	52.3	800
4	D6	49	711

The condition of the material being pushed affects the blade fill factor, so that dozer productivity will be corrected along with changes and differences in the type of material. The use of dozer equipment must be adjusted to the condition of the material and its ground pressure, so that dozer performance will be more optimal and avoid other operational constraints such as dozer units collapsing, ineffective dozer cycle time and reduced dozer productivity.

Analyze Phase

It was known that the loader productivity of loader has the lowest CpK value of 0.14 and is included in the operational activity process that is categorized as Poor Control (Table 4). Therefore, further analysis is needed to determine the root cause of the low productivity of the loader and the low sigma level value.

Root Cause Analysis with 5 Why Method

Root cause analysis has been conducted using the 5 why method. The failure to achieve production is influenced by 2 things, namely effective working hour (EWH) and mining equipment productivity. The focus that will be detailed in this study is on the aspects that are the causes, either directly or indirectly, related to the low achievement of loader equipment productivity due to support for supporting equipment activities with low sigma level values. Based on the results of Forum Group Discussions with engineering and operational parties regarding the evaluation of production achievement, the focus of the root cause analysis is focused on 3 main problems, namely problems related to material conditions, transport equipment work cycles and work supervision. There are 12 root causes identified as root causes that need to be followed up so that improvements can be made. The root cause analysis diagram can be seen in the image below.

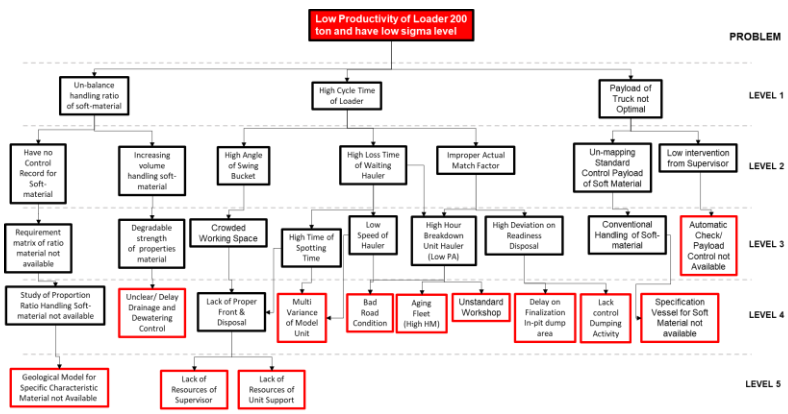


Figure 10. Root Cause Analysis with 5 why method of Low Performance Loader

Based on the analysis, the root of the problem can be grouped according to their respective categories according to controllability and the relevance of their concerns, which can be seen in the table 6 below.

Table 6. Matrix Root Caused Analysis

No.	Root Cause	Controllability	*Concern To*
1	Geological Model for Specific Characteristic Material not Available	Controllable	*Material Ballance*
2	Unclear/ Delay Drainage and Dewatering Control	Controllable	*Material Ballance*
3	Lack of Resources of Supervisor	Controllable	*Out of Concern*
4	Lack of Resources of Unit Support	Controllable	*Material Balance & Unit Ratio*
5	Multi Variance of Model Unit	*Un*-Controllable	*Out of Concern*
6	Bad Road Condition	Controllable	*Speed & Material Ballance*
7	Aging Fleet (Loader & Hauler)	Controllable	*Match Factor*
8	Un-standard Workshop	*Un*-Controllable	*Out of Concern*
9	Delay on Finalization In-pit dump area	*Un*-Controllable	*Out of Concern*

10	Lack Control Dumping Activity	Controllable	*Material Balance & Unit Ratio*
11	Specification Vessel for Soft Material not available	Un-Controllable	*Ouf of Concern*
12	Automatic Check/ Payload Control not Available	Un-Controllable	Out of Concern

The root of the problem is related to the concern of the Matching fleet settings based on the availability of loader & hauler units, the availability of the ratio of support units to handle the material conditions faced, and the availability of roads to accommodate the optimal speed of the hauler unit. For the root of the problem that falls into the un-controllable and out of concern categories of this study, no further analysis was carried out.

Back Analysis of The Correlation Actual Performance Unit Loader

This analysis is conducted to determine the relationship between loader productivity and various factors that influence the actual productivity value including material conditions, hauler settings and the influence of hauler speed. The following are the correlation results of each factor:

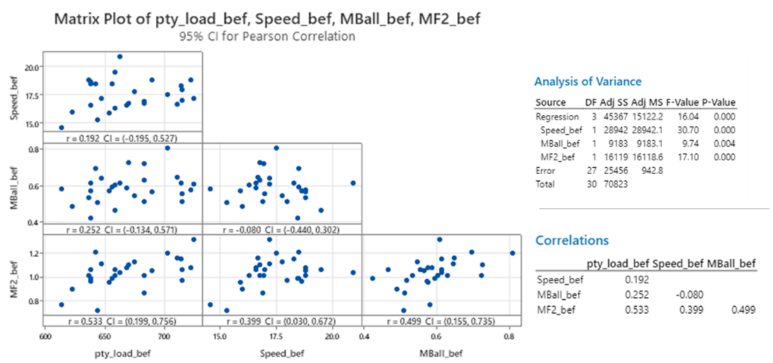
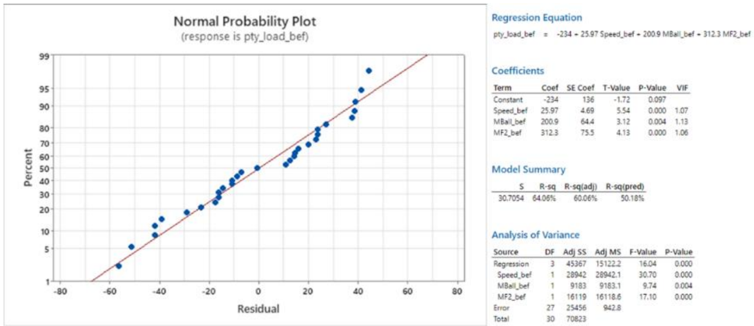


Figure 11. Correlation and Analysis of Variance for Speed, Material Balance and Match Factor.

Based on the above observations, it shows that the condition of material balance, the matching of fleet and hauler tool settings, and the speed of the hauler unit have a significant positive correlation to loader productivity (Figure 11). Multivariate regression analysis has been carried out on the actual condition of loader productivity and is known to have an R-sq value (Before Optimization) of 64.06% (Figure 12) and R-sq value (After Optimization) of 81.36% (Figure 13). That value can explain the condition of the model that is close to the actual process in the field.

Data processing of back analysis was conducted using a population of 124 result from production recording data on productivity load, speed of hauler and match factor data. The normality test for that variables produced P-Value of < 0.05 indicating that the data follows a normal distribution. Multicollinearity testing has been conducted on the regression model with these variables, the results of the test show that the Variance Inflation Factor (VIF) values for all variables are below 2, indicating the absence of strong multicollinearity. Analysis of variance (ANOVA) shows that the overall model is significant, with an F-value of 16.04 and a p-value of

0.000, which means that the independent variables together have a significant effect on the dependent variable.



Regression Equation

pty_load_bef = -234 + 25.97 Speed_bef + 200.9 MBall_bef + 312.3 MF2_bef

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-234	136	-1.72	0.097	
Speed_bef	25.97	4.69	5.54	0.000	1.07
MBall_bef	200.9	64.4	3.12	0.004	1.13
MF2_bef	312.3	75.5	4.13	0.000	1.06

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
30.7054	64.06%	60.06%	50.18%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	45367	15122.2	16.04	0.000
Speed_bef	1	28942	28942.1	30.70	0.000
MBall_bef	1	9183	9183.1	9.74	0.004
MF2_bef	1	16119	16118.6	17.10	0.000
Error	27	25456	942.8		
Total	30	70823			

Figure 12. The model Multiple Regression for Productivity of Loader Before Adjusted.

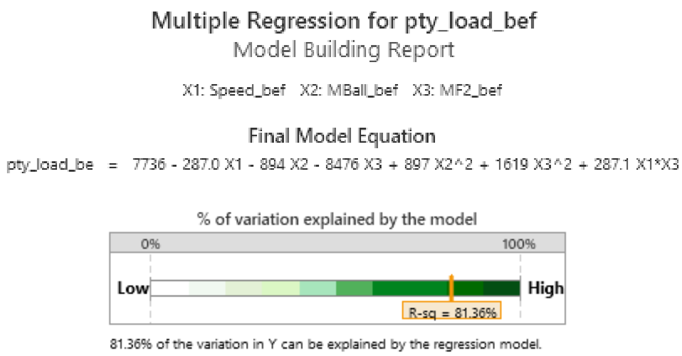


Figure 13. The Fit model Multiple Regression for Productivity of Loader After Adjusted (Optimize)

The following are the results of the fit model between the results of the regression analysis model and the actual conditions of the 200-ton class loader (Figure 14). In the week 16 data, it is known that there is a fairly high anomaly because in that condition there is a rain condition that exceeds normal rain. However, in general, the trend pattern at each time is still close to the model value explained previously.

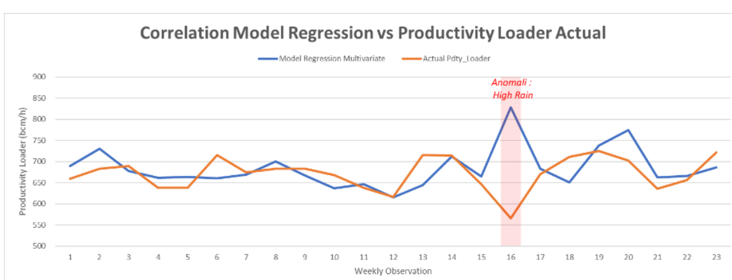


Figure 14. Correlation Model Regression vs Productivity Loader Actual

Improve Phase

Referring to the magnitude of the impact of each factor on loader productivity, it was known that the speed of the hauler unit is the factor that had the greatest impact on increasing loader productivity by 46.45%. The second factor is the compatibility of the loader and hauler tools which had an influence of up to 40.43%. While the Material Balance between the 3 factors had an influence on loader productivity of 10.56% (Figure 15).

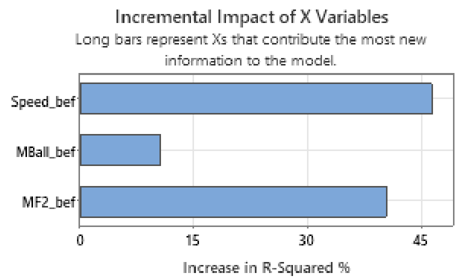


Figure 15. Distribution Impact of X Variable to Productivity of Loader

The list of improvements that can be used as options to make improvements according to the concern of improvement is as follows:

Table 7. Estimate Decision Analysis & Priority for Improvement

No	*Concern of Improvement*	*Leading Activity*	*Target*	*I**	*T***	*C****	Priority
0	*Un-improvement*	*No Improvement Occurred*	*as usual*	*L*	*L*	*L*	N/A
1	*Speed*	Improve All Road Geometry	width 30 m (Base 25 m)	*H*	*H*	H	1
2	*Speed*	Improve Road Segregation 50 km/jam	> 20 km/jam (Base 17 km/jam)	*H*	*M*	H	2
3	*Speed*	Upgrade Road Surface	Gravel Treatment	*H*	*L*	M	3
4	*Speed*	Increasing Ratio Unit Support Ratio	Ratio 1.3 (Base Ratio 1.0)	*H*	*L*	L	8
5	*Match Factor*	Additional/Replace Hauler to increase Matching Fleet Allocation	MF 1.05 (Base 0.94)	*M*	*L*	L	9
6	*Match Factor*	Build Proper Workshop to Increasing PA unit Hauler	PA 90% (Base PA 85%)	*M*	*L*	M	5
7	*Match Factor*	Implementation Fleet Management System	Opt. Semi-Auto Control (Base Manual)	*H*	*L*	L	4
9	*Material Balance*	Supply Good Material for Road & Dump Ballance	Score Material Condition 0.6	*M*	*L*	L	7
10	*Material Balance*	Improve Drainage System and Handle Soft Material	Ratio Dozer >1.0	*M*	*L*	M	6
Notes : *I = Impact, **T = Timing, ***C= Cost							

The determination of the assessment is based on the weight of the aspects of impact, timing and cost (Table 8). The aspects of impact and cost are the most important aspects in this assessment. The assessment mapping uses the following references:

Table 8. Estimate Scoring of Concern Evaluation

Evaluation	Code		Score	Notes
Impact (35%)	H	High	3	Potential High Impact
	M	Medium	2	Potential Medium Impact
	L	Low	1	Potential Low Impact
Timing (32%)	H	High	3	Quick Time to Finish
	M	Medium	2	Moderate Time to Finish
	L	Low	1	More Take Time to Finish
Cost (33%)	H	High	3	Low Add. Capital & Operational Cost
	M	Medium	2	Medium Add. Capital & Operational Cost
	L	Low	1	More Add. Capital & Operational Cost

SMART Analysis

The results of the priority value estimation from several evaluations related to the impact, timing and cost required, it is known that the solution of Concern of Improvement on the Speed factor is included in the 3 main priorities (Table 9). In mining operations, Safety and Production are factors that must be prioritized in every policy or improvement plan. So that these factors are normalized weight so that each factor is considered proportionally (Table 10).

Table 9. Alternative Solution for improvement

Option	Alternative Solution
1	Improvement Haul Road Geometry from minimum width 25 m to 30 m
2	Improvement Road Segregation for increasing Maximum Segment Road Speed from max. 40 km/h to 50 km/h
3	Upgrade Segment Road Surface - Semi All Weathered (Gravel Treatment)

Table 10. Normalized weigh of Value

No	Value	Original Weight	Normalized Weight
1	Production	90	27%
2	Duration	75	22%
3	Technical	50	15%
4	Safety	100	30%
5	Sustainability	20	6%
Total		335	100%

Mining roads are actually divided into 2 based on their duration of use, namely main roads that have a usage time of > 6 months up to LOM and mining roads that are relatively quickly moved due to the need for moving according to the mining sequence. Therefore, the sustainability attribute has the smallest weight value. It is expected that every mining road that is made can provide significantly to the achievement of production and safety. The aggregate results of the weighted value of the 3 alternative solutions can be seen in the table 11 below.

Table 11. Aggregate of Weighted Value for the solution

Option	Attribute					Aggregate of Weighted Value
	Production	Duration	Technical	Sustainability	Safety	
	27%	22%	15%	6%	30%	

1	75	85	92.5	75	97.5	86.57
2	80	90	85	80	77.5	82.24
3	82.5	90	72.5	87.5	92.5	85.97

The determination of the aggregate value of weight value is carried out through discussions with the operational and engineering teams directly involved in mining operational activities. The results of the observation of the assessment of alternative solutions are known that Alternative solution number 1 related to the widening of the standard geometry of the road has a higher aggregate value than other options, namely 86.57. This has considered various attributes related to aspects of the impact on production, the duration of the speed of road repairs, technical convenience, safety support and the influence of the benefits of the sustainability of its operational activities.

Control Phase

This phase is the final stage of the DMAIC method which is a follow-up to the discussion of the improvement phase. In the period August - December 2024, the implementation of Alternative Solution 1 has been carried out, with changing the minimum geometry of the road on all mine access roads from 25 meters to 30 meters on 3 Pit hauling roads. The fulfilment of the completeness of support unit ratio was prepared using 1.3 from the workload Grader and Dozer as a the best practice evaluation reference around the actual mining area. The response to increasing loader productivity has increased to reach the target compared to the conditions before implementing alternative 1 (Figure 16).

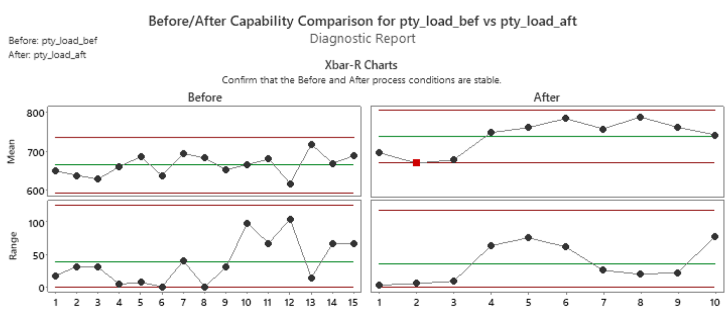


Figure 16. Before/After Capability Comparison for Control of Productivity Loader

The result of observation matrix from implementation solution 1 shows that the response control not all can control acceptable (Table 12). Still needed other better controls in the form of real-time recording, digitalization, and implementation of fleet management system to achieve accurate and precise work control results.

Table 12. Capability Proses Before and After Improvement

Control of	Before Improvement					Remark
	Mean	% Out of Spec	DPMO	Cpk	Sigma Level	
Match Factor	0.94	21	207,792	0.43	2.31	Poor Control/ Not Acceptable
Speed	17.4	37	372,382	0.20	1.83	Poor Control/ Not Acceptable

Road Quality	62.4	65	645,433	0.25	1.13	Poor Control/ Not Acceptable
Material Ballance	0.60	51	512,761	0.01	1.47	Poor Control/ Not Acceptable
Productivity Loader	665	34	343,597	0.14	1.90	Poor Control/ Not Acceptable
Control of	**After Improvement**					**Remark**
	Mean	**% Out of Spec**	**DPMO**	**Cpk**	**Sigma Level**	
Match Factor	1.07	8.90	88,991	0.52	2.85	Poor Control/ Not Acceptable
Speed	19.3	0.76	7,608	1.39	3.93	Acceptable Control
Road Quality	83.3	4.17	41,741	0.96	3.23	Control not Capable
Material Ballance	0.57	59.43	594,340	0.08	1.26	Poor Control/ Not Acceptable
Productivity Loader	738	3.05	30,472	0.89	3.37	Control not Capable

In figure 17 we can see that when speed control has the potential for increase and decrease, then the step that must be taken is to adjust the match factor reference between the hauler and loader to keep MF> 1.05 prepared. The condition of MF <1 will have a significant impact on the decrease in the productivity of the 200 ton loader.

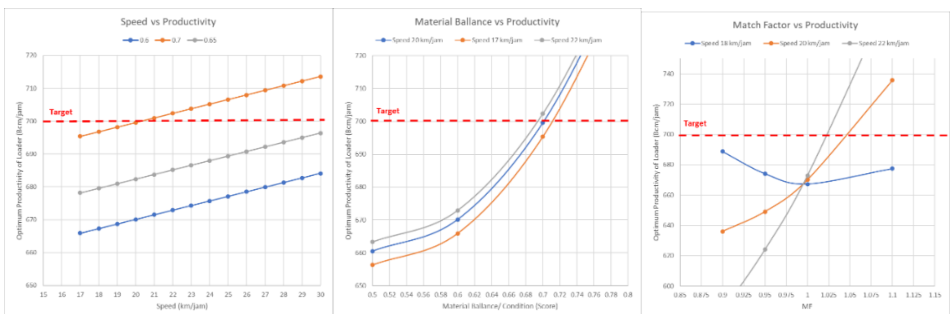


Figure 17. Forecast Correlation Speed, MF and Material to achieve Target Loader Productivity

In figure 18 we can observe that the actual overall loader performance has increased after the implementation of improvements to be more stable and higher than its regression model. The MAPE value of the regression model after the improvement control is carried out shows a value of 4.3% which means have highly accurate forecasting. These references are expected to be able to be a reference in conducting future performance evaluations both in manual management and digital work control or the implementation of a fleet management system.

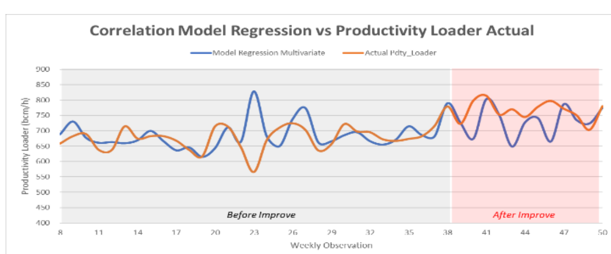


Figure 18. Actual achievement of Loader 200 ton vs Model Forecast Regression

The implementation increase in speed on Hauling Road Pit GRB on 2025 can significantly increase loader productivity with a potential additional Revenue of up to USD 1.14 million with MF 1.0, but the target productivity of 700 bcm/h cannot reach consistency. If the availability of haulers can be met up to MF > 1.05, then the target productivity of > 700 bcm / h will be achieved and can provide potential revenue from additional exposed coal areas ranging from USD 4.8 - 12.4 million (Table 15). So this is worth considering to increase loader productivity and provide optimal match factors.

Table 15. Simulation Potential Additional Revenue by Road Improvement

SIMULATION MF 1.00

Object	Skenario	Forecast Productivity	MF	MatBall	Speed	Jumlah Fleet	Yearly Production	Deviation with baseline	Potential Additional Exposed	Potential Additional Revenue $
Jl. Segregasi Sanjaya	No Improvement	666	1.00	0.6	17.4	2	6,055,637.28			
	Alternatif 1 Option	669	1.00	0.6	19.3	2	6,079,806.04	24,168.76	3,462.57	USD 177,214
	Alternatif 2 (Jl. Segregasi)	677	1.00	0.6	24.79	2	6,149,592.82	93,955.54	13,460.68	USD 688,918
Jl. OPD GH	No Improvement	666	1.00	0.6	17.4	3	9,083,455.92			
	Alternatif 1 Option	669	1.00	0.6	19.3	3	9,119,709.06	36,253.14	5,193.86	USD 265,822
	Alternatif 2 (Jl. Segregasi)	671	1.00	0.6	20.64	3	9,145,364.08	61,908.16	8,869.36	USD 453,934

Notes : ICI 4, $51.18/ton

SIMULATION MF 1.05

Object	Skenario	Forecast Productivity	MF	MatBall	Speed	Jumlah Fleet	Yearly Production	Deviation with baseline	Potential Additional Exposed	Potential Additional Revenue $
Jl. Segregasi Sanjaya	No Improvement	659	1.05	0.6	17.4	2	5,990,045.45			
	Alternatif 1 Option	688	1.05	0.6	19.3	2	6,254,002.83	263,957.39	37,816.24	USD 1,935,435
	Alternatif 2 (Jl. Segregasi)	772	1.05	0.6	24.786	2	7,016,174.12	1,026,128.68	147,009.84	USD 7,523,964
Jl. OPD GH	No Improvement	659	1.05	0.6	17.4	3	8,985,068.17			
	Alternatif 1 Option	688	1.05	0.6	19.3	3	9,381,004.25	395,936.08	56,724.37	USD 2,903,153
	Alternatif 2 (Jl. Segregasi)	709	1.05	0.6	20.645	3	9,661,193.69	676,125.52	96,866.12	USD 4,957,608

Notes : ICI 4, $51.18/ton

CONCLUSION

Operational improvement of mining equipment by implementing DMAIC and Lean Six Sigma methods can provide a measurable and systematic picture of changes in the performance improvement of 200-ton excavators from sigma level 1.9 to 3.37 with an average achievement above 700 bcm/hour. This is very useful for assessing how much influence the control has on the achievement of performance improvement. The cause of the low performance of the 200-ton excavator is known to be due to low effective working hours and productivity, primarily from work area preparation and repairs. Root cause analysis identified material conditions, transport cycles, and supervision as key issues, stemming from inadequate fleet matching, support unit ratios, and road conditions.

Mine road conditions have a direct positive correlation with hauler speed, while effective deployment of support units enhances hauler efficiency and improves loader match factors. Dozer operations in disposal areas must consider material type and water management to maximize capacity and reduce loader delays. Key strategies for achieving the target loader productivity of 700 bcm/hour include controlling material moisture, optimizing support unit allocation, maintaining equipment availability, improving road conditions (aiming for speeds over 20 km/h and wider roads), real-time fleet management, specialized handling of soft materials, and the use of segregated roads to increase hauler speeds.

REFERENCES

Dabbagh, A., & Bagherpour, R. (2019). Development of a Match Factor and Comparison of Its Applicability with Ant-Colony Algorithm in a Heterogeneous Transportation Fleet in an Open Pit Mines. Journal of Mining Science, 55(1), 45–46. Pleiades Publishing Ltd.

Dowdy, S. M., Wearden, S., & Chilko, D. (2004). Statistics for research. John Wiley & Sons.

Jacobs, F. R., & Chase, R. B. (2018). Operations And Supply Chain Management (15th ed.). McGraw-Hill Education.

Kęsek, M., Bogacz, P., & Migza, M. (2019). The application of Lean Management and Six Sigma tools in global mining enterprises. IOP Conference Series: Earth and Environmental Science, 214, 012090. https://doi.org/10.1088/1755-1315/214/1/012090

Kusuma, I. N. D. (2024). Penggunaan Peta Road Severity Index Sebagai Panduan Arah Kerja Grader Dalam Perawatan Jalan Tambang [Penggunaan Peta Road Severity Index Sebagai Panduan Arah Kerja Grader Dalam Perawatan Jalan Tambang]. Indonesian Mining Professionals Journal.

Mudya, D. R. (2024). Increasing Overburden Productivity Achievement By Using Lean Six Sigma Framework: A Case Study of Mining Activity at PT. BETA by Contractor PT. DELTA [Increasing Overburden Productivity Achievement By Using Lean Six Sigma Framework: A Case Study of Mining Activity at PT. BETA by Contractor PT. DELTA] (Final Project, SBM-ITB). Institut Teknologi Bandung.

Molotov, S. G., et al. (2009). Methodical Principles for Planning The Mining and Loading Equipment Capacity for Open Cast Mining With The Use of Dumpers: Engineering Capacity Calculation. Journal of Mining Science, 45(1). Moscow.

Mnzool, M., Almujibah, H., Bakri, M., Gaafar, A., Elhassan, A. A. M., & Gomaa, E. (2024). Optimization of cycle time for loading and hauling trucks in open-pit mining. Mining of Mineral Deposits, 18(1), 18–26. https://doi.org/10.33271/mining18.01.018

Ramadan, D. R., & Anaperta, Y. M. (2023). Optimizing Production By Increasing The Speed of Komatsu HD 785-7 PT. Kalimantan Prima Persada Site Indexim Kaliorang, Est Kutai, East Kalimantan. Jurnal Bina Tambang, 9(1s). UNP, Indonesia.

Sitorus, E. C. H., & Yudoko, G. (2024). Enhancing Fuel Ratio Efficiency for Sustainable Operation in Pit KX Mining: DMAIC Methodology. International Journal of Current Science Research and Review, 2581–8341.

Tannant, D. D., & Regensburg, B. (2021). Guidelines for Mine Haul Road Design. School of Engineering, University of British Columbia – Okanagan.

U.S. Department of Labor. (1999). MSHA Handbook Series. Metal and Nonmetal Mine Safety and Health, Technical Support. United States.