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Improving Excavator Productivity and Loading-Hauling Efficiency Through Double Side Loading in Open-Pit Mining Operations

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A B S T R A C T

Open-pit mining operations require efficient loading and hauling systems to achieve production targets while minimizing operational delays and equipment idle time. Conventional Single Side Loading systems often result in high queuing time, hanging time, and cycle time, which reduce excavator productivity and overall operational efficiency. This study evaluates the effectiveness of Double Side Loading (DSL) implementation in improving excavator productivity and loading-hauling performance in an open-pit mining operation in East Kalimantan, Indonesia. A quantitative before-and-after operational analysis was conducted using actual field data collected from 250-ton and 300-ton excavator fleets, comprising more than 1,000 observed loading cycles. The analyzed parameters included excavator productivity, queuing time, hanging time, cycle time, and match factor. Descriptive statistical analysis and paired sample t-tests were employed to assess the significance of operational changes following DSL implementation. The results indicate that DSL significantly improved excavator productivity by 20% for the 250-ton fleet and 17% for the 300-ton fleet. Queuing time decreased by 25% and 29%, while hanging time was reduced by 34% and 26% for the 250-ton and 300-ton fleets, respectively. In addition, cycle time decreased by 12.46% and 13.04%, whereas match factor improved from 0.96 to 1.00 and from 0.98 to 1.02. Statistical testing further confirmed the significance of the observed improvements. The paired sample t-test indicated significant productivity gains for both excavator fleets, with the 250-ton fleet yielding a t-value of 4.12 and a 95% confidence interval of 124.5–211.5 BCM/h, while the 300-ton fleet yielded a t-value of 3.89 and a 95% confidence interval of 145.2–256.8 BCM/h.

1. Introduction

Open-pit mining operations are continuously challenged to improve productivity while maintaining operational efficiency and cost competitiveness. Among various mining activities, loading and hauling constitute the largest portion of the production cycle and significantly influence overall mine performance. Previous studies have reported that loading and hauling activities may contribute more than 50% of total mining operating costs due to fuel consumption, equipment utilization, waiting time, and operational delays (Elijah et al., 2021). Consequently, mining companies continuously seek operational improvement strategies to maximize equipment productivity without requiring additional capital investment. The adoption of efficient loading practices has therefore become an important component of modern mining operations aimed at achieving sustainable production performance (Aguayo et al., 2021).

Efficient loading operations depend on several operational factors, including cycle time, equipment compatibility, truck availability, and loading patterns, which collectively influence the performance of truck–excavator systems in open-pit mines. In many open-pit mining operations, conventional loading practices often generate non-productive activities such as truck queuing, waiting time at loading points, and excessive maneuvering movements that reduce

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operational efficiency (Setiawan et al., 2025). These inefficiencies may increase excavator idle time and prolong the overall loading-hauling cycle, resulting in lower equipment utilization and reduced production performance (Pathan et al., 2024). Previous studies have shown that truck-shovel matching, loading location, and equipment interaction significantly affect loading cycle time and excavator productivity in surface mining operations (Manyele, 2017).

Several previous studies have investigated productivity improvement in open-pit loading and hauling systems using various operational and analytical approaches. Research (Manyele, 2017) analyzed more than 62,000 loading dispatch records from an open-pit mine and found that excavator type, loading location, shift availability, and truck–shovel combinations significantly influenced loading cycle time and overall productivity. Similarly, study (Aguayo et al., 2021) highlighted that the loading and hauling stage frequently becomes a major bottleneck in open-pit mining operations. Furthermore, a subsequent simulation-based investigation reported that the incorporation of a surge loader increased shovel utilization by 11% and improved shovel and truck productivity by 13%. Research conducted by (Mnzool et al., 2024) further demonstrated that optimizing truck loading and hauling cycle times provides practical opportunities to enhance productivity while reducing operational inefficiencies. Likewise, (Zhang et al., 2022) showed that determining an appropriate truck–shovel configuration through simulation can improve equipment allocation decisions and support more efficient fleet operations. In addition, recent studies on truck dispatching and simulation-based optimization have emphasized that minimizing truck waiting time, reducing shovel idle time, and improving fleet balance are critical factors for increasing production throughput and operational efficiency in open-pit mines. While these studies provide valuable insights into loading-hauling optimization, their primary focus has been on dispatching algorithms, fleet allocation strategies, equipment configuration analyses, simulation models, or auxiliary loading systems. Consequently, they provide limited empirical evidence regarding how changes in loading patterns influence operational performance under actual mining conditions. In particular, the direct operational impacts of Double Side Loading (DSL) on loading continuity, fleet synchronization, and productivity have received relatively little attention in the existing literature. However, most of these studies focus primarily on simulation models, dispatching strategies, fleet configuration, or auxiliary loading systems. Quantitative investigations evaluating the operational impact of DSL using actual before-and-after field data remain limited, particularly in relation to its simultaneous effects on queuing time, hanging time, cycle time, match factor, and excavator productivity.

Despite the growing body of research on loading and hauling optimization, a significant gap remains in understanding the practical effectiveness of Double Side Loading (DSL) under actual open-pit mining conditions. Most previous studies have primarily relied on simulation models, dispatching algorithms, fleet configuration analyses, or theoretical approaches, with limited validation using real operational data. Consequently, the operational impacts of DSL on key performance indicators have not been comprehensively quantified in large-scale mining environments. To address this gap, the present study evaluates the implementation of DSL using actual production data collected from 250-ton and 300-ton excavator fleets through a before-and-after operational analysis approach. The novelty of this research lies in its simultaneous assessment of queuing time, hanging time, cycle time, match factor, and excavator productivity, providing a comprehensive evaluation of the operational impacts of loading pattern optimization. Unlike previous studies that primarily relied on simulation-based analyses, this study provides empirical evidence from actual mining operations through a before-and-after evaluation of DSL implementation. Furthermore, the study establishes a quantitative relationship between loading pattern optimization, fleet synchronization, and productivity improvement, providing a practical framework for evaluating operational design changes in open-pit mining operations. Therefore, this study aims to analyze the effectiveness of DSL in improving excavator productivity and enhancing loading-hauling operational efficiency in open-pit mining operations.

2. Research Methods

This study employed a quantitative research approach to evaluate the operational impact of DSL on excavator productivity and loading-hauling efficiency in an open-pit mining operation. A before-and-after operational analysis framework was used to compare the performance of conventional Single Side Loading and DSL configurations. The evaluation focused on key operational indicators, including excavator productivity, queuing time, hanging time, cycle time, and match factor, using actual field observations and Fleet Management System (FMS) records from 250-ton and 300-ton excavator fleets. The collected data were analyzed using descriptive statistics and paired sample t-tests to assess the significance of operational performance changes following DSL implementation. The overall research methodology consisted of six main stages, as illustrated in Figure 2.

2.1 Study Area and Operational Context

This study was conducted at an open-pit mining operation located in East Kalimantan, Indonesia, focusing on loading and hauling activities involving large-scale excavator and dump truck fleets. The observed production system consisted of 250-ton and 300-ton class excavators operating as primary loading units, supported by a fleet of haul trucks responsible for material transportation from the loading face to designated dumping locations. Loading and hauling activities represent one of the most critical stages in the mining production cycle because they directly influence equipment utilization, production achievement, and overall operational efficiency (Elijah et al., 2021).

Prior to the implementation of DSL, loading activities were performed using a conventional Single Side Loading configuration, where haul trucks approached and positioned themselves on only one side of the excavator. Under this arrangement, truck replacement at the loading point often required additional maneuvering time, resulting in longer swing movements of the excavator and increased waiting periods between loading cycles. These conditions contributed to higher queuing time, hanging time, and cycle time, which ultimately affected excavator productivity and fleet synchronization (Litvin & Litvin, 2020).Operational observations indicated that the existing loading pattern created inefficiencies associated with truck positioning and loading continuity. To address these challenges, a Double Side Loading configuration was introduced, allowing haul trucks to alternately occupy loading positions on both sides of the excavator. The implementation was expected to reduce truck waiting time, minimize excavator idle periods, improve match factor, and enhance overall loading and hauling performance. The operational configuration of the existing Single Side Loading system is illustrated in Figure 1.

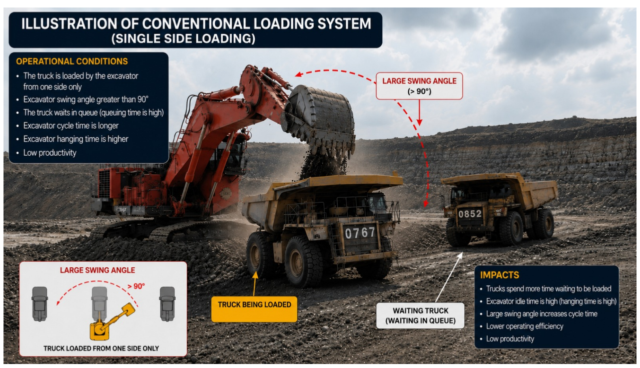

Figure 1. Existing single side loading configuration at the study site

2.2 *Research Design*

This study employed a quantitative research approach using a before-and-after operational analysis framework to evaluate the effectiveness of DSL implementation on excavator productivity and loading-hauling performance in an open-pit mining operation. The approach was selected because it enables direct comparison of operational performance under two different loading configurations, namely the conventional Single Side Loading system and the proposed Double Side Loading system. By comparing operational conditions before and after implementation, the study provides a practical assessment of the operational benefits achieved through loading pattern optimization.

The research process consisted of several sequential stages. The first stage involved baseline observation and data collection under the existing Single Side Loading configuration to establish reference operational performance. The second stage focused on identifying operational inefficiencies associated with loading activities, including excessive queuing time, hanging time, and prolonged cycle time. Following the baseline assessment, the Double Side Loading configuration was implemented and monitored under actual production conditions. Operational data were subsequently collected and compared with the baseline condition to evaluate changes in productivity and efficiency indicators.

To ensure a systematic evaluation, the collected data were analyzed using both descriptive and inferential statistical methods. Key operational performance indicators, including excavator productivity, queuing time, hanging time, cycle time, and match factor, were assessed before and after DSL implementation. The overall methodological workflow adopted in this study is illustrated in Figure 2.

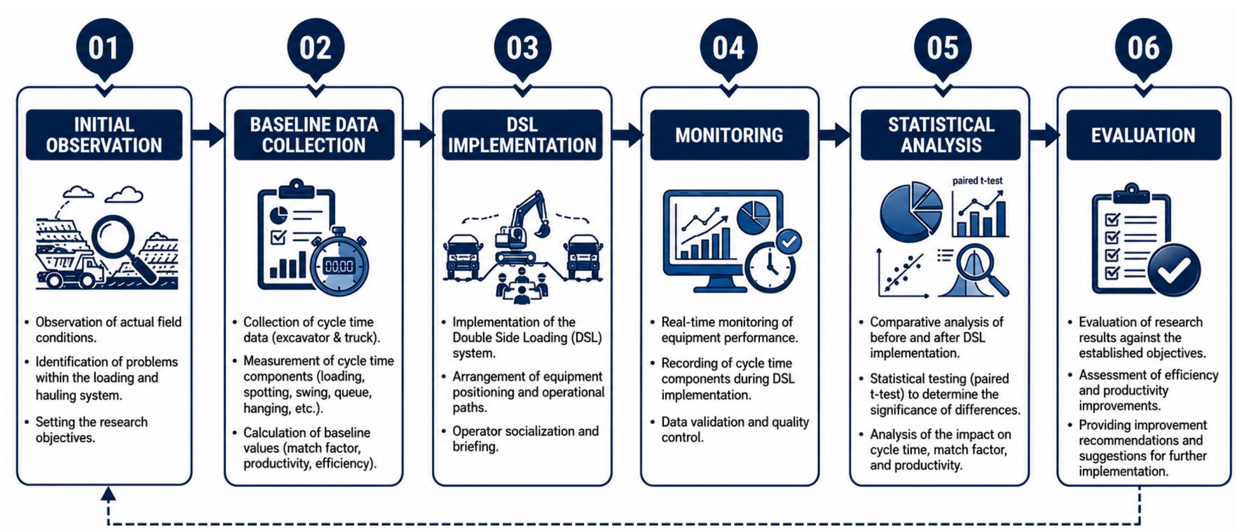

Figure 2. Research framework and methodological workflow

Following the research framework presented in Figure 2, it is essential to understand the operational characteristics of the loading configurations evaluated in this study. The effectiveness of Double Side Loading was assessed by comparing its operational arrangement with the conventional Single Side Loading system. Therefore, the configuration and operational principles of both loading patterns are described in the following section.

2.3 Double Side Loading Configuration

Loading configuration plays an important role in determining the efficiency of excavator and haul truck interactions during material loading operations. Prior to the implementation of DSL, loading activities at the study site were conducted using a conventional Single Side Loading arrangement, where haul trucks approached and positioned themselves on only one side of the excavator. Under this configuration, truck replacement occurred sequentially, requiring the incoming truck to complete its maneuver before loading could resume. This arrangement often resulted in longer excavator waiting periods, higher truck queuing time, and larger excavator swing movements, which collectively reduced operational efficiency. Figure 3 illustrates the existing Single Side Loading configuration applied during the baseline observation period. In this arrangement, loading activities were concentrated on a single loading side, causing interruptions in loading continuity whenever truck positioning or replacement was delayed. As a consequence, excavator utilization was affected by truck availability and maneuvering performance at the loading point.

To improve loading continuity and reduce non-productive operational time, a Double Side Loading configuration was introduced. Under this arrangement, haul trucks were positioned alternately on both sides of the excavator, allowing the next truck to be prepared while the current loading process was still ongoing. This configuration reduced truck replacement delays and enabled more continuous excavator operation. In addition, truck positioning on both sides of the excavator helped maintain a more consistent swing angle of approximately 45°, thereby reducing swing movement duration and improving loading efficiency.

Figure 3. Existing single side loading configuration

Figure 4. Double Side Loading Configuration Implemented at the Study Site

The operational concept of DSL is illustrated in Figure 4. By reducing truck waiting time, excavator idle periods, and truck maneuvering requirements, the DSL configuration was expected to improve match factor, shorten cycle time, and enhance overall loading and hauling performance. The operational effectiveness of this configuration was subsequently evaluated using actual production data collected before and after implementation.

2.4 Data Collection and Sampling

Operational data were collected from loading and hauling activities conducted before and after the implementation of the DSL configuration. The observation was performed at an open-pit mining operation in East Kalimantan, Indonesia, involving 250-ton and 300-ton excavator fleets and their associated haul trucks. A before-and-after sampling approach was adopted to ensure that operational performance under both loading configurations could be evaluated under comparable production conditions. The observation period covered 14 operational days consisting of 28 production shifts. Data collection included direct field observations, cycle time measurements, operational documentation, and records obtained from the FMS. The use of FMS data improved data reliability by providing automatically recorded operational information related to equipment activities and production performance (Kasa, 2026). The observed operational parameters included excavator productivity, queuing time, hanging time, cycle time, and match factor.

A purposive sampling technique was employed to select operational units that met the study requirements. The selection criteria included: (1) excavators operating under both Single Side Loading and Double Side Loading configurations, (2) availability of complete operational records during the observation period, and (3) relatively similar mining face conditions to minimize external operational variations. In total, more than 1,000 loading cycles were observed and analyzed to ensure that the collected data adequately represented actual operational conditions and provided sufficient statistical reliability for subsequent analysis (Manyele, 2017), (Mnzool et al., 2024). A summary of the data collection process and observation characteristics is presented in Table 1.

Table 1. Summary of Data Collection and Observation Characteristics

Item	Description
Mining Method	Open-Pit Mining
Study Location	East Kalimantan, Indonesia
Observation Approach	Before-and-After Analysis
Observation Period	14 Operational Days
Number of Shifts	28 Shifts
Excavator Fleet	250T and 300T
Data Sources	Field Observation and FMS
Observed Parameters	Productivity, Queuing Time, Hanging Time, Cycle Time, Match Factor
Sampling Method	Purposive Sampling
Total Observed Cycles	>1,000 Cycles

The collected operational data were subsequently used to evaluate the performance of the loading and hauling system. To quantify the impact of DSL implementation, several key operational indicators were selected and analyzed, as described in the following section.

2.5 Operational Performance Indicators

To evaluate the effectiveness of DSL, several operational performance indicators were selected based on their relevance to loading and hauling efficiency. These indicators represent key operational parameters that directly influence excavator productivity, fleet utilization, and loading continuity. The selected indicators include excavator productivity, cycle time, queuing time, hanging time, and match factor (Taufiq et al., 2024). Together, these parameters provide a comprehensive assessment of the operational performance of the loading system before and after DSL implementation. The operational performance indicators used in this study are summarized in Table 2.

Table 2. Operational Performance Indicators

Indicator	Unit	Description
Excavator Productivity	BCM/h	Volume of material moved per operating hour
Cycle Time	s	Total time required to complete one excavator loading cycle
Queuing Time	s	Truck waiting time before entering the loading point
Hanging Time	s	Excavator idle time while waiting for truck arrival
Match Factor	Ratio	Degree of compatibility between loading and hauling equipment

Excavator productivity was calculated using the standard mechanical equipment productivity equation, which considers bucket capacity, bucket fill factor, equipment efficiency, and cycle time (Taufiq et al., 2024), (Caterpillar Inc., 2015). Meanwhile, match factor was used to evaluate the balance between excavator production capacity and haul truck transportation capacity. A match factor value close to 1 indicates an optimal balance between loading and hauling fleets, while values below or above 1 indicate under-trucking or over-trucking conditions, respectively (Mustafa Wadi et al., 2025). Excavator productivity, as shown in Eq. (1):

$$P = \frac{BC\ x\ FF\ x\ E\ x\ 3600}{CT} \tag{1}$$

Where, P represents excavator productivity (BCM/h), BC denotes bucket capacity (m3), FF represents bucket fill factor, E represents equipment efficiency, CT represents cycle time (s). Matching factor, as shown in Eq. (2):

$$MF = \frac{N_t\ x\ CT_e}{N_e\ x\ CT_t} \tag{2}$$

Where, MF represents the matching factor, N_t denotes the number of hauling trucks, N_e denotes the number of excavators, CT_e represents excavator cycle time (h), and CT_t represents truck cycle time (h). A matching factor value approaching 1.0 indicates a balanced allocation between loadings.

Following the identification of the operational performance indicators, statistical analysis was performed to evaluate the significance of changes observed after DSL implementation. The analytical procedures employed in this study are presented in the following section. and hauling equipment.

2.6 Statistical Analysis

The collected operational data were analyzed using both descriptive and inferential statistical methods to evaluate the effectiveness of DSL implementation. Descriptive statistics were first applied to summarize the operational performance indicators under Single Side Loading and Double Side Loading configurations. The analysis included the calculation of mean values, percentage changes, and performance improvements for excavator productivity, queuing time, hanging time, cycle time, and match factor.

To determine whether the observed operational changes were statistically significant, a paired sample t-test was employed. This method was selected because the study compared two related operational conditions, namely the performance of the same loading system before and after DSL implementation. The paired sample t-test is commonly used to evaluate whether the mean difference between two dependent observations is statistically significant (Xu et al., 2017), (Wilkerson, 2008). Prior to hypothesis testing, the operational data were examined to ensure their suitability for parametric analysis. The statistical hypotheses adopted in this study are defined as follows:

$$H\_0: \mu\_before = \mu\_after \tag{3}$$

$$H\_1: \mu\_before \neq \mu\_after \tag{4}$$

where μ_before represents the mean value of the operational parameter before DSL implementation and μ_afterrepresents the mean value after DSL implementation.

A significance level of 5% (α=0.05) was used throughout the analysis. Therefore, if the calculated p-value was less than 0.05, the null hypothesis was rejected, indicating that DSL implementation had a statistically significant effect on the evaluated operational parameter. All statistical analyses were performed using Microsoft Excel and statistical software to ensure objective and reliable evaluation of operational performance changes.

To perform the inferential analysis, a paired sample t-test was conducted by pairing active production data collected under the baseline Single Side Loading configuration directly with data from the post-implementation Double Side Loading configuration. The observations were systematically paired based on identical excavator fleet classes, geological mining blocks, and shift schedules to ensure comparability between the two operational conditions. In addition, the paired observations were obtained from relatively similar operating environments, including comparable hauling distances, material characteristics, equipment configurations, road conditions, operator competency grades, and production targets, thereby minimizing the influence of external factors on productivity performance. A total of 1,025 loading cycle observations were included in the paired analysis, providing sufficient statistical power to evaluate the operational impact of DSL implementation and detect statistically meaningful changes in loading-hauling performance.

3. Result

The implementation of DSL was evaluated using operational data collected before and after its deployment in the study area. The analysis focused on key performance indicators associated with loading and hauling efficiency, including excavator productivity, queuing time, hanging time, cycle time, and match factor. These indicators were selected because they directly reflect equipment utilization, fleet synchronization, and operational continuity within the loading system. The results presented in this section provide a quantitative assessment of the operational impact of DSL and are subsequently discussed in relation to previous studies and loading-hauling optimization practices in open-pit mining operations.

3.1 Overall Impact of Double Side Loading on Operational Performance

The implementation of DSL resulted in consistent improvements across all evaluated operational performance indicators for both excavator fleets. Overall, the results indicate higher productivity, lower non-productive time, shorter cycle time, and improved fleet synchronization after DSL implementation. These findings suggest that optimizing truck positioning and loading continuity can significantly enhance the effectiveness of loading and hauling operations. A summary of the operational performance before and after DSL implementation is presented in Table 3.

Table 3 demonstrates that the operational benefits of DSL were observed consistently across both the 250-ton and 300-ton excavator fleets. The most notable improvement was the increase in excavator productivity, accompanied by substantial reductions in queuing time, hanging time, and cycle time. In addition, match factor values moved closer to the optimal condition of 1.0, indicating better synchronization between loading and hauling equipment. The simultaneous improvement across all performance indicators suggests that DSL enhanced not only loading efficiency at the equipment level but also the overall interaction between excavators and haul trucks. Consequently, the observed productivity gains were achieved through a combination of improved loading continuity, reduced waiting-related losses, and better fleet synchronization across the loading-hauling system.

3.2 Effect of DSL on Excavator Productivity

Excavator productivity is one of the most important indicators for evaluating the effectiveness of loading operations because it directly reflects the amount of material moved within a given operating period. Following the implementation of DSL, both excavator fleets exhibited noticeable productivity improvements, indicating a more efficient loading process and better utilization of available equipment. The productivity comparison before and after DSL implementation is presented in Figure 5.

Table 3. Comparison of operational performance indicators before and after DSL implementation

Parameter	250T Before	250T After	Improvement	300T Before	300T After	Improvement
Productivity (BCM/h)	852	1020	+20%	1178	1379	+17%
Hanging Time (s)	40	29	-34%	22	14	-26%
Queuing Time (s)	156	110	-25%	159	116	-29%
Cycle Time (s)	33.7	29.5	-12.46%	34.5	30.0	-13.04%
Match Factor	0.96	1.00	+3.8%	0.98	1.02	+4.6%

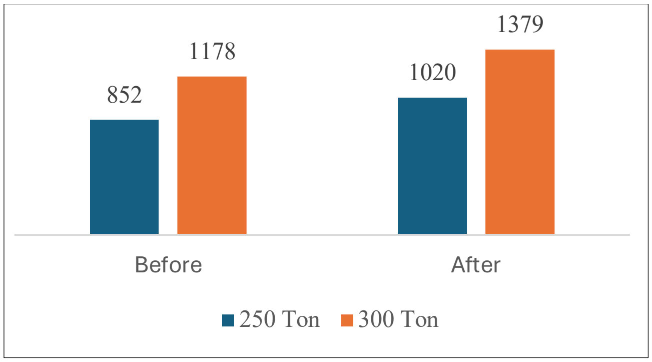

Figure 5. Excavator productivity before and after DSL implementation

As shown in Figure 5, excavator productivity increased significantly after the implementation of DSL for both fleet categories. The 250-ton excavator fleet recorded an increase from 852 BCM/h to 1,020 BCM/h, representing a productivity improvement of approximately 20%. Similarly, the 300-ton fleet achieved an increase from 1,178 BCM/h to 1,379 BCM/h, corresponding to a productivity gain of approximately 17%. In absolute terms, productivity increased by 168 BCM/h for the 250-ton fleet and 201 BCM/h for the 300-ton fleet. The observed productivity improvement can be attributed primarily to the reduction of operational interruptions during truck replacement activities. Under the conventional Single Side Loading configuration, loading continuity was frequently affected by truck maneuvering and positioning delays, causing temporary excavator idle periods between loading cycles. In contrast, the DSL configuration enabled the next truck to be positioned and prepared while loading activities were still in progress, thereby reducing waiting time and improving loading continuity. This improvement indicates that a larger proportion of the excavator operating time was converted into productive loading activities, thereby increasing material movement capacity without additional equipment deployment.

From an operational perspective, the productivity gains achieved in this study demonstrate that loading pattern optimization can substantially improve material movement efficiency without requiring additional loading or hauling equipment. The results indicate that improvements in fleet interaction and truck availability at the loading point can generate significant productivity benefits through more continuous utilization of excavator operating time. These findings suggest that operational design improvements can deliver measurable production gains while maintaining the same fleet composition and operating resources.

The productivity improvements observed in this study are consistent with previous research highlighting the importance of loading-hauling optimization in improving mining performance. (Aguayo et al., 2021) reported that improvements in loading system configuration increased shovel-truck productivity by approximately 13%, while (Zhang et al., 2022) demonstrated that optimized truck-shovel allocation could improve production performance by 3.75%. Compared with these findings, the productivity gains achieved through DSL implementation (17–20%) indicate that loading pattern optimization can provide substantial operational benefits under actual mining conditions.

3.3 *Effect of DSL on Non-Productive Time*

Non-productive time is one of the primary factors affecting loading efficiency and equipment utilization in open-pit mining operations. In this study, non-productive operational losses were represented by queuing time and hanging time, which reflect delays experienced by haul trucks and excavators during loading activities. The implementation of DSL was expected to improve loading continuity by reducing equipment waiting periods and truck replacement delays. The comparison of queuing time and hanging time before and after DSL implementation is presented in Figure 6.

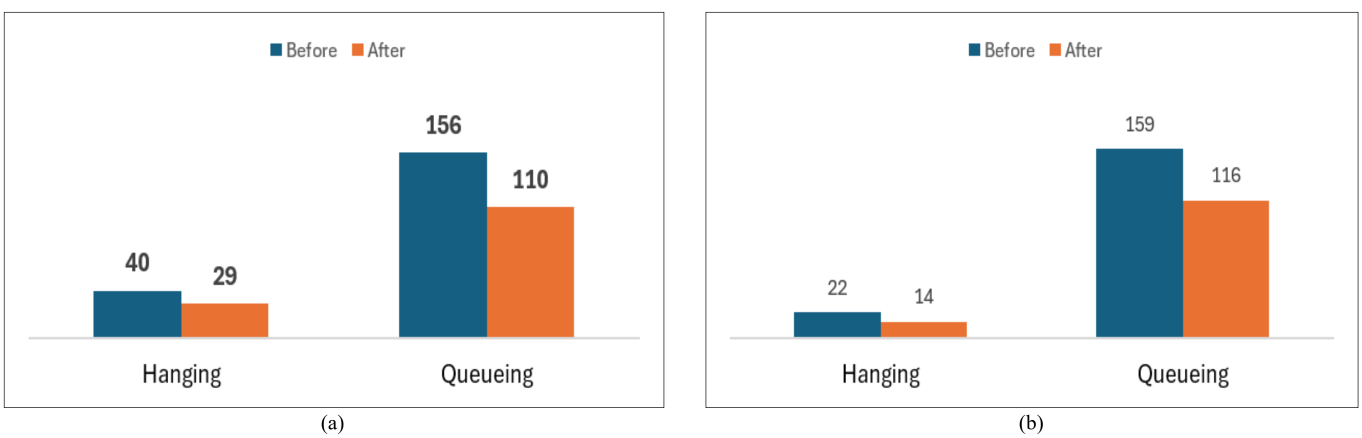

Figure 6. Comparison of hanging time and queuing time before and after DSL implementation for (a) 250-ton and (b) 300-ton excavator fleets.

Figure 6 shows that DSL significantly reduced both queuing time and hanging time for the two excavator fleets. For the 250-ton fleet, queuing time decreased from 156 s to 110 s, representing a reduction of approximately 25%, while hanging time decreased from 40 s to 29 s, corresponding to a 34% reduction. Similarly, for the 300-ton fleet, queuing time decreased from 159 s to 116 s (29%), whereas hanging time was reduced from 22 s to 14 s (26%).

The reduction in queuing time indicates that haul trucks were able to access loading positions more efficiently after the implementation of DSL. Under the conventional Single Side Loading configuration, incoming trucks often had to wait for the preceding truck to complete loading and exit the loading area before positioning could begin. This sequential process created truck queues at the loading point, particularly during periods of high fleet activity. By allowing trucks to occupy alternating loading positions on both sides of the excavator, DSL reduced truck positioning delays and improved the flow of loading operations. An equally important finding is the substantial reduction in hanging time, which represents periods when excavators were idle while waiting for truck arrival or positioning. The reduction observed in both fleets indicates that DSL improved truck availability at the loading point and minimized interruptions between consecutive loading cycles. As a result, excavators spent a greater proportion of operating time performing productive loading activities rather than waiting for haul trucks, contributing directly to improved equipment utilization and operational efficiency.

3.4 *Effect of DSL on Cycle Time and Match Factor*

Cycle time and match factor are important indicators for evaluating the effectiveness of fleet interaction during loading and hauling operations. Reductions in equipment waiting time are expected to improve loading continuity, shorten cycle duration, and enhance the balance between loading and hauling capacities. The comparison of cycle time before and after DSL implementation is presented in Figure 7, while changes in match factor are summarized in Table 3.

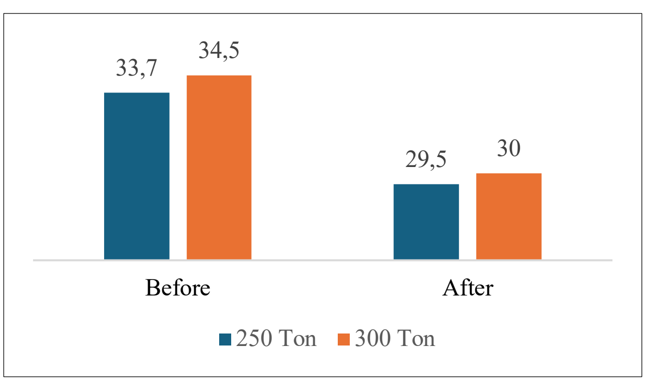

Figure 7. Comparison of cycle time before and after DSL implementation for 250-ton and 300-ton excavator fleets.

As illustrated in Fig. 7, DSL implementation resulted in a noticeable reduction in cycle time for both excavator fleets. The average cycle time of the 250-ton fleet decreased from 33.7 s to 29.5 s, representing a reduction of 12.46%. Similarly, the 300-ton fleet experienced a decrease from 34.5 s to 30.0 s, corresponding to a reduction of 13.04%.

The reduction in cycle time can be attributed to improvements in truck positioning and loading continuity achieved through the DSL configuration. Under the conventional Single Side Loading arrangement, excavators frequently experienced interruptions while waiting for trucks to complete maneuvering and positioning activities. By enabling trucks to alternate loading positions on both sides of the excavator, DSL reduced truck replacement delays and allowed loading activities to proceed more continuously. Consequently, a greater proportion of the operating cycle was utilized for productive loading activities rather than waiting-related losses.

In addition to cycle time improvement, match factor values increased from 0.96 to 1.00 for the 250-ton fleet and from 0.98 to 1.02 for the 300-ton fleet. These values indicate that the interaction between loading and hauling equipment became more balanced after DSL implementation. Match factor values approaching unity suggest that truck arrivals were better synchronized with excavator loading capacity, reducing inefficiencies associated with both under-trucking and over-trucking conditions.

A particularly important observation is that the reduction in cycle time was accompanied by an improvement in match factor. This relationship indicates that the benefits of DSL extended beyond local improvements at the loading point and influenced the overall coordination of the loading-hauling system. While reductions in queuing time and hanging time primarily reflect improvements at the equipment level, match factor represents a system-level performance indicator. Therefore, the movement of match factor values toward the optimal range demonstrates that DSL contributed to better fleet synchronization and more efficient utilization of both excavators and haul trucks. These findings suggest that loading pattern optimization can enhance operational performance not only by accelerating individual loading cycles but also by improving the balance of the entire loading-hauling process.

The findings are consistent with previous studies emphasizing the importance of cycle time optimization and fleet balancing in mining operations. (Mnzool et al., 2024) reported that reducing loading-hauling cycle time is one of the most effective approaches for improving operational productivity. Similarly, (Zhang et al., 2022) demonstrated that better truck-shovel coordination can improve production performance through more efficient equipment allocation. The results obtained in this study further indicate that such improvements can also be achieved through loading pattern optimization, without requiring additional loading or hauling equipment.

3.5 Effect of DSL on Cycle Time and Match Factor

To verify whether the operational improvements observed after DSL implementation were statistically significant, a paired sample t-test was conducted for all evaluated performance indicators. The analysis compared operational performance under Single Side Loading and Double Side Loading configurations using a significance level of 5% ($\alpha = 0.05$). The results of the statistical analysis are presented in Table 4.

As shown in Table 4, all evaluated parameters produced p-values below the significance threshold of 0.05. These results indicate that the observed differences between the pre-implementation and post-implementation conditions were statistically significant. Therefore, the null hypothesis was rejected for all operational performance indicators, confirming that DSL implementation had a measurable effect on loading and hauling performance.

Among the evaluated parameters, queuing time and hanging time exhibited the strongest statistical evidence of improvement, reflecting the direct impact of DSL on reducing operational delays and equipment waiting periods. The significant reduction in cycle time and corresponding improvement in match factor further support the conclusion that DSL enhanced fleet synchronization and loading continuity. Consequently, the productivity gains observed in both excavator fleets can be attributed to systematic operational improvements rather than random variations in operating conditions. Overall, the results demonstrate that Double Side Loading is an effective operational strategy for improving loading and hauling performance in open-pit mining operations. The implementation successfully reduced non-productive activities, shortened cycle time, improved fleet balance, and increased excavator productivity for both excavator classes. The statistical analysis further confirmed that these improvements were significant, providing strong evidence that loading pattern optimization can generate substantial operational benefits without requiring additional equipment or major infrastructure modifications.

Table 4. Results of paired sample t-Test for operational performance indicators

Parameter	p-value	Interpretation
Excavator Productivity	0.003	Significant
Queuing Time	0.001	Significant
Hanging Time	0.0001	Significant
Cycle Time	0.004	Significant
Match Factor	0.008	Significant

4. Discussion

The results demonstrate that the implementation of DSL generated measurable improvements across multiple dimensions of loading and hauling performance. Significant gains were observed in excavator productivity, fleet synchronization, cycle time efficiency, and reductions in non-productive operational activities. These findings suggest that loading pattern optimization can improve operational effectiveness without requiring additional loading or hauling equipment. The observed improvements indicate that operational efficiency should not be viewed solely as a function of equipment capacity but also as a consequence of how effectively loading and hauling activities are coordinated within the mining system.

First, the productivity improvements observed in this study indicate that DSL played a critical role in reducing operational interruptions associated with truck replacement and positioning activities. The simultaneous reduction in queuing time, hanging time, and cycle time demonstrates that the productivity gains were achieved through improved loading continuity rather than increased equipment capacity. Under conventional Single Side Loading operations, excavators frequently experience temporary idle periods while waiting for truck maneuvering and positioning activities to be completed. By allowing trucks to occupy alternating loading positions on both sides of the excavator, DSL minimized these interruptions and increased the proportion of productive loading time. The productivity improvements of 20% for the 250-ton fleet and 17% for the 300-ton fleet exceeded those reported in several previous loading and hauling optimization studies. (Aguayo et al., 2021) reported approximately 13% productivity improvement through loading system optimization, while (Zhang et al., 2022) observed production improvements of approximately 3.75% through truck-shovel allocation optimization. The higher productivity gains achieved in the present study suggest that loading pattern optimization can generate substantial operational benefits under actual mining conditions when implemented at the loading face level.

Second, the results highlight the importance of fleet synchronization as a key mechanism underlying operational performance improvement. The reduction in queuing time reflects improved truck access to loading positions, whereas the reduction in hanging time indicates fewer excavator idle periods caused by truck unavailability. These improvements were accompanied by reductions in cycle time and match factor values approaching the optimal condition of 1.0. From an operational perspective, match factor represents a system-level indicator that reflects the balance between loading and hauling capacities. The improvement from 0.96 to 1.00 for the 250-ton fleet and from 0.98 to 1.02 for the 300-ton fleet demonstrates that DSL improved the interaction between excavators and haul trucks, reducing inefficiencies associated with both under-trucking and over-trucking conditions. The findings therefore suggest that the operational benefits of DSL extend beyond individual equipment performance and contribute to improved coordination across the entire loading-hauling system.

Third, the findings demonstrate that DSL provides a practical and cost-effective operational improvement strategy for open-pit mining operations. Unlike productivity improvement initiatives that require additional equipment, fleet expansion, or major infrastructure investment, DSL primarily relies on optimizing truck positioning and loading sequence arrangements. Consequently, significant productivity gains can be achieved with relatively limited capital expenditure while maintaining the same fleet composition. This characteristic makes DSL particularly attractive for mining operations seeking short-term productivity improvements under capital constraints. Furthermore, the operational simplicity of DSL may facilitate implementation across different mining environments where loading and hauling activities represent a major production bottleneck.

Despite the positive results, several limitations should be acknowledged. First, the study was conducted within a single mining operation using specific excavator and haul truck configurations, which may limit the direct applicability of the findings to other mining environments with different fleet compositions, bench geometries, and operational constraints. Second, the evaluation focused primarily on operational performance indicators, including productivity, queuing time, hanging time, cycle time, and match factor, while broader economic and environmental impacts were not explicitly assessed. Third, the analysis covered a relatively limited observation period and did not evaluate the long-term sustainability of the observed improvements under changing production targets, mining sequences, or operational conditions. Therefore, caution should be exercised when generalizing the results to different mining contexts.

Future research should expand the evaluation across multiple mining sites, fleet configurations, and loading conditions to improve the robustness and generalizability of the findings. In addition, further studies could investigate the integration of Double Side Loading with digital mining technologies such as Fleet Management Systems, real-time dispatch optimization (Wang et al., 2023), (Fadillah & Yandri, 2025), machine learning-based fleet allocation models (Huo et al., 2023), and web-based operational intelligence platforms (Ghifara et al., 2026), (Storey et al., 2024) incorporating real-time monitoring, automated performance reporting, and improvement management functionalities. Such integration may enable mining operations to dynamically adjust loading strategies based on equipment availability, production priorities, and real-time operational conditions while supporting data-driven decision making and continuous operational improvement.

Future investigations may also explore the relationship between loading pattern optimization and fuel efficiency (Alamdari et al., 2022), greenhouse gas emissions (Huo et al., 2023), sustainable mining (Rahnema et al., 2025), and renewable energy integration (Fadillah et al., 2026). Since reductions in waiting-related losses have the potential to decrease fuel consumption and idle operating conditions, evaluating the environmental benefits of DSL could provide a more comprehensive understanding of its contribution to sustainable mining practices. Furthermore, comprehensive techno-economic assessments incorporating operating costs, maintenance requirements, productivity gains, return on investment, and lifecycle impacts would provide valuable insights into the long-term feasibility and economic value of DSL implementation in modern mining operations.

5. Conclusion

This study evaluated the implementation of Double Side Loading (DSL) in an open-pit mining operation using actual operational data collected before and after its implementation. The findings demonstrate that DSL can effectively improve loading-hauling performance by reducing operational interruptions, enhancing loading continuity, and strengthening synchronization between loading and hauling equipment. The observed improvements indicate that loading pattern optimization contributes not only to higher equipment utilization and operational efficiency but also to a more balanced interaction between excavators and haul trucks throughout the production cycle. From a scientific perspective, this study provides empirical evidence on the operational impacts of DSL under actual mining conditions, addressing a gap in the predominantly simulation-based loading-hauling optimization literature. From a managerial perspective, the findings provide practical guidance for mine operators and production planners by demonstrating that meaningful productivity improvements can be achieved through operational redesign and improved fleet synchronization without requiring additional equipment, major infrastructure modifications, or capital-intensive fleet expansion. The findings therefore support operational decision-making by highlighting loading pattern optimization as a viable strategy for improving equipment utilization and production efficiency in open-pit mining operations. Therefore, DSL represents a practical and cost-effective operational improvement strategy that can support productivity enhancement and operational excellence in open-pit mining operations.

Disclosure Statement

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