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OPTIMIZATION OF DUMP TRUCK PRODUCTIVITY IN OPEN-PIT GOLD MINING USING FLEET MANAGEMENT SYSTEM (FMS) TECHNOLOGY

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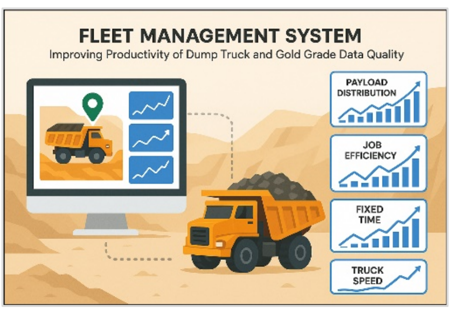
Graphical abstract



Abstract

Hauling rocks or minerals in open-pit mines often experience inefficiencies due to a lack of real-time monitoring and assignment of dump trucks, resulting in reduced productivity and error prone manual data recording. This study evaluates the impact of the Fleet Management System (FMS) on dump truck productivity and discrepancies in gold grade data using four data sources: manual production data, block model data, raw FMS data, and geological sampling data from the processing plant. Key productivity metrics including payload, job efficiency, fixed time, and truck speed were analyzed along with comparisons of gold grade data between Ore Movement and Ore Crusher datasets. Results showed a 15% productivity increase for the CAT773 dump truck (from 147 BCM/km to 169 BCM/km) and a 15.6% rise for the CAT745 (from 96 BCM/km to 111 BCM/km). Additionally, the discrepancy in gold grade decreased by 5.3%, achieving a tonnage difference of 0%. Statistical analysis via a paired t-test confirmed significant improvements (p-value < 0.05). The FMS implementation significantly enhances productivity and gold grade data accuracy in mining material transport, driven by improvements in payload, job efficiency, fixed time, and truck speed.

Keywords: dump truck productivity, productivity indicators, gold grade data, fleet management system, paired t-test

1.0 INTRODUCTION

Open-pit mining is a method employed in the extraction of deposits that are located near the surface, characterized by its non-selectivity and low grade [1]. In this process, the excavated material is subsequently loaded into a transportation system tailored to the specific type of material, whether it be ore or waste, and then transported to designated locations such as a mill, stockpile, or waste dump [2].

In the gold mining operation under study, this method is employed for the extraction of gold, whereby the excavated material must be transported using dump trucks, which serve as the primary choice within the transportation system for open-pit mining operations [3]. The optimization of dump trucks can be delineated into several stages, including the determination of their quantity and distribution, as well as the identification of the most efficient route from the loading point to the disposal site [4].

The productivity of dump trucks is inherently dependent on the size of the load being transported and the number of trips that can be accomplished within a given timeframe. The number of trips per hour is a function of cycle time, which comprises the activities of loading, hauling, dumping, and traveling [5]. The cycle time of dump trucks that does not account for the hauling or traveling activities is referred to as Fixed Time, as its value remains unaffected by the distance of material relocation. Consequently, Fixed Time is utilized to measure the duration of dump truck operations at both the excavation site and the material disposal site. Meanwhile, the activities of hauling and traveling can be represented by the truck's speed.

Payload variance is a critical parameter in the productivity of dump trucks, as ideally, the load being transported should reach its maximum capacity. However, any increase in payload must adhere to the limitations set by the heavy equipment manufacturers to minimize adverse effects on the lifespan of the components [6]. Optimal payload can be defined through various approaches, yet fundamentally, it always aims for dump truck to carry as much material as possible while maintaining the lowest possible level of load variation [7]. The primary challenge in managing payload variance during dump truck operations resides in the loading process [8], which is highly dependent on the performance and precision of the excavator operator. Therefore, a monitoring system that can measure the weight of the material loaded by the excavator in real-time is essential to ensure operational efficiency and reliability.

Heavy equipment utilized for ancillary activities without enhancing production can lead to a decline in overall productivity [9]. Job efficiency is one of the parameters that takes into account operational delays during normal working hours, encompassing factors such as refueling, operator changes, lubrication, traffic, and other variables [10]. The same principle applies to the fixed time theory in optimizing dump truck activities at both excavation and disposal sites, which includes the processes of loading, maneuvering, dumping, and placement [11].

Travel time serves as a crucial parameter for measuring transportation efficiency and effective utilization. Its matrix is highly dynamic, as it depends on numerous operational variables, including truck speed [12].

Errors in ore data recording can lead to discrepancies in the calculation of the gold grade of the material transported by dump trucks, ultimately affecting excavation strategies and production. This issue may arise because ore data is still recorded manually by checkers. Data accuracy is essential for production reports that support short-term excavation planning [13].

To optimize the productivity of dump trucks, a heavy equipment management system capable of real-time monitoring is essential, specifically the Fleet Management System (FMS) [14]. The FMS is designed to automate the management of trucks and excavating equipment, thereby enhancing the productivity of transportation processes by maximizing equipment utilization and reducing operational costs. Each vehicle is equipped with a computer that provides mobile data to the FMS [15]. This system also serves as an exceedingly effective tool for data recording and acquisition. The FMS refers to a database to obtain the necessary operational information and take appropriate actions. When new decisions are required, the FMS is reactivated after those decisions have been implemented in operations (Figure 1) [16].

Recent studies in the mining sector have demonstrated that Fleet Management Systems (FMS) play a critical role in enhancing the efficiency and adaptability of open-pit mining operations. [17] developed a Truck Dispatching System (TDS) that dynamically integrates ore blending decisions with truck scheduling using IoT and wireless communication technologies, enabling improved hauling efficiency and stable ore quality under dynamic operational conditions. Building on this, [18] proposed an adaptive real-time dispatching model that accounts for both loaded and empty truck movements through a multi-objective optimization framework, resulting in increased productivity, reduced operational costs, and improved shovel utilization and energy efficiency. Meanwhile, [19] introduced the concept of an upper bound on mine productivity for long-term planning and simple dispatching rules for short-term operations, showing that simplified strategies can achieve near-optimal productivity, although efficiency declines as the fleet approaches saturation. Addressing the limitations of conventional FMS [20] proposed a modular, real-time data-driven smart fleet management architecture capable of adapting to dynamic operational conditions, positioning FMS as an intelligent decision support system. Furthermore, [21] demonstrated that integrating FMS with GPS, GIS, and real-time data communication reduces empty truck idle time, operational costs, and CO_2 emissions, highlighting the role of FMS in both productivity improvement and sustainable mining operations.

This study introduces several key novelties compared to previous FMS research in open-pit mining. Focusing on gold mining—where grade accuracy is critical due to high economic value and low tolerance for error—it uniquely examines discrepancies between ore movement and crusher grade data, an aspect rarely addressed in prior studies. A comprehensive evaluation framework is applied using four operational parameters (payload, job efficiency, fixed time, and truck speed), supported by real-time data integration from Equipment Onboard Monitoring (EOM). This enables a multi-parameter productivity analysis that goes beyond conventional cycle time or utilization metrics. Statistical validation through paired t-tests further strengthens the robustness of the findings, distinguishing this work from predominantly descriptive studies. Moreover, separate analyses for CAT773 and CAT745 trucks provide fleet-type-specific insights into FMS effectiveness. Overall, the study demonstrates that FMS implementation enhances not only operational efficiency but also production data quality, significantly reducing tonnage and grade discrepancies in hauling operations.

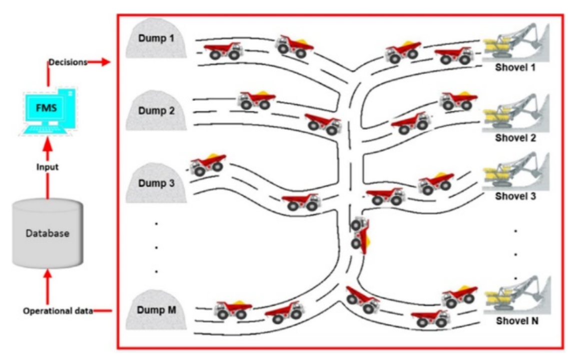


Figure 1 Illustrates the operational schema of open-pit mining and the communication methods employed with the FMS [16]

2.0 METHODOLOGY

2.1 Tools and Materials

This study utilizes four sources of data. First, manual production data from the first and second months, which represent the operational conditions of mining without the FMS. This data includes the number of trips (rit/load) reported manually by the operators to the Dispatcher. Second, FMS production data collected over a five-month period. Data from the first and second months serve as supplementary information for the pre-implementation phase of the FMS, particularly for parameters absent from the manual data, such as cycle time, material relocation distance, and dump truck payload. The data from the third to fifth months illustrates the period following the implementation of the FMS. Third, block model data obtained from geological sampling conducted in the planned blasting area or excavation site. Fourth, ore sampling data that has undergone the crushing process at the processing plant. Sampling is carried out periodically every 30 minutes on the material situated on the belt conveyor.

Several tools were employed in this study. Among them, the FMS software was utilized to monitor the activities and assignments of dump trucks. Microsoft Excel was employed to cleanse the data of outliers pertaining to fixed time, calculate the productivity of dump trucks, and compute the average of each production parameter for inter-month comparisons. Additionally, Minitab software was used to test hypotheses through paired t-tests across the data. A detailed account of the tools and materials used in this research is presented in Table 1.

Table 1 Tools and Materials

Tools	Materials	
	Category	Details
FMS Software Ms. Excel Minitab	Manual production data	Dump truck trips (load), excavator ID, block reference, material type, dump location, dump truck capacity
	FMS production data	Dump truck trips (load), excavator ID, block reference, material type, dump location, payload and dump truck capacity, haul distance, cycle time, dump truck activities
	Block model data	Material type, ore grade, material density
	Ore crusher sampling data	Material type, ore grade, material density

2.2 Methods

Data processing was conducted using Microsoft Excel and Min itab software. Operational indicators were derived from raw data and their relationships with dump truck productivity were analyzed using Microsoft Excel. Gold grade data obtained from geological sampling at the processing plant were compared with manual production records and FMS production data from hauled materials, and the results were presented on a monthly basis to illustrate grade variations. The analysis included monthly comparisons of dump truck productivity and its relationships with payload, job efficiency, fixed time, and truck speed. The payload performance of CAT773 dump trucks was evaluated against the manufacturer-recommended target (10/10/20), while job efficiency and fixed time were assessed on a monthly basis. In addition, gold grade values derived from FMS data were compared with manual production data and geological sampling results. Prior to statistical analysis, outliers in the FMS cycle time data were removed using the Z-score method to enhance data accuracy and mitigate potential recording discrepancies caused by poor GSM signal quality.

Finally, the research hypotheses were tested using paired t-tests in Minitab to determine whether statistically significant differences existed between conditions before and after FMS implementation.

2.3 Dump Truck Productivity and Associated Indicators

Dump truck productivity refers to the amount of material or ore that can be transported by a single dump truck within a specified work period and can be calculated using equation (1).

$$Pdty_{\,(bcm)} = T_f \; x \; L_d \; x \; E \; x \;\; MA \qquad (1)$$

By multiplying the truck factor (Tf) by the number of dump truck cycles in a day (Ld) and the work efficiency of the dump truck (E), then further multiplying by mechanical availability (MA), the daily productivity of the dump truck (Pdty) can be computed [22].

The nominal payload of the Caterpillar 773E dump truck is 55 tons, which can be evaluated against the targets recommended by Caterpillar through the load distribution graph illustrated in Figure 2.

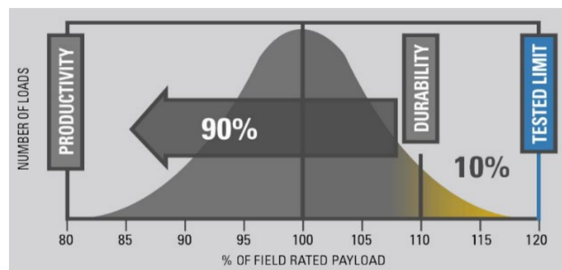


Figure 2 The 10/10/20 payload policy for Caterpillar dump trucks [6]

Job efficiency (JE) is employed to reflect the delays that occur during standard working hours and can be calculated using equation (2).

$$Job\ Efficiency\ (JE) = \frac{EH}{OH} \qquad (2)$$

Job efficiency (JE) is defined as the ratio of efficiency hours (EH) to operating hours (OH), where operating hours (OH) is the sum of efficiency hours (EH) and operating delay hours (OD) [10].

The fixed time (Ft) for the dump truck can be expressed by equation (3), which is derived by summing the queue time at the excavator (tql), maneuvering time in the excavation area (tsp), loading time (tld), queue time at the dump site (tqd), and the unloading time (tdp).

$$F_t = \; t_{ql} \; x \; t_{sp} \; x \; t_{ld} \; x \;\; t_{qd} \; x \; t_{dp} \qquad (3)$$

The travel time of a dump truck is defined as the ratio of the distance traveled to the average speed [12]. Consequently, the average speed of the dump truck (ATS) can be calculated using equation (4), which represents the ratio of distance traveled (HD) to the average travel time (ATT).

$$Avg.Truck\ Speed\ (ATS) = \frac{HD}{ATT} \qquad (4)$$

2.4 Gold Grade Data

The sample data at the processing plant is reconciled with the sample data from the blast holes to connect the production tonnage and the gold grades dispatched from the pit to the processing facility. The production tonnage is derived from manual recording data and FMS data, allowing for a comparison of data accuracy before and after the FMS implementation.

2.5 Paired t-Test

In this experiment, the productivity of the dump truck and its associated indicators are assessed over two distinct time periods: two months prior to the implementation of the FMS and three months subsequent to its implementation.

3.0 RESULTS AND DISCUSSION

3.1 Trends in Dump Truck Productivity and Related Indicators

The calculations of dump truck productivity indicate a consistent upward trend following the implementation of the FMS, with values remaining relatively stable. This improvement is noted for both types of dump trucks, namely the CAT773 and CAT745, showing increases of 15% (from 147 BCM/km to 169 BCM/km) and 15.6% (from 96 BCM/km to 111 BCM/km), respectively, as illustrated in Table 2 and Figure 3.

Table 2 Productivity of dump trucks per kilometer

Period		Productivity (BCM)		Distance (km)		Productivity (BCM/km)	
		CAT773	CAT745	CAT773	CAT745	CAT773	CAT745
Before	Month 1	51	36	2.95	2.66	151	97
	Month 2	50	32	2.90	2.92	144	95
After	Month 3	53	38	3.11	2.94	165	111
	Month 4	55	39	3.10	2.86	171	111
	Month 5	52	38	3.32	2.90	173	112

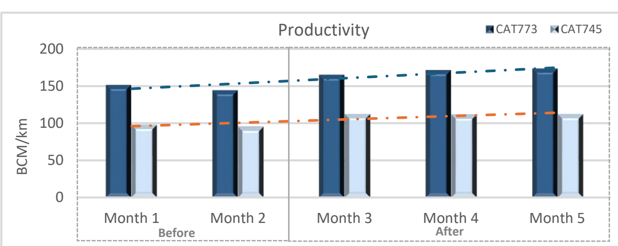


Figure 3 Trend of dump truck productivity per kilometer

This rise in productivity is aligned with enhancements in related indicators, including an increase in average payload of 6%, rising from 51.7 tons to 54.9 tons (Figure 4). Furthermore, the distribution of payloads exhibited significant improvement, with 83% falling within the target range, up from a mere 58% of total cycles previously (Figure 5).

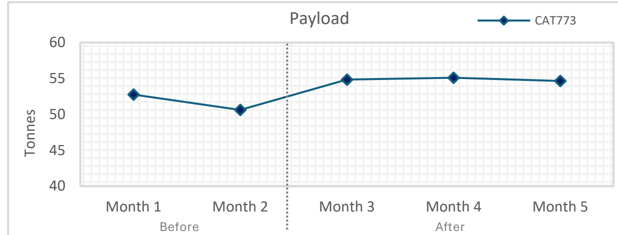


Figure 4 Trend of dump truck payload

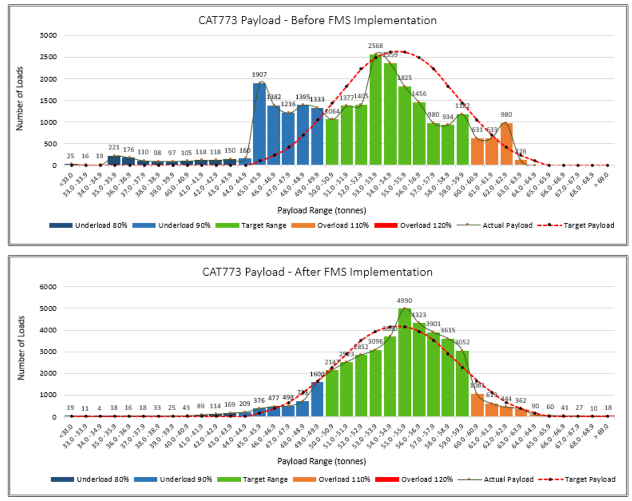


Figure 5 Payload Distribution Before and After FMS Implementation

The trend of job efficiency for both types of dump trucks also reflects an increase of 2%, rising from an average of 92% to 94% (Figure 6). This enhancement is primarily attributed to the reduction in the duration of delay activities, including shift changes, refueling, toilet stops, operator changes, and daily prayers. Notably, the delay time due to operator changes has seen the most significant decrease, with an average reduction of 49% for the CAT773 and 54% for the CAT745.

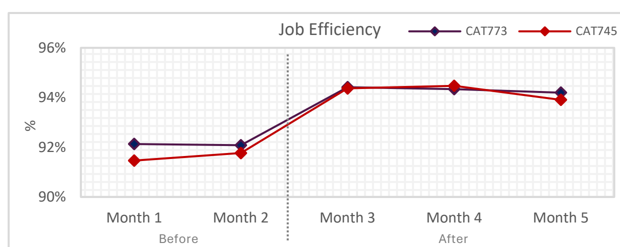


Figure 6 Trend of dump truck job efficiency

Moreover, the trend of fixed time has also experienced a decline for both types of dump trucks. For the CAT773 model, there was an 11% reduction, equivalent to 0.53 minutes, whereas the CAT745 model saw a 17% decrease, amounting to 0.83 minutes (Figure 7). On the other hand, the trend in truck speed indicates an improvement following the implementation of the FMS. The average truck speed of the CAT773 increased by

11%, or 1.8 km/h, while the CAT745 saw an 8% rise, or 1.4 km/h (Figure 8).

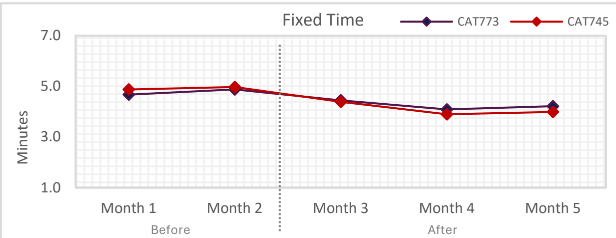


Figure 7 Trend of dump truck fixed time

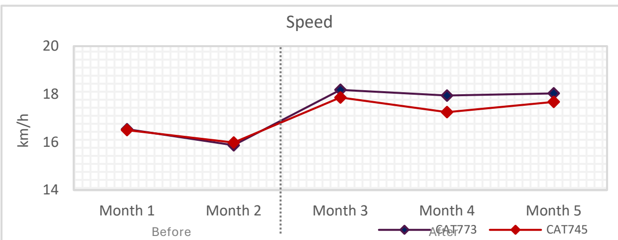


Figure 8 Trend of dump truck speed

It is noteworthy that prior to the implementation of the FMS, the impact of adverse weather on truck speed was recorded to be 38% greater than in the period following the implementation. This factor significantly contributed to the findings of this analysis, as presented in Table 3.

Table 3 Duration of Adverse Weather in Dump Truck Operational Areas

Period		Weather (hours)			
		Rain	Slippery	Foggy	Total
Before	Month 1	89.2	14.2	78.1	181.5
	Month 2	139.7	15.0	144.1	298.8
After	Month 3	32.0	0.6	42.4	75.0
	Month 4	52.7	1.6	77.7	132.0
	Month 5	26.8	-	213.0	239.8

3.2 Gold Grade Data Quality

Based on the data analysis presented in Table 4, it was discovered that the difference in tonnage experienced a decline, ultimately reaching 0% following the implementation of the FMS. This figure remained stable when compared to the preceding average difference of 6.4%. This indicates that after the application of the FMS, there were no variance in tonnage between the Data Ore Movement and the Data Ore Crusher.

Table 4 Variance between the Data of Crushed Ore and Moved Ore

Period		Ore (kt)		Ore Grade (Au)		Variance	
		Crushed	Moved	Crushed	Moved	Ore	Grade
Before	Month 1	695	748	0.53	0.50	7.1%	5.7%
	Month 2	607	644	0.61	0.57	5.7%	6.4%
After	Month 3	762	762	0.84	0.84	0%	0.5%
	Month 4	721	721	0.79	0.80	0%	1.0%
	Month 5	806	806	0.82	0.83	0%	0.8%

On the other hand, the variance in gold grade has also experienced a decrease, with an average difference of 0.8% following the implementation of the FMS, compared to the preceding average of 6.1%. Although the tonnage for both datasets is identical, the variance in gold grade cannot reach 0% due to the fact that the two datasets were obtained from distinct sampling locations, namely the blasting plan area and the Crusher area. A visualization of the tonnage and gold grade variances for the periods before and after the FMS implementation is presented in Figure 9.

The reduction in the discrepancy of tonnage and gold grade following the implementation of the FMS indicates an enhancement in data quality compared to prior periods. This improvement facilitates a more optimal strategy for the distribution of ore materials in alignment with the required gold grades intended for production, both in the short term and long term, in accordance with planning objectives.

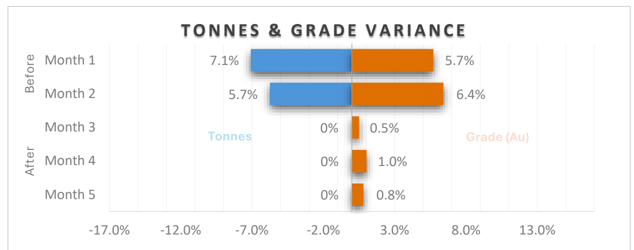


Figure 9 Variance in Tonnage and Gold Grade

3.3 Paired t-Test Analysis

The data employed in the paired t-test analysis includes the productivity of dump trucks and key performance indicators such as payload, job efficiency, fixed time, and truck speed. Prior to conducting the paired t-test, a normality test was performed to assess the distribution of the data. Both the paired t-test and normality test analyses were executed using Minitab® software version 21.4.2 (64-bit).

The normality test was conducted on the entire dataset using a standard criterion of p-value > 0.05 to determine whether the data follows a normal distribution. The results of the normality test are presented in Table 5, indicating that the p-value for the entire dataset exceeds 0.05. Therefore, it can be concluded that the data is normally distributed and meets the assumptions of the normality test.

Table 5 Results of the normality test for productivity data and Its indicators

Data	P-Value	
	CAT773	CAT745
Productivity	0.133	0.885
Payload	0.213	-
Job Efficiency	0.191	0.390
Fixed Time	0.068	0.743
Truck Speed	0.569	0.059

The paired t-test conducted in this study followed several steps. Firstly, the hypotheses were formulated: H_0 posits that there is no significant difference between the data collected before and after the implementation of the FMS, while H_1 asserts that a significant difference exists. The significance level was set at 0.05. The analysis was performed using Minitab software. The results were interpreted based on the p-value: if the p-value is less than 0.05, H_0 is rejected, indicating a significant difference; if the p-value is greater than or equal to 0.05, H_0 fails to be rejected, indicating no significant difference.

The results of the paired t-test calculations demonstrate that the p-value is less than 0.05 for all data, including both productivity and its indicators for CAT773 and CAT745, as presented in Table 6. This finding indicates a significant enhancement in dump truck productivity, accompanied by notable improvements in its supporting indicators, namely increases in payload and job efficiency, a decrease in fixed time, and an improvement in truck speed.

Table 6 Results of the Paired t-Test for Productivity Data and Its Indicators

Data	P-Value	
	CAT773	CAT745
Productivity	0,0000000000146	0,0000034155271
Payload	0,0000000092397	Not Tested
Job Efficiency	0,0000000142396	0,0000000019326
Fixed Time	0,0000003855145	0,0000000710982
Truck Speed	0,0000000000004	0,0000000516317

The implementation of the FMS has demonstrated a positive impact on fleet productivity, resulting in stable performance improvements across both types of dump trucks. Productivity has increased in tandem with a 6% rise in payload and an 83% distribution of loads within the target range. This enhancement is indicative of improved operational efficiency rather than a mere reduction in the quantity of material, as it stems from real-time load monitoring facilitated by the FMS interface, which aids in achieving payload targets with greater consistency and efficiency.

Furthermore, job efficiency has also risen by 2%, propelled by a decrease in delay durations associated with shift changes, refueling, operator transitions, and daily prayers. The most significant reduction has been observed in operator change times, which fell by 49% for CAT773 and 54% for CAT745. This reflects the pivotal role of the FMS in monitoring operational activities in real-time, thereby enabling dispatchers to respond swiftly to instances of unproductive activity.

Moreover, the fixed time exhibited a reduction of 11% for CAT773 and 17% for CAT745, indicating the effectiveness of the FMS in monitoring unproductive time. Real-time monitoring facilitates prompt actions such as optimizing the number of units, enhancing work areas, and improving operator competency.

The average truck speed also experienced an increase of 11% for CAT773 and 8% for CAT745, in alignment with improvements in road infrastructure and more efficient traffic management. Prior to the implementation of the FMS, the impact of adverse weather conditions on truck speed was observed to be 38% greater compared to the post-implementation period, further contributing to performance enhancements.

Overall, the FMS enables a more adaptive and data-driven approach to fleet management. Flexible unit assignment, coupled with real-time monitoring of operational indicators such as payload, job efficiency, fixed time, and truck speed, promotes quicker and more accurate decision-making by operators, dispatchers, and field supervisors.

These findings corroborate the study by [18], which underscores the significance of adaptive and real-time truck dispatching in reducing fixed time. [16] also assert that flexible truck allocation across multiple excavators significantly impacts productivity, while [23] emphasize the advantages of real-time data in enhancing efficiency and the quality of decision-making.

Furthermore, the accuracy of production data has also improved. The discrepancy in the gold grade of material transferred to the plant has declined from 6.1% to 0.8%, and the difference between ore movement and ore crusher has been reduced to 0%. This improvement is attributed to the automated recording of dump truck activities by the FMS, which eliminates manual input errors and presents data in a readily usable format.

As elucidated by Gopalan & Raphael [24], the transition from manual recording to a digital system represents a significant advancement in fleet management. Digitalization not only enhances accuracy and efficiency but also reduces human error and workload, creating a more precise and reliable operational system.

4.0 CONCLUSIONS

The results of the study indicate that the implementation of the FMS has a positive impact on dump truck productivity and the quality of gold production data. The CAT773 dump truck experienced a productivity increase of 15%, rising from 147 to 169 BCM/km, while the CAT745 improved by 15.6%, from 96 to 111 BCM/km. This productivity was consistently maintained throughout the implementation period. Additionally, other indicators exhibited improvements: the average payload of the CAT773 increased by 6%, from 51.7 tons to 54.9 tons, along with a significant 25% enhancement in payload distribution within the target range. Job efficiency rose from 92% to 94%, while fixed time decreased by 11% for the CAT773 and 17% for the CAT745. Truck speed also showed an upward trend, increasing by 11% for the CAT773 and 8% for the CAT745. Furthermore, the implementation of the FMS contributed to reducing the gold grade discrepancy between Ore Movement and Ore Crusher data from 6.1% to 0.8%, effectively eliminating the tonnage discrepancy to 0% during that period. The statistical analysis from the paired t-test revealed significant changes between the periods before and after the FMS implementation, with a p-value < 0.05 for all analyzed data, reinforcing that the FMS effectively enhances productivity and operational efficiency. To maximize the benefits of the FMS and support further research, three key recommendations are proposed. First, the development of a Material Blend feature within the FMS could enhance the efficiency of stockpile management and reduce reliance on manual adjustments through automated assignments based on metal grade requirements. Second, utilizing more detailed operational data, such as material fragmentation conditions, road improvements, and dust impact, is crucial for a more accurate productivity analysis. Finally, a financial analysis of the FMS implementation is necessary to assess cost efficiency, productivity gains, and its impact on the mine's profitability.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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