DIJEMSS: Dinasti International Journal of Education Management and Social Science
E-ISSN: 2686-6331
P-ISSN: 2686-6358
https://dinastipub.org/DIJEMSS dinasti.info@gmail.com +62 811 7404 455
DINASTI PUBLISHER
DOI: https://doi.org/10.38035/dijemss.v7i1

Monte Carlo Simulation Approach To Improve Overburden Operational Performance: Case Study of PT Bukit Asam TBK

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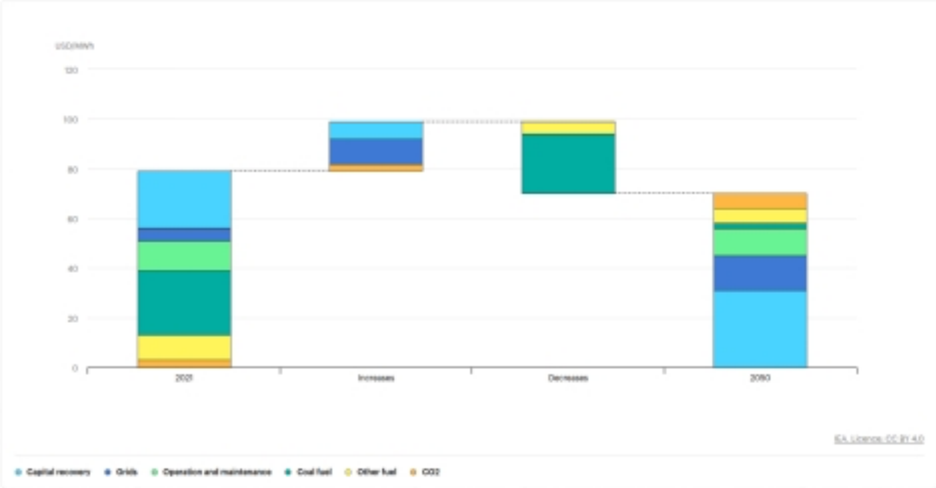
Abstract: This research develops a data-driven approach to improve overburden operational performance at PT Bukit Asam Tbk by utilizing Monte Carlo simulation as the primary analytical tool. Simulation results identified two main operational constraints. First, although the Matching Factor between loading and hauling equipment was balanced, the total fleet capacity was insufficient to achieve production targets. Second, poor synchronization (evidenced by high occurrences of "Wait Hauler" and "No Hauler" standby time) contributed to low Use of Availability (UA) and Equipment Utilization (EU), which reduces Effective Working Hours (EWH). First is to give addition to the fleet setting in East Pit 3, and second is to implement a real-time Mine Traffic Control (MTC) system. The proposed solutions were tested through simulation. Results showed that equipment addition could increase production by up to 26.8% and improve productivity by 1.76%. Meanwhile, the MTC system was projected to reduce controllable standby by 10.44%, increase EWH by 4.77%, and raise production under stable productivity conditions to 4.77%. Overall, the use of simulation and data-driven strategies proves effective in identifying root causes, designing measurable interventions, and validating their impact on productivity. The findings offer practical insights for improving operational efficiency of mining equipment operations in PT Bukit Asam Tbk

Keyword: Overburden Hauling, Monte Carlo Simulation, Data-Driven Approach, Operational Performance, Matching Factor, Effective Working Hours (EWH)

INTRODUCTION

For decades, Coal has long been essential in meeting global energy demands, particularly for electricity generation, steelmaking, and cement production. Despite its high carbon emissions, coal remains widely used due to its low cost and broad availability. However, as global and domestic policies shift toward renewable energy, coal demand is projected to decline, which impacts revenue streams and poses challenges for long-term sustainability.

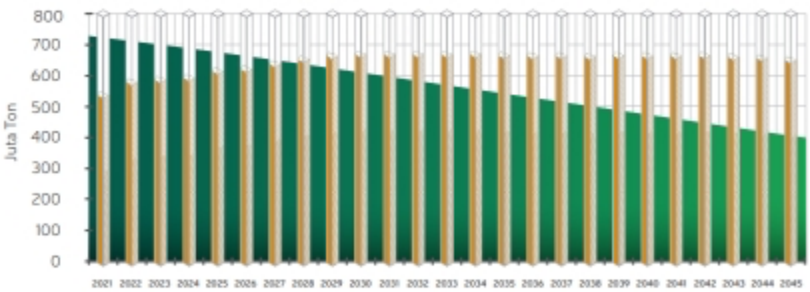


(Source: IEA (2022)

Figure 1. Transition of Electricity System Cost Components in Developing Economies (2021-2050)

Total electricity system costs per unit by component in emerging market and developing economies in the Announced Pledges Scenario, 2021-2050, Licence: CC BY 4.0)

From 2021 to 2050, the structure of electricity system costs in developing and emerging markets is expected to shift dramatically. In the early years, much of the cost was tied to coal and other fuel-related spending. As time goes on, there's a clear move away from these operational expenses. By 2050, investments in things like renewable energy, power grids, and battery storage take center stage. The largest share of costs by then comes from recovering capital tied to these clean technologies, showing a shift from paying for fuel to funding long-term infrastructure for a lower-carbon future. This shift is also taking shape in Indonesia.



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Sisa Cadangan	38.205	37.596	36.982	36.349	35.712	35.062	34.403	33.727	33.041	32.349	31.659	30.969
Forecast Produksi	601	608	615	633	637	650	659	675	686	692	690	690

	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Sisa Cadangan	30.280	29.592	28.904	28.216	27.532	26.850	26.163	25.477	24.790	24.104	23.423	22.745	22.074
Forecast Produksi	689	688	688	687	684	682	687	685	687	686	681	678	671

(Source: Directorate General of Minerals and Coal)

Figure 2. Indonesia's Projection of Production, DMO's, and Remaining Reserves (2020–2045)

While coal production may appear stable over time, reserves are steadily shrinking from 38.2 to 22 billion tons between 2021 and 2045. The gradual drawdown highlights growing pressure on the coal sector and the need to speed up the move toward cleaner energy options.

In PT Bukit Asam Tbk, the production realization in the last 2 years (2023 and 2024) requires at least 80 Mil MT be produced, and according to the Work Plan & Budget in 2025, it also expected that at least 50 Mil MT to be produced which presents both challenges and opportunities in achieving these targets. In order to respond to these challenges, this study explores how to enhance operational performance in overburden activity. Operational performance in this research is specifically for production and productivity, which plays a critical role in East Pit 3 activity. By improving this area, the company stands to increase efficiency and better position itself to meet production goals amid ongoing changes in the mining sector.

Company Profile

PT Bukit Asam Tbk operates as a state-owned enterprise under the Mining Industry Indonesia (Mind ID) Holding. Based in Tanjung Enim, South Sumatra, the company has conducted extensive coal mining operations and plays a key role in meeting both domestic and international coal demand.

Strategic Position of PT Bukit Asam Tbk

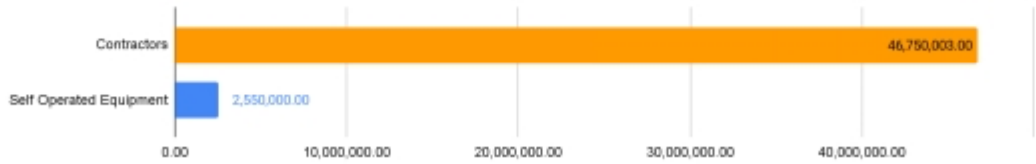
PT Bukit Asam Tbk as a coal mining company in a market-driven industry, is deeply influenced by global price volatility and domestic demand, two factors it cannot directly control. International coal prices shift in response to supply-demand balances and global energy transition trends, while domestic market conditions are shaped by industrial activity, regulatory frameworks, and the DMO. In order to assess PT Bukit Asam Tbk's strategic position in the coal industry in Indonesia, a TOWS strategic comparison was conducted with two major players: PT Adaro Energy Tbk (Adaro Energy) and PT Kaltim Prima Coal (KPC), which outlines each company's internal strengths and weaknesses, along with the external opportunities and threats they face in shifting energy landscape.

Electrification in PT Bukit Asam Tbk

PT Bukit Asam Tbk is required to maintain steady production to meet both domestic and export demands, despite being exposed to external factors like coal price volatility and changing market demand. One of the main challenges faced by the company is the use of contractor agreements, where costs continue to rise over time, regardless of whether market conditions justify the increase. In response, the company has started shifting toward reducing its reliance on external contractors by strengthening its self-operated operations named "Electrification". This shift is reflected in the use of environmentally friendly equipment such as electrified shovels (PC3000E) and hybrid trucks (HD BELAZ) for overburden removal.

Figure 3. Electrification Unit (PC3000E & HD BELAZ) of PT Bukit Asam Tbk

These self-operated units help lower fuel consumption and emissions while improving control over operational costs. By handling the equipment directly, PT Bukit Asam benefits from more adaptable operations, better real-time coordination, and reduced exposure to cost uncertainties typically tied to contractor-based systems.



(Source: Internal Company Document)
Figure 4. PT Bukit Asam Overburden Removal Yearly Plan in Q1 2025

In Q1 of 2025, approximately 5% of PT Bukit Asam Tbk's overburden removal target for the first quarter of 2025 was allocated to self-operated equipment. This allocation highlights the company's growing focus on strengthening its internal hauling operations, thus signalling a shift toward greater efficiency and operational independence through the use of self-managed equipment.

Electrification in East Pit 3

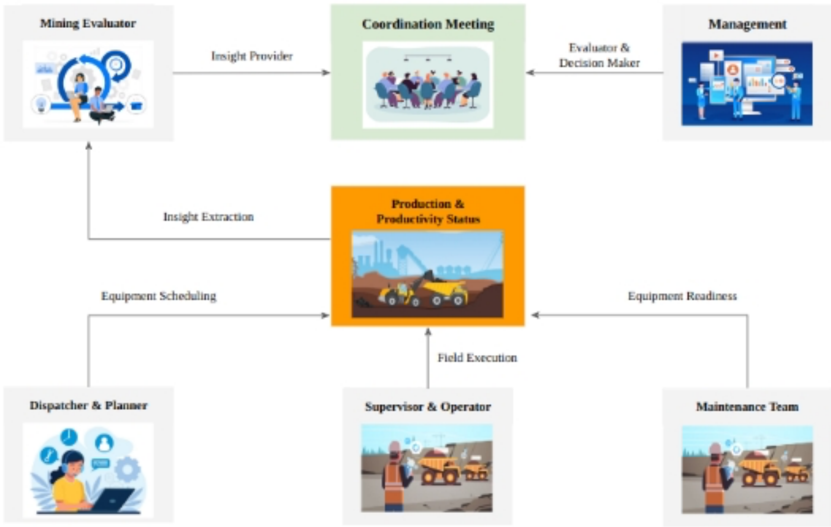
In Q1 of 2025, East Pit 3 became the major primary site for implementing the company's electrification efforts, marked by the operation of self-managed equipment such as the PC3000E electric shovel and HD BELAZ hybrid trucks. As part of this shift, several electrified units were designated for operation in East Pit 3 as part of this deployment.

(Source: Internal Company Document)
Figure 5. Operational Layout in East Pit 3

The area enclosed by the red line in Figure 5 represents the specific boundary of East Pit 3 where PT Bukit Asam operates its electrification unit. Within this zone, only PC3000E shovels (identified by purple circles) and HD BELAZ haul trucks (yellow icons) are utilized as main equipment.

Business Issue

Coal mining is a high-risk industry where business outcomes rely heavily on how well operational units perform. Since production levels directly affect costs and revenue, any drop in unit productivity can quickly impact the company's overall performance. This makes efficient equipment use essential to staying competitive and meeting production targets.



(Source: Internal Company Document)
Figure 6. Rich Picture of Overburden Removal in PT Bukit Asam Tbk

METHOD

The research method in this study employs a quantitative descriptive approach, aiming to analyze the productivity and operational challenges of overburden hauling activities at East Pit 3 of PT Bukit Asam Tbk. The research focuses on the performance of the PC3000E electric shovels and BELAZ trucks fleet during the electrification program implementation. The population of the study comprises the entire hauling operation at East Pit 3, while the sample includes field data from Q1 2025 reflecting actual operational conditions. The research was conducted at PT Bukit Asam's East Pit 3 in South Sumatra, where the data were gathered directly from company records, GPS-based monitoring, and stakeholder reports. The data sources include operational logs, productivity reports, and performance metrics such as SWT, EWH, ST, BT, PA, MA, UA, and EU, which provide a comprehensive view of equipment utilization and production output.

The instruments used in this study include internal company documents, GPS tracking systems, productivity logs, and Monte Carlo simulation software to model and analyze the performance of the hauling process. Data collection was carried out through three main stakeholder groups: the Dispatcher & Planner, the Hauling Executor, and the Evaluator. The Dispatcher & Planner provided fleet setting configurations as the operational baseline; the Hauling Executor recorded daily activities and productivity logs; and the Evaluator analyzed production reports, cycle times, and matching factors. The procedure started with reviewing fleet assignments and operational data, then observing field conditions, collecting quantitative metrics, and finally conducting a simulation-based analysis. Data processing also incorporated control charts, Pareto diagrams, and the Five Whys technique to identify inefficiencies and root causes systematically.

The research technique employed in the analysis stage was a Monte Carlo simulation framework designed to replicate daily hauling operations and assess productivity under varying operational conditions. This simulation iteratively generated cycle time data for shovels and trucks, accounting for minimum, maximum, mean, standard deviation, median, and mode parameters derived from field records. The procedure included setting up simulation parameters, running 10,000 iterations per shift cycle, and analyzing the outcomes to ensure stability through the Coefficient of Variation (CV). The simulation outcomes were then compared to monthly targets to evaluate the effectiveness of current operations and identify improvement opportunities. This methodological framework ensures that the research produces actionable, data-driven insights aligned with PT Bukit Asam's operational goals.

RESULTS AND DISCUSSION

Analysis

This chapter builds on the methodological framework from Chapter III to evaluate the hauling system performance at East Pit 3 during the first quarter of 2025. Using real operational data, a Monte Carlo simulation was developed to replicate field conditions. The analysis focuses on three key elements: hauling plan, hauling execution, and periodic evaluation. To summarize the issues and root causes in each phase, a Current Reality Tree (CRT) is used to map the linkages between observed problems, contributing factors, and systemic origins providing a clear foundation for the business solutions presented in the next section.

Monte Carlo Simulation Result

The first configuration of the simulation is described in Table 1.

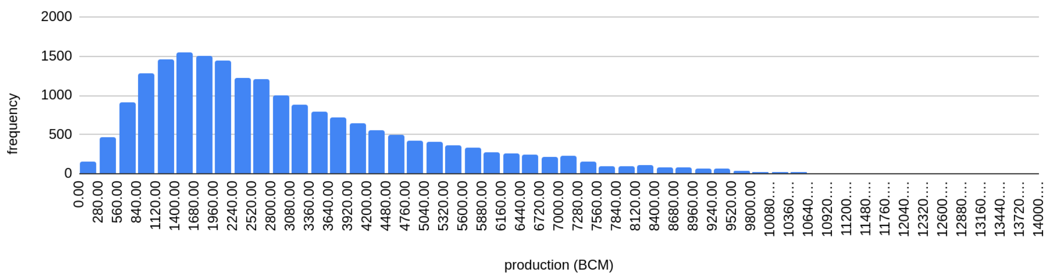
Table 1. Simulation Settings

Setting	Attributes
RT Belaz Fleet	32
Shovel PC3000E Fleet	4
Number of iteration (n)	20000
Scheduled Working Time (SWT)	12

The next step is to run the simulation based on the initialized configuration. Since the minimum value of each attribute is 0 and the total of EWH, UST, CST_{NH}, CST_{SP}, CST_{WH} and BT must be the same as SWT, the simulation process is executed according to the sequence outlined in Table 2.

Table 2. Simulation Process Sequence under Fixed SWT

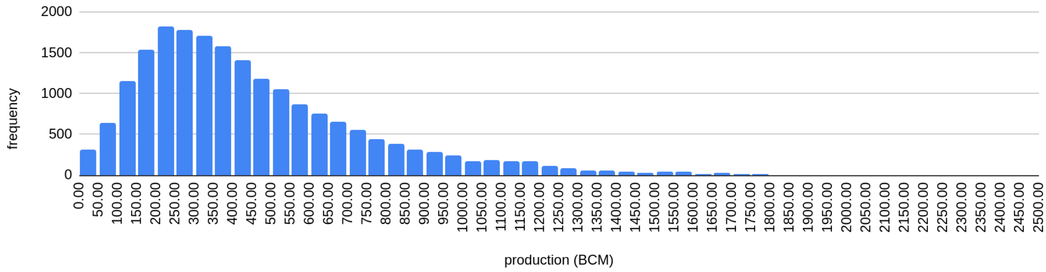
Attribute	Min Constraint	Max Constraint
EWH	0	SWT
UST	0	min(SWT - EWH, E(UST))
CST_{WH}	0	min(SWT - EWH - UST,E(CST_{WH}))
CST_{SP}	0	min(SWT - EWH - UST – CST_{WH} , E(CST_{SP}))
CST_{NH}	0	min(SWT - EWH - UST – CST_{WH} - CST_{SP}, E(CST_{SP}))
BT	0	SWT - EWH - UST – CST_{WH} - CST_{SP} – CST_{NH}
Productivity	0	-



(Source: Internal Analysis)

Figure 7. Production Simulation Histogram Result of Shovel PC3000E

Simulation results are presented in Fig. 7 for PC3000E and Fig 8. for RT Belaz in the form of histograms to visualize the distribution of production values generated across iterations. Specifically, histograms for both **the shovel and the truck** help identify variability and central tendencies in the output. More importantly, the histogram serves as a basis for determining whether the simulation has reached a steady state by evaluating the consistency of production across iterations.



(Source: Internal Analysis)

Figure 8. Production Simulation Histogram Result of RT Belaz

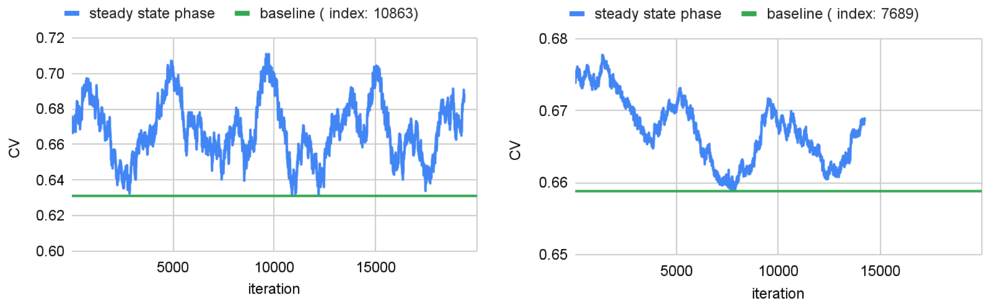
Since production is generated in each iteration, it's important to determine when the output reaches a steady state. In this research, firstly the process is done by tracking the Coefficient of Variation (CV) across the data. The steady state is identified from the point where CV is considered as stable. This ensures that only consistent and low-variability data is used for further analysis.

In this research, the CV is considered stable when it stays below a defined threshold over a specified iteration window. The configured iteration window is based on the fleet setting that is configured in Table 1 multiplied with total days in Q1 2025, which is formulated in Formula as follows.

$j = N_f \times s \times (31_{Jan} + 28_{Feb} + 31_{Mar}) = Nf \times s \times 90_{Q1}$	IV.1
Where: **j:** sliding window length of iteration **Nf:** Number of fleet s: total shift	

Based on Formula 1., the sliding window length of shovel fleet (4) is 720, while sliding window length of RT Belaz fleet (32) is 5760. Given that the Coefficient of Variation (CV) values remain below 1 and the sampling size is considerably large (reaching up to 5760 iterations), it becomes essential to identify the most statistically stable segment within the data. Rather than relying solely on fixed or arbitrary starting points, this research adopts a tail-based CV minimization approach. The optimal observation window is determined by locating the starting iteration from which the sum of CVs across all subsequent iterations is minimized. This method ensures that the selected data block reflects the lowest cumulative variability, thereby enhancing the reliability and consistency of the analysis drawn from the simulation results. The formulation of this tail-based CV minimization approach is described in Formula IV.2.

$i = \arg.\min\left(\sum_{j=1}^{N} CV_j\right)$	IV.1
Where: **i:** starting index of observational data **CV:** Coefficient of Variation **j:** sliding window length of iteration	



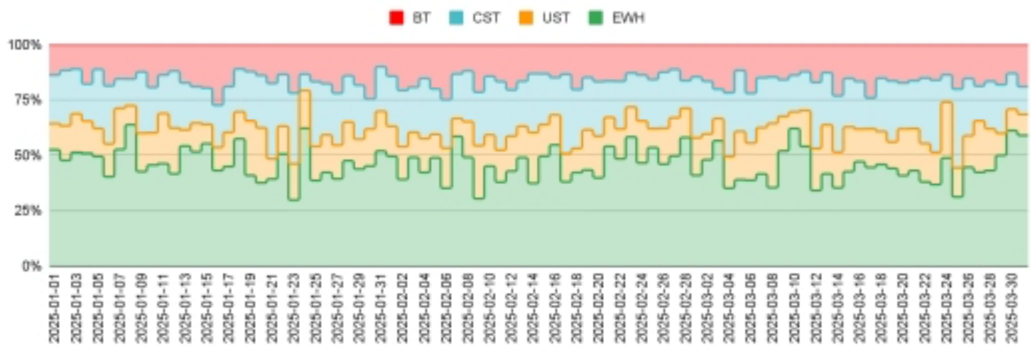
(Source: Internal Analysis)

Figure 9. Starting Iteration Index of Shovel PC3000E (Left) & RT Belaz (Right)

Based on Figure 9, the observation window of Shovel PC3000E starts from index 10863 to 720 data after it, while based on Figure IV.4, the observation window of the RT Belaz fleet is on iteration 7689 to 5760 data after it. The results derived from these observation windows are the SWT Simulation Results, the Equipment Performance Simulation Results, and the EWH, Productivity, and Production Results, will be further discussed in three later subsections.

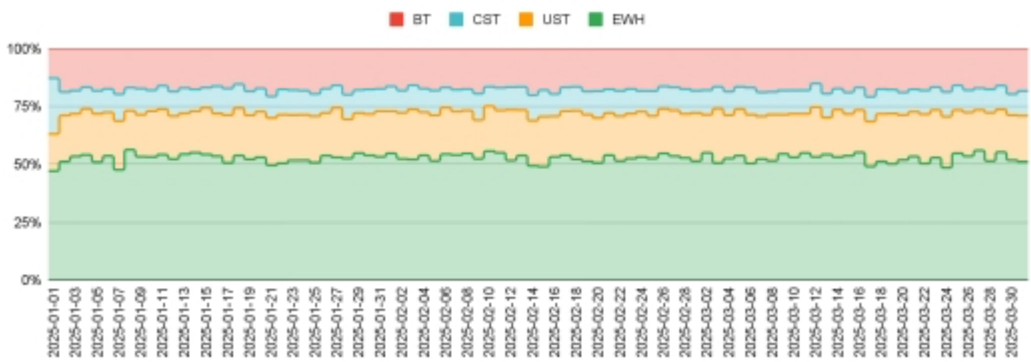
SWT Simulation Result

The Scheduled Working Time (SWT) refers to the full operational time allocated. SWT functions as the baseline duration, which serve as the starting point for evaluating how working time is distributed across various activities such as Effective Working Hour (EWH), Uncontrollable Standby Time (UST), Controllable Standby Time (CST) and Breakdown Time (BT).



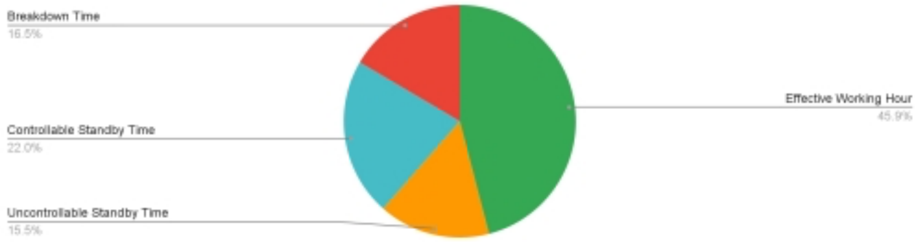
(Source: Internal Analysis)

Figure 10. Daily SWT Simulation Result of Shovel PC3000E



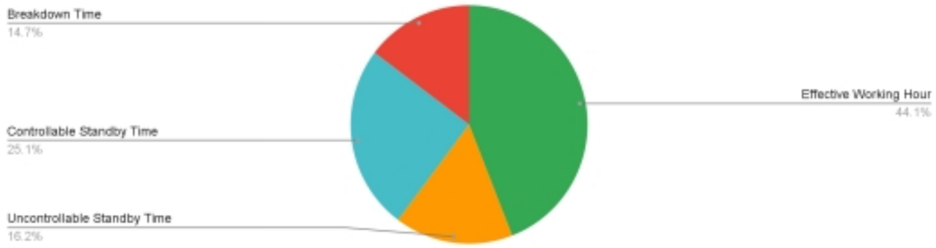
(Source: Internal Analysis)

Figure 11. Daily SWT Simulation Result of RT Belaz



(Source: Internal Analysis)

Figure 12. Cumulative SWT Simulation Result of Shovel PC3000E



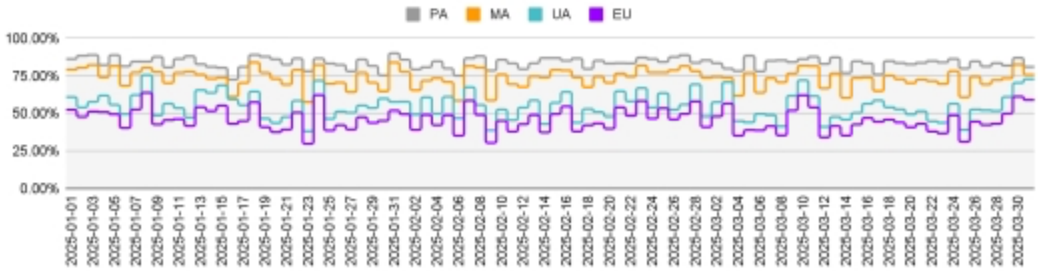
(Source: Internal Analysis)

Figure 13. Cumulative SWT Simulation Result of RT Belaz Truck

SWT also serves as a reference point to assess operational efficiency when compared with other performance indicators. SWT also serves as a reference point to assess operational efficiency when compared with other performance indicators, such as PA, MA, UA, and EU, which will be explained in the later section.

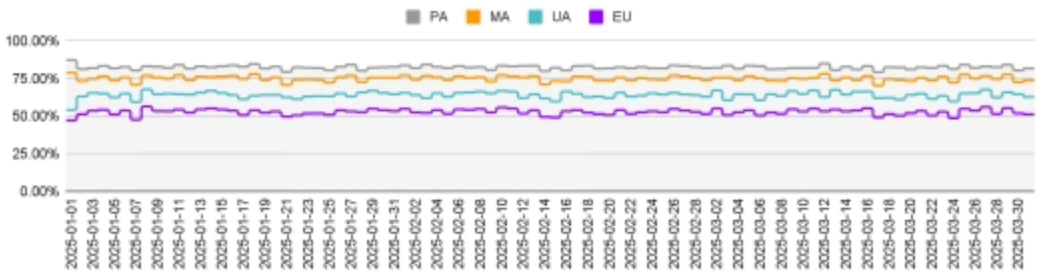
Equipment Performance Simulation Result

This subsection shows the simulated results for equipment performance using key indicators: Physical Availability (PA), Mechanical Availability (MA), Use of Availability (UA), and Equipment Utilization (EU).



(Source: Internal Analysis)

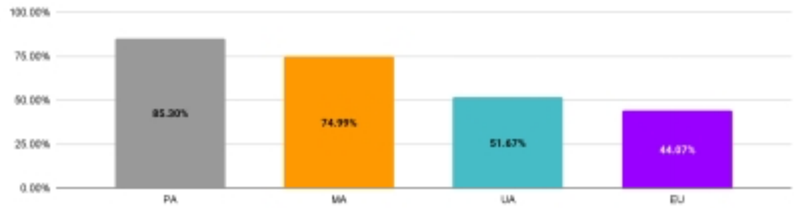
Figure 14. Daily PA, MA, UA, EU Simulation Result of Shovel PC3000E



(Source: Internal Analysis)

Figure 15. Daily PA, MA, UA, EU Simulation Result of RT Belaz

(Source: Internal Analysis)
Figure 16. Cumulative PA, MA, UA, EU Simulation Result of Shovel PC3000E

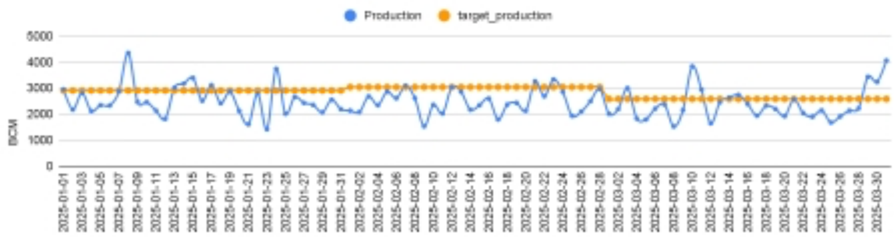


(Source: Internal Analysis)
Figure 17. Cumulative PA, MA, UA, EU Simulation Result of RT Belaz

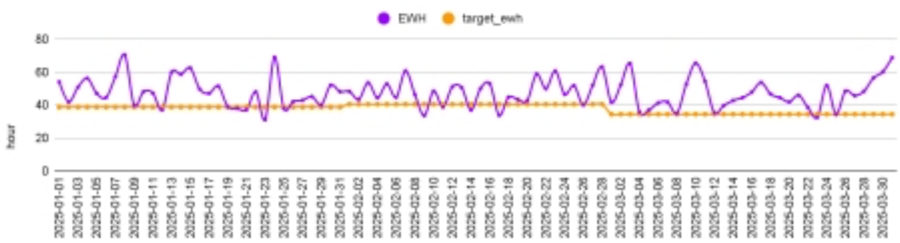
The PA, MA, UA and EU metrics are calculated from simulated EWH, standby, and breakdown time to evaluate how effectively equipment is used during scheduled shifts. The results are shown in daily, monthly, and cumulative formats to capture both short-term variations and overall performance trends.

Production, EWH & Productivity Simulation Result

This analysis examines production, EWH and productivity outcomes in relation to their planned targets to determine their contribution to overall productivity. By visualizing daily and cumulative trends alongside PT Bukit Asam Tbk's Q1 2025 targets, the charts provide insights into performance trends.



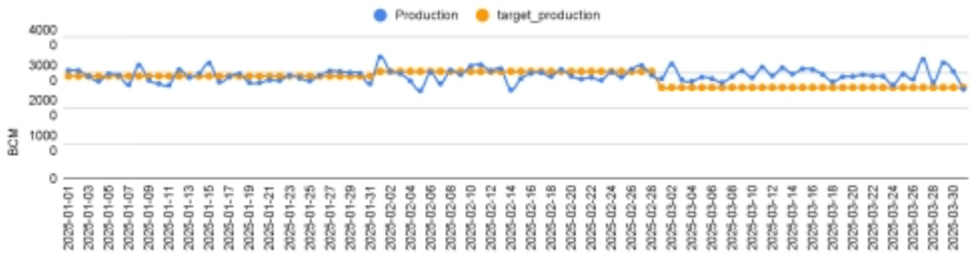
(Source: Internal Analysis)
Figure 18. Daily Production Simulation Result of Shovel PC3000E



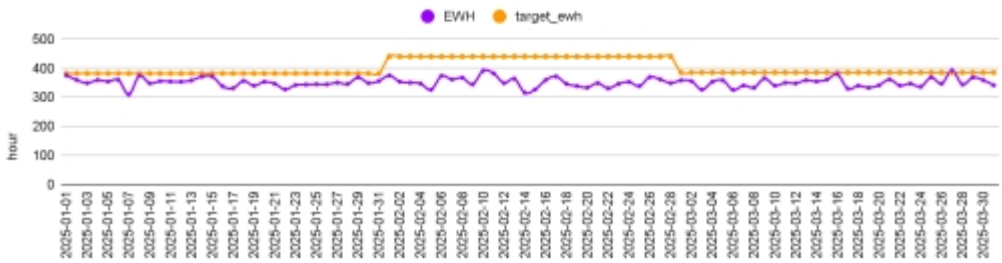
(Source: Internal Analysis)
Figure 19. Daily EWH Simulation Result of Shovel PC3000E

(Source: Internal Analysis)
Figure 20. Daily Productivity Simulation Result of Shovel PC3000E

For the Shovel PC3000E, productivity remains consistently below the target line across most days in the observation window, highlighting inefficiencies in operational execution. When compared to the actual realization in Q1 2025 from Figure 18-20, the simulated output aligns with the underperformance trend observed historically, which indicates that the simulation accurately reflects the existing operational challenges faced in the field.



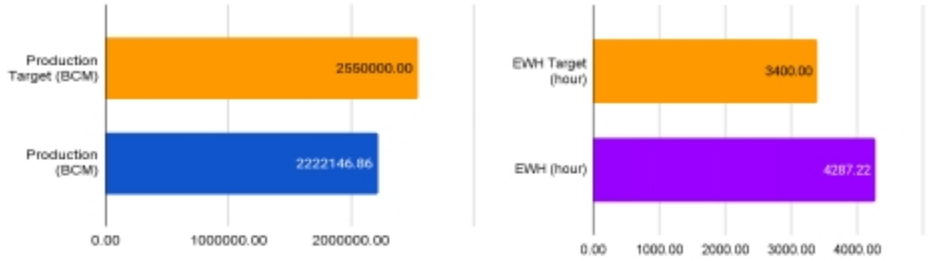
(Source: Internal Analysis)
Figure 21. Daily Production Simulation Result of RT Belaz



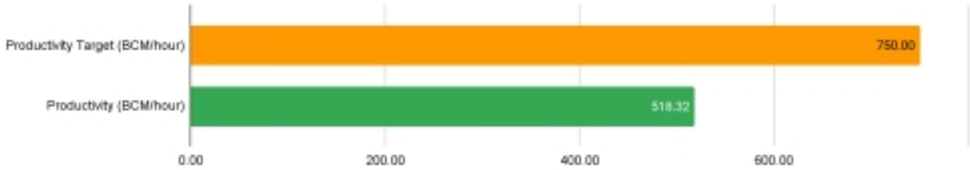
(Source: Internal Analysis)
Figure 22. Daily EWH Simulation Result of Shovel PC3000E

(Source: Internal Analysis)
Figure 23. Daily Productivity Simulation Result of Shovel PC3000E

Meanwhile, the RT Belaz fleet shows fluctuating productivity levels throughout the observation window, with an average above the target, though several days still fall below the benchmark.

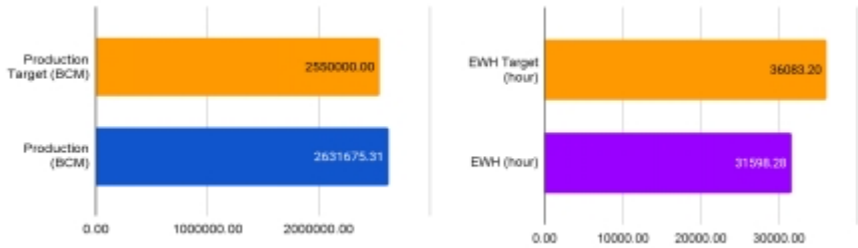


(Source: Internal Analysis)
Figure 24. Cumulative Production (Left) & EWH (Right) Simulation result of Shovel PC3000E

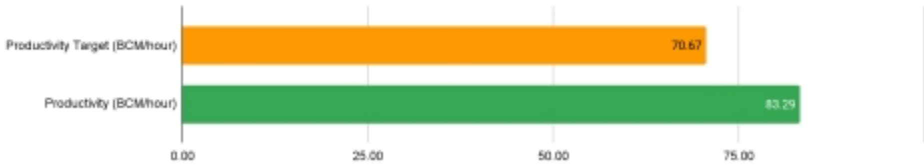


(Source: Internal Analysis)
Figure 25. Cumulative Productivity Simulation Result of Shovel PC3000E

The gap between planned targets and the simulated outcomes for the Shovel PC3000E from Figure 21-23 shows clear signs of underperformance. The simulated productivity also closely reflects the trends seen in Q1 2025.



(Source: Internal Analysis)
Figure 26. Total Production (Left) & EWH (Right) Simulation Result of RT Belaz



(Source: Internal Analysis)
Figure 27. Cumulative Productivity Simulation Result of RT Belaz

The gap between planned targets and the simulated outcomes for the RT Belaz from Figure 27 also closely reflects the trends seen in Q1 2025. This similarity suggests that the model captures the real operating conditions well and can be used confidently for exploring alternative scenarios.

Hauling Plan & Evaluation Analysis

The hauling plan simulation was based on PTBA's approach in Q1 2025 to maximize use of its in-house electrified fleet, with a fixed configuration of 32 BELAZ trucks and 4 PC3000E shovels. This setup aimed to support efficient overburden removal and meet production targets. The objective of this section is to assess whether the selected fleet composition is effective for maintaining balanced operations.

The main tool used in hauling plan evaluation is the Matching Factor (MF), which measures the alignment between loading and hauling capacity. The analysis of the MF each month can help to gauge whether the current hauling plan maintains a productive balance between loading and transport activities. This approach offers insight into how effectively the assigned equipment configuration meets operational needs and supports production targets over time.

(Source: Internal Analysis)

Figure 28. Matching Factors Simulation Result

The results shown in Figure 28. display values slightly above the target, indicating that the loading capacity of the PC3000E shovel slightly exceeds the hauling capacity of the RT Belaz trucks, which means that shovel is occasionally waiting for trucks to return, but not significantly. However, an average Matching Factor (MF) of 1.086 is still generally acceptable, suggesting the fleet was well-balanced. While this balance is a positive sign, actual production figures remained below expectations. To explore the cause of this gap, a Five Why analysis was conducted to trace the underlying factors limiting output.

Table 3. Five Why Analysis of Matching Factor Imbalance

Stage	Why	Attributes
1	Why	Why were production targets not met despite a good Matching Factor?
	Cause	Because the total volume of overburden moved was below the planned target.
2	Why	Why was the overburden volume lower than planned?
	Cause	Because the existing hauling capacity could not support the required production pace.
3	Why	Why couldn't the hauling capacity support the required pace?
	Cause	Because the number of trucks and loaders, while balanced, was not sufficient to handle the volume target.
Root Cause	"The number of trucks and loaders was not sufficient to handle the volume target."	

Based on the root cause analysis in Table IV.3, the underperformance was not caused by an imbalance between trucks and shovels, but by a fixed fleet configuration that failed to scale with increasing production demands. Although the MF showed balanced hauling and loading, the fleet size was insufficient to meet volume requirements, which highlighted the need for flexible planning that adjusts to production targets

Hauling Execution: Equipment Utilization

In East Pit 3 hauling operations, to support operational efficiency, equipment performance is essential to assess availability and utilization.

Table 4. Equipment Performance Simulation Result

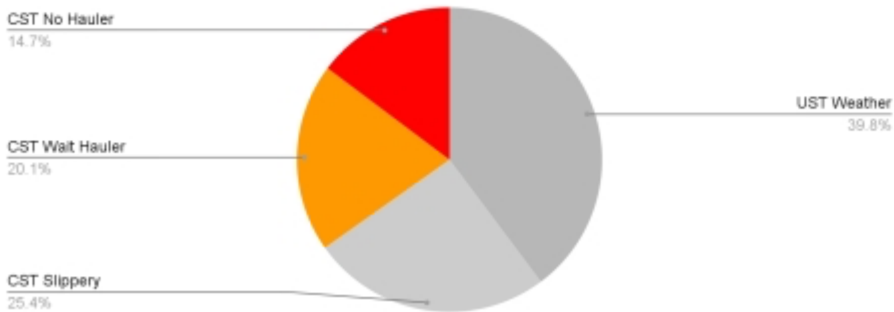
Month	Physical Availability		Mechanical Availability		Use of Availability		Effective Utilization	
	Shovel	Truck	Shovel	Truck	Shovel	Truck	Shovel	Truck
1	83.58%	85.35%	74.19%	75.06%	56.50%	51.67%	47.22%	44.10%
2	83.69%	85.38%	73.89%	75.17%	55.16%	51.83%	46.17%	44.25%
3	83.13%	85.19%	72.52%	74.77%	53.55%	51.51%	44.52%	43.89%

While PA and MA remained high throughout the simulation result, both UA and EU showed consistently low and declining trends. This gap indicates issues in hauling execution, where available equipment is not used optimally. Therefore, further analysis of actual hauling operations is needed to identify inefficiencies, idle time, and coordination problems across the system. The analysis highlights two key issues in hauling operations. First, the EU remains low despite high MA and PA, indicating that equipment is often idle even when fully operational. Second, trucks show lower UA and EU than shovels, suggesting poor coordination and frequent delays during loading and hauling cycles.

Furthermore to address the notable issues, a visual breakdown using a Pareto chart can help to identify which disturbances occurred most frequently and caused the greatest impact based on the simulation result. These disruptions are grouped into two main types: common (<81%) and contributing factors (>=81%).

(Source: Internal Company Document)

Figure 29. Pareto Graph of Standby Time Simulation Result



(Source: Internal Company Document)

Figure 30. Composition of Standby Time Simulation Result

Based on Figure 29., the contributing factors to standby time are “Wait Hauler” and “No Hauler”, with the composition of each standby time is shown in Figure 30. The “Wait Hauler” (20.1%) were reflecting delays in truck arrivals and dispatch inefficiencies. This condition is linked to low Use of Availability (UA), as equipment remains idle despite being operational. Meanwhile, “No Hauler” (14.7%) were caused by the absence of available trucks due to fleet shortages or poor scheduling. This directly relates to the low Equipment Utilization (EU) in the simulation results, as a large portion of the SWT is not converted into actual output.

In practice, as seen in Fig III.2, all four PC3000E shovels are positioned within the same working zone, which allows flexible access for the fleet of haul trucks. Shovel assignment is determined in real-time by field supervisors, who instruct truck operators to queue at the shovel that either has the fewest waiting units & nearest to the trucks. This manual approach is intended to reduce idle time and balance the queue length across loaders.

However, the lack of a standardized dispatching and coordination system has led to prolonged queuing and inefficient shift transitions, which contributes significantly to increased standby time. These inefficiencies are evident in two major internal obstacles, where “Wait Hauler” means that shovels are delayed due to late or poorly timed truck arrivals, and “No

Hauler" means that no trucks are available at all due to fleet shortages or scheduling issues. Together, these two factors represent a substantial portion of internal disruptions, highlighting that the root cause of lost productivity lies more in coordination and planning gaps than in mechanical failures. To explore these issues in depth, a Five Why Analysis was conducted to trace the underlying causes behind "Wait Hauler" and "No Hauler" conditions

Table 5. Five Why Analysis of Wait Hauler Issues

Stage	Why	Attributes
1	Why	Why are trucks queuing for too long?
	Cause	Because the arrival of trucks is not synchronized with the readiness of shovels.
2	Why	Why is there no synchronization between truck arrival and shovel readiness?
	Cause	Because dispatching decisions are made without real-time operational data.
3	Why	Why is dispatch not based on real-time data?
	Cause	Because the operation lacks a standardized and integrated coordination system.
Root Cause		"Lack of standardized and integrated coordination system."

Table 6. Five Why Analysis of No Hauler Issues

Stage	Why	Attributes
1	Why	Why is the shovel idle due to no hauler?
	Cause	Because no trucks are available when loading is required.
2	Why	Why are trucks not available at the required time?
	Cause	Because fleet allocation does not adapt to real-time loading demands.
3	Why	Why isn't truck allocation adjusted in real time?
	Cause	Because there is no integrated dispatch system to synchronize truck movement with shovel cycles.
Root Cause		"Lack of standardized and integrated coordination system."

Both "Wait Hauler" and "No Hauler" originate from the same root cause: the lack of a standardized, real-time coordination system. Without synchronized dispatch and structured shift protocols, equipment remains idle during queues and transitions. These operational gaps reduce effective working hours and highlight the need for an integrated control system to improve utilization and cycle efficiency.

Problem Summary

Based on the main findings collected from the earlier analysis of the hauling plan, its execution, and periodic evaluations, the study connects recurring operational issues using a Current Reality Tree (CRT) to give overall perspective about the case.

Undesirable Effect (UDE)	Low Productivity in East Pit 3		
	↓	↓	↓
	Production targets not met despite a good Matching Factor?	Hauling Execution idle time is majorly affected by wait hauler.	Hauling Execution idle time is majorly affected in no hauler.
	↓	↓	↓
Intermediate Effect(s)	Total volume of overburden moved was below the planned target.	Arrival of trucks is not synchronized with the readiness of shovels.	No trucks are available when loading is required.
	↓	↓	↓
	existing hauling capacity could not support the required production pace.	Dispatching decisions are made without real-time operational data.	Fleet allocation does not adapt to real-time loading demands.
	↓	↓	
Root Cause(s)	**The number of trucks and loaders was not sufficient to handle the volume target.**	**Lack of standardized and integrated coordination system.**	

(Source: Internal Analysis)

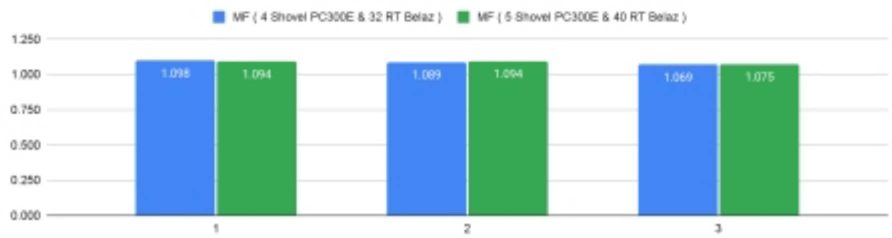
Figure 31 CRT Analysis of Major Problem Based on The Simulation Result

The Current Reality Tree (CRT) analysis identifies the collected issues as the Undesirable Effect (UDE). These issues branch into several contributing problems as Intermediate Effect(s) and ultimately trace back to Root Cause(s).

Business Solution

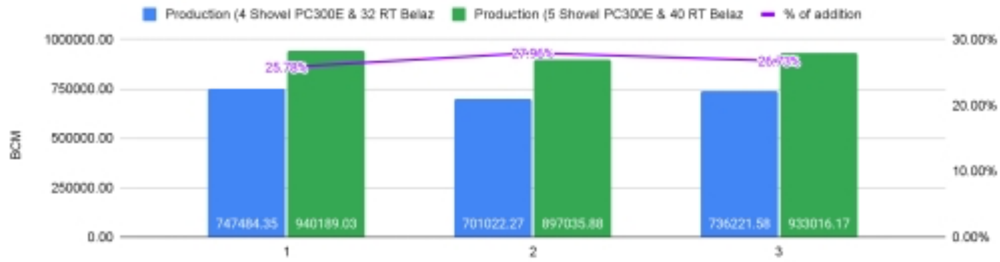
In order to address the production shortfall identified in East Pit 3 during Q1 2025, a key business solution is to increase the overall capacity of the hauling system while maintaining operational balance. Although the Matching Factor (MF) values indicate that the current fleet configuration of 4 PC3000E electric shovels and 32 BELAZ trucks is well-balanced, the total scale of this configuration is insufficient to meet growing production demands. Therefore, it is proposed to increase the number of active units to 5 Shovel PC3000E and 40 RT Belaz. This adjustment is feasible given the availability of 8 spare rigid trucks on the same site and 1 active PC3000E shovel in another site, allowing for an immediate capacity upgrade without requiring external procurement.

In order to evaluate the impact of this proposed adjustment, the simulation will be extended by adding a new observation sample using Formula 1, which estimates production based on the number of EWH and equipment productivity. The proposed simulation uses the new fleet setup of 5 PC3000E shovels and 40 RT Belaz trucks to represent the increased hauling capacity. Once the extended dataset is generated, the Matching Factor (MF) will be recalculated to confirm whether the revised fleet maintains a balanced operation. Simulated production results will then be compared with the original scenario to assess improvements.



(Source: Internal Analysis)

Figure 32. Matching Factor Simulation Result with 5 Loader & 40 Hauler Compared to 4 Loader & 32 Hauler

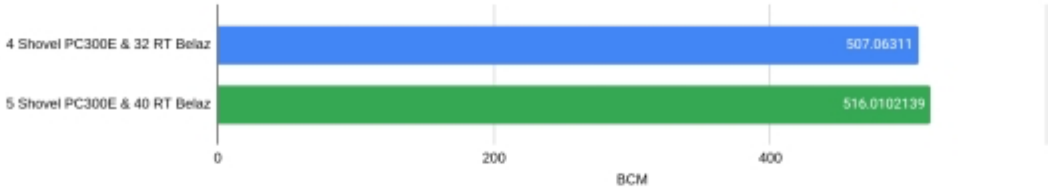


(Source: Internal Analysis)

Figure 33. Monthly Production Simulation Result with 5 Loader & 40 Hauler Compared to 4 Loader & 32 Hauler

(Source: Internal Analysis)

Figure 34. Cumulative Production Simulation Result with 5 Loader & 40 Hauler Compared to 4 Loader & 32 Hauler



(Source: Internal Analysis)

Figure 35. Cumulative Production Simulation Result With 5 Loader & 40 Hauler Compared To 4 Loader & 32 Hauler

Based on the simulation results shown in Figures 32-35, it is evident that increasing the fleet size to 5 PC3000E shovels and 40 Belaz trucks significantly improves production output while maintaining a favorable Matching Factor. The Matching Factor remains close to 1 across all three months, indicating that the balance between loading and hauling capacity is preserved even after scaling up the fleet. More importantly, the simulated production values show a substantial increase compared to the baseline, with total production rising to 2,770,241.09 BCM (26.80% of previous 2,184,728.19 BCM) and total productivity increase to 516.01 (1.7.6% of previous 507.06). This confirms that adding equipment settings for five PC3000E shovels and forty Belaz trucks not only maintains operational balance but also unlocks higher productivity, making it a viable and effective solution to close the production gap identified in Q1 2025.

Implementing Real-Time Mine Traffic Control

The inconsistent truck-to-shovel assignments (caused by the lack of a formal dispatch system) led to avoidable operational delays. This issue arises when supervisors make allocation choices based mainly on what they observe in the field, which often results in uneven use of shovels.

(Source: Internal Analysis)
Figure 36. Mine Traffic Control Visual

The proposed solution is a more structured dispatch method using predefined rules and visual tools to enhance coordination during hauling operations. The Mine Traffic Control (MTC) serves as a real-time coordination platform, which allows supervisors to manage equipment allocation directly. Each shovel (e.g., SE-3004, SE-3006) is shown in its own column with queued trucks and status indicators (green: ready, yellow: delay, blue: standby, red: breakdown). Instead of relying on visual judgment, truck assignments can be adjusted through the system as conditions change. The shovel lock feature helps fix assignments and supports more stable handovers between shifts. Updates are also visible to all operators through integrated Belaz head units.

In order to assess how the MTC system with shovel lock could reduce delays, an impact analysis was conducted for each historical delay in the "Wait Equipment" and “Change Shift” category. Based on its relevance to dispatching, each was assigned a weight factor to reflect its expected improvement (high = 0.5, medium = 0.3, and low = 0).

Table 7. Impact of Mine Traffic Control on Wait Equipment Delays

Category	Impact	Weight Factor	Description
Wait Hauler	High	0.5	Caused by delayed truck arrivals; highly responsive to dispatch system improvements.
No Hauler	Medium	0.3	Occurs when no trucks are available; moderately improved by better fleet coordination.

These factors were then used in a Monte Carlo simulation, applying a uniform distribution to model potential reductions in the Shovel’s Controllable Standby Time (CST) based on its proportional contribution to Total Standby Time. The simulated lost time calculation can be expressed as follows:

$$E(CST_C) = \frac{1}{N}\sum_{i=1}^{N} CST_C \ (1 - \alpha \cdot N(0,1)) \qquad \text{IV.4}$$

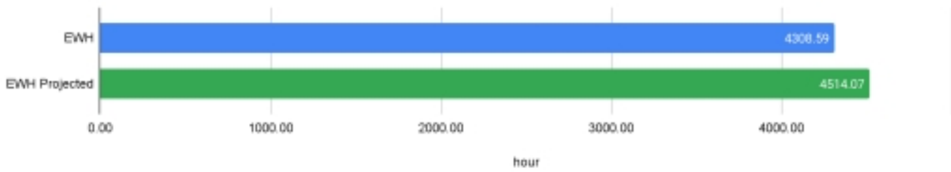
Where:
$E(CST_C)$: expected adjusted CST on specific category
C: Category
CST_C: Controllable Standby Time on specific category
α: weight factor
N(0,1): Random value from uniform distribution

The Monte Carlo simulation provides an estimation of the potential reduction in "Wait Hauler" and “No Hauler” delays after implementing the Mine Traffic Control system with shovel lock. Using weighted impact factors (α) assigned and with random variability drawn from a uniform distribution U(0,1). In this model, adjustments are applied only to shovel-side to avoid overlapping standby time that can occur simultaneously at both the shovel and truck in the same operational situation.

(Source: Internal Analysis)
Figure 37. Expected Reduction by Category after Mtc Implementation

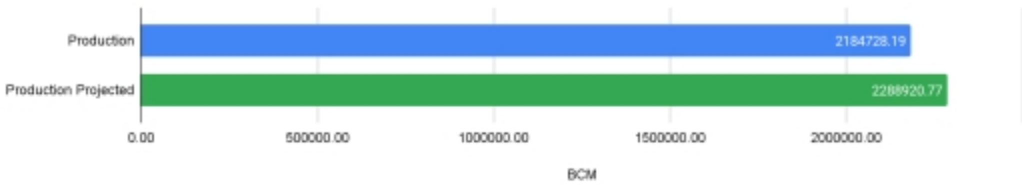
(Source: Internal Analysis)
Figure 38. Expected Reduction in CST after MTC Implementation

The simulation suggests that implementing the Mine Traffic Control (MTC) system has the potential to reduce lost time in the "Wait Hauler" category up to 23.85% and "No Hauler" up to 14.06%. This improvement is associated with a projected reduction in the CST of the PC3000E shovel to 1761.82 hours (10.44% from 1967.31 hours).



(Source: Internal Analysis)
Figure 39. Projected EWH increase after MTC implementation

Furthermore, assuming that the CST is reduced, the duration of time equipment is actively engaged in productive tasks which directly increase EWH, with the projected value is up to 4514.07 hours (4.77% of 4308.59 hours). This assumption aligns with practical observations in mining operations, where minimizing delays such as truck unavailability or dispatch inefficiencies enhances the actual use of equipment without modifying its technical performance.



(Source: Internal Analysis)
Figure 40. Projected EWH Increase After MTC Implementation

Based on the reverse of Formula I.1, where production is calculated as the product of EWH and the average productivity rate, an increase in EWH under the same productivity conditions is expected to result in a proportional increase in total production output up to

2288920.77 BCM (4.77% of 2184728.19 BCM). Therefore, the model estimates gains in production by optimizing time usage within the existing system.

Total Impact of Proposal on Productivity

Building on the results of the two previous subsections, the list of factors that can be an impactful factor for productivity is detailed as follows: 1.) Giving 1 additional Shovel PC3000E & 8 additional RT Belaz can increase production up to 26.80%; 2.) Giving 1 additional Shovel PC3000E & 8 additional RT Belaz can also increase productivity up to 1.76%.; 3.)Implementation of Mine Traffic Control can reduce lost time on the "Wait Hauler" and "No Hauler" category up to 10.44%. ; 4.)Implementation of Mine Traffic Control is also expected to increase EWH of the equipment up to 4.77%; 5.0Although productivity is directly influenced by EWH, production can still increase by up to 4.77% assuming the productivity level remains stable.

CONCLUSION

This research aimed to investigate the underperformance of the electrified equipment fleet at East Pit 3 in Q1 2025 and to identify strategies for improving productivity. The findings revealed that although the fleet setup appeared technically balanced (as indicated by a stable Matching Factor), the number of active units (4 shovels and 32 trucks) was insufficient to meet production targets, creating an operational capacity bottleneck. Additionally, poor coordination due to the absence of an integrated system led to significant standby times: "Wait Hauler" accounted for 10.6% and "No Hauler" for 14.7% of Controlled Standby Time, resulting in low Use of Availability (UA) and Equipment Utilization (EU) because Scheduled Working Time (SWT) was not effectively converted into productive output.

To explore improvements, Monte Carlo simulations tested alternative setups and operational changes. Increasing the fleet to 5 shovels and 40 trucks showed a potential production increase of up to 26.8%, while introducing a real-time Mine Traffic Control (MTC) system to enhance coordination further reduced standby time and could improve production by an estimated 4.77%. The study also recommended moving beyond simple average-based planning by adopting Monte Carlo simulations, which better reflect operational variability and deliver more reliable forecasts. Overall, the research pinpointed key performance barriers, quantified their impacts, and proposed actionable, data-driven strategies to enhance efficiency and output at East Pit 3.

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