Mining of Mineral Deposits
Volume 18 (2024), Issue 1, 18-26

https://doi.org/10.33271/mining18.01.018

Optimization of cycle time for loading and hauling trucks in open-pit mining

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Abstract

Purpose. The purpose of the paper is to provide open-pit mining operations with practical strategies and insights to optimize truck loading and hauling cycles, ultimately leading to enhanced productivity and economic advantages.

Methods. The objectives are to minimize loading time, optimize the haul road network, enhance truck performance, and optimize dumping and return time. By diligently implementing these methods and achieving these objectives, open-pit mining operations can significantly reduce the truck cycle times, resulting in increased productivity, lower costs and improved profitability.

Findings. In this case, the total loading time of the excavator and shovel is determined to be 3.98 and 2.92 minutes, respectively, while the hauling time for total loading of the open-pit floor depends mainly on the average distance and speed of 239 m and 10.1 km/hour, which results in 1.53 minutes.

Originality. As a result, the total cycle time for open-pit mining is 19.765 minutes, resulting from the total loading time, hauling time for total loading, total dumping time, and total return time for empty transport of 4.265, 8.46, 0.86 and 6.18 minutes, respectively.

Practical implications. By combining theoretical analysis with practical insights and site-specific considerations, the paper aims to provide a comprehensive and applicable framework for optimizing truck cycle time in open-pit mining, resulting in improved efficiency and profitability of mining operations.

Keywords: *cycle time, trucks, loading time, open pit, minimization, dumping time, sustainability*

1. Introduction

Optimization of loading and hauling is intended to solve the problems that occur during the loading and hauling of mine materials. When these problems are solved, the project is going to have a good quality of roads, an improved rate of production, and short cycle time. The paper addresses the optimization of the cycle time for loading and hauling equipment for surface mining. Given the mine plan, the ultimate objective is to select trucks and loaders such that overall material handling costs are minimized. Such a fleet must be robust enough to cope with the dynamic nature of mining operations, where production schedule can sometimes depend on refinery requirements and demand. Due to the scale of operations in the mining industry, even small improvements in operational efficiency result in substantial savings over the life of the mine. Improvements include haul road optimization, where the ultimate efficient track for the system is used through production analysis, reducing cycle time and hauling costs, as well as improving productivity and sustainability [1], [2].

Mine fleets are equipment used in mining operations such as drilling, blasting, loading and hauling. The movement of large volumes of bulk materials, such as soil, gravel, and broken rock, in road construction, mining, building, quarrying, and land clearance may be handled by off-road vehicles. A wide range of working tool attachments can be added (and removed) without modifying the basic machine and are available to enhance the efficiency and versatility of the equipment [3].

The primary advantage of truck haulage is its ability to flexibly adjust haulage routes in response to ongoing operations, future mining procedures, and expansions or modifications in mining plans as the mine's lifespan extends. The potential advantages of flexibility are evident as mining becomes increasingly difficult in mines characterized by the segregation of resources into multiple dispersed work areas, greater depths, high rock stress, or the need to access smaller deposits that may not justify the installation of fixed or flow infrastructure such as railway lines, conveyors and shafts [4]-[7].

Received: 30 October 2023. Accepted: 6 January 2024. Available online: 30 March 2024

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

In this study, the main objective is to optimize the insufficient mine production at Bisha Mining Share Company (BMSC), Eritrea, East Africa, based on activity, cycle time and production data collected from the mine site.

On the surface, mining hauling and loading can be considered the most important part, since its cost is quite dependent on expenses for mining hauling [8]. Loading and hauling is the crucial stage throughout open-pit mining [9]. The objective of the paper is to manage and develop loading and hauling, and a concerted effort has been made to make it easier, simpler, and more efficient. All focus is on improving production units, decreasing cycle time, and adjusting factors affecting production such as dust, groundwater and pollution.

The profitability ratio is one of the most significant operation factors. Overall Equipment Efficiency (OEE) is used as an essential factor in the profitability index. Additional profitability ratios can be improved by optimizing the equipment combination using a matching factor [10]. To continually improve and increase both quality and output [11], it is recommended that the association propose maintenance services. OEE is one of the performance appraisal procedures common in the manufacturing industry. OEE has been designed to minimize stoppage time, reduce machine breakdown, limit idling, reduce quality defects, increase productivity index, optimize process factors and improve profits [12].

Optimized analysis through Design of Experiments (DOE), K.K. WAGH Institute of Engineering Education and Research noted that OEE is an important performance measurement for the effectiveness of any equipment. However, accurate analysis is required to understand the impact of the various elements. The loading and hauling approach in open-pit mining has been considered the main important part of the mining sector for a long time due to its expansion in size, scale and modernization of machinery. In open-pit mining, the Shovel-Truck (ST) is the widespread method for the loading and hauling stage [13]-[15]. The Mine Production Index (MPI) has been adjusted by several scholars due to the limitations of the original OEE. This study is aimed to modify the OEE for the mining industry by introducing weights to its elements for the Mine Production Index (MPI). As a specific application of MPI, the shovel has been developed [16], which can be used for estimating the shovel efficiency. Based on the analysis, utilization comes first, followed by performance and availability [17].

The concept of Total Productive Maintenance (TPM) was introduced by Nakajima in 1971 in Japan. According to TPM, operators and maintenance personnel share responsibility for keeping the machine in working order. The operator must be thoroughly trained to effectively monitor and address a range of maintenance and problem detection concerns. Under this scenario, it is recommended to create small teams dedicated to production and maintenance tasks to minimize downtime and optimize the use of equipment, thus enhancing the equipment life cycle. The primary aim of Total Productive Maintenance (TPM) is to minimize operational and maintenance defects, resulting in zero breakdowns. Additionally, TPM strives to achieve minimal waste and accidents, approaching a state of zero [18]. In this context, a range of metrics including cycle time, bucket-fill factor, material-swell factor, dependability, availability, maintainability, utilization and production efficiency are widely utilized to assess the performance of BELT equipment [19].

The purpose of this paper is to provide open-pit mining companies with suitable practical methodology and profound insights to maximize the efficiency of truck loading and hauling cycles, ultimately leading to increased production and substantial economic benefits. Objectives include reducing loading times, optimising the haul road network, increasing truck performance and optimizing unloading and return times.

2. Methodology

The research is mainly dependent on data determined on the site: loading and hauling supervisors travelling to the site, mining planners working on the site, and also on machine operators observing and recording the process behaviour.

2.1. Case study

The Bisha Pit is planned to be approximately 1.5 km long and 1 km wide, as shown in Figure 1. In addition, the slope heights range from 160 to 290 m. BMSC has completed work on rock mass characterization, structural geology and slope stability assessments to develop the open-pit slope designs for the Main Zone. There are two permanent waste dumps: the North Waste Dump (NWD) for dumping potential acid-generating (PAG) material, the South Waste Dump (SWD) for dumping non-acid-generating (NAG) material, as well as a third temporary waste dump known as the West Waste Dump (WWD) for dumping NAG materials. But the NWD is no longer used, and the WWD will no longer be used for dumping after the NAG materials are finished. Thus, only the SWD is considered for the purpose of optimisation.

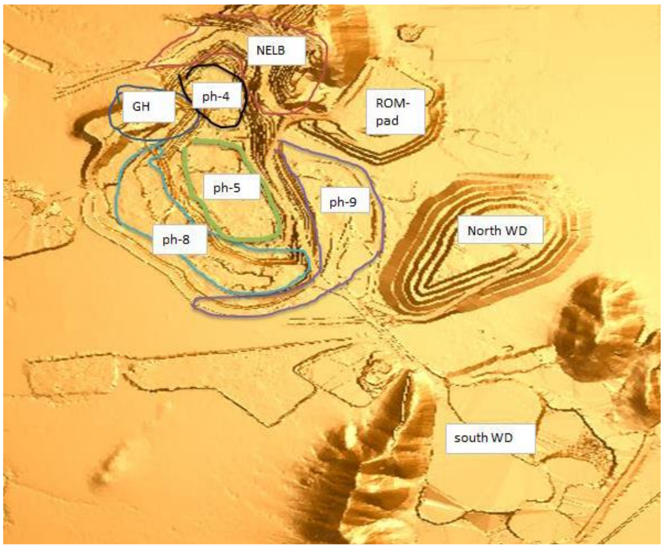

Figure 1. Overall view of the mine

The mine operator (BMSC) uses the purchased equipment to perform mining operations. Conventional open-pit front-shovel-truck methods are used for mining. The current equipment fleet productivity as of March 2017 is shown in Table 1.

The main reasons are reduced production and poor material fragmentation due to improper blasting, truck distribution, working bench heights for diggers, and poor haul road condition. Also, it will help in reducing operator dissatisfaction, fleet size mismatch, dust and some uncontrollable reasons such as rain, wind, etc. Based on the data collected from the company, the equipment is classified in Table 2.

Table 1. Available equipment on the Bisha site

Equipment unit	Current fleet
Loading equipment	–
Terex RH40 shovel	2
Terex RH40 excavator	3
CAT 990H loader	2
Haul trucks	–
CAT 775 truck	25
Auxiliary equipment	–
Dozers	5
Graders	3
Water trucks	3

Table 2. Detailed information on available equipment at BMSC

Code	Machine	Model	Capacity
PE-01	Hydraulic shovel	TEREX RH40	7 m^3
PE-02	Hydraulic excavator	TEREX RH40	6 m^3
PE-03	Hydraulic excavator	TEREX RH40	6 m^3
PE-04	Hydraulic excavator	CAT 6015	6 m^3
PE-05	Hydraulic excavator	CAT 6015	6 m^3
PE-06	Hydraulic shovel	–	–
10 DT	Rear dump truck	CAT775F	32 m^3 struck capacity
15 DT	Rear dump truck	CAT775G	32 m^3 struck capacity

2.2. Methods

The loading and hauling operations are the main concern of optimization, and the company can increase production and gain profit. Analysis of the collected sample data reveals the key factors affecting production efficiency in the case of the mine under study, which are shown in the production flowchart in Figure 2.

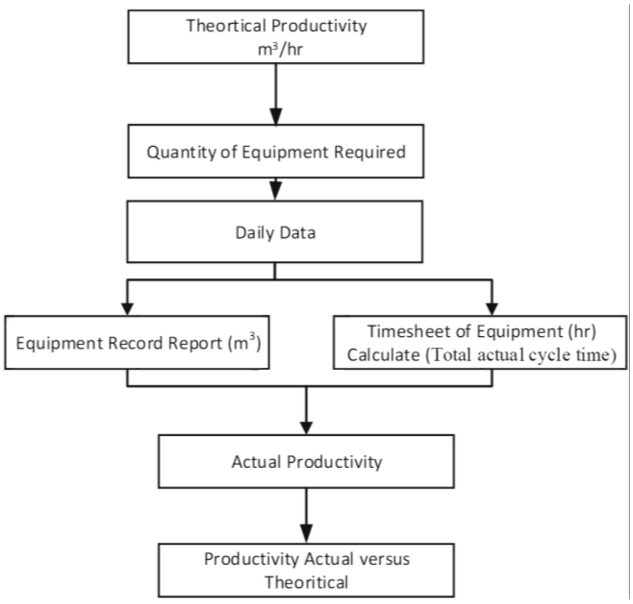

Figure 2. Methodology flowchart

Approaching semantically to mathematical models, it shows approximately positive results. Loading is the process of putting the fragmented materials from a mine face onto a haulage unit using loading equipment (a loader). Loaders are used to lift the ore or waste material onto trucks or other types of equipment for removal from the mine. In an open-pit mine, loader types may include electric ropes and hydraulic excavators, hydraulic backhoe excavators and front-end loaders (also wheel loaders). This variety of machines differs significantly in reliability, maintenance requirements, as well as compatibility with different truck types, volumetric lifting capacity and unit cost. Hauling is the business of transporting goods by road or rail, involving the horizontal transport of ore, coal, materials and waste.

2.3. Optimization of loading and hauling

Equipment cycle time is the time required for equipment to complete one cycle. For example, the cycle time of an excavator is the time required to complete one pass. It includes filling the bucket, swinging, unloading, and swinging empty to fill the next bucket, while loading time is the time required to load a dump truck. Generally, the loading system in Bisha is a single-sided loading system. In this loading system, the digger's loading time must include the positioning and reverse time, because the digger hangs its first bucket (first pass) until the positioning of the dump truck. Based on this loading system (single-sided loading), the digger's loading time has been classified into two components:

– first bucket time: the time taken to place the first bucket onto the dump truck, including the reverse time. It consists of time to fill the bucket, swing, and hang it until the positioning or reversing the truck, as well as unloading. This time is longer than the rest bucket cycle times because it includes the hang time until the dump truck reversal;

– rest bucket time: the time taken to fill the dump truck, excluding the first bucket time. This time is highly dependent on the number of passes required to fill the dump truck and the cycle time of one pass. It can be calculated by:

$$T_{rb} = (n-1) \cdot P_{ct} , \quad (1)$$

where:

T_{rb} – rest bucket time;

n – number of the bucket passes to fill the truck;

P_{ct} – cycle time of the bucket.

The cycle time of the bucket in one pass includes the bucket filling time, the time of turning the loaded bucket, bucket unloading time, and the time of turning the empty bucket. But it excludes the bucket hang time, which is the time taken by the truck to get into position. Then, total loading time (T_{tl}) can also be calculated by adding the first bucket time (T_{fb}) and the cycle time of the bucket (P_{ct}). That is:

$$T_{tl} = T_{fb} + T_{rb} , \quad (2)$$

where:

T_{tl} – total loading time;

T_{fb} – first bucket time;

T_{rb} – rest time of the bucket cycle (average cycle time of the excavator bucket).

Therefore, the actual loading time recorded on the site is equal to the actual loading time calculated using the average number of passes. Actual loading time is the time taken to load a dump truck, considering delays and the actual number of passes. According to our observations, the actual loading time exceeds the optimal loading time. This is mainly due to poor fragmentation, clearing and relocation during loading, dust, and insufficient bench height. The dump truck cycle time is the time taken by the dump truck to complete one cycle. This process includes time for loading, maneuvering, hauling (full and empty), positioning, and queuing time.

Loading time is determined by the number of shovel, dragline, or loader passes per one loading and the resulting loading time by dividing the rated haulage unit capacity (tons or kg) by the number of passes. On the other hand, the loading time can be determined by multiplying the number of passes by the excavator cycle time:

$$L_{tl} = N_p \cdot T_{rb}, \quad (3)$$

where:

L_{tl} – loading time, min;

N_p – number of passes;

T_{rb} – excavator cycle time, min.

The hauling time for a loaded truck is the time taken by the dump truck to reach the dump site. This time depends on the distance travelled, truck speed, grade resistance, and rolling resistance:

$$T_t = \frac{D}{16.7S}, \quad (4)$$

where:

T_t – travel time, min;

D – distance, m;

S – speed, km/hr.

The normal queuing time is added to the optimal cycle time to consider the unavoidable delay caused by the excess truck that should be assigned to keep the loading equipment busy. In [20], a simplified sample is provided to determine whether a fleet is suitable for a truck or not. So, the number of trucks assigned to each digger should be:

$$N = \frac{\text{Optimal cycle time}}{\text{Optimum loading time}}. \quad (5)$$

The total actual cycle time is calculated by summing total loading time, total hauling time when loaded, total unloading time, and total hauling time when empty.

Total actual cycle time is equal to loading time plus total hauling time when loaded plus the total unloading time plus total hauling time when empty.

In this case, the total loading time includes queuing time, positioning time, and loading time, while the total hauling time when loaded is the time taken to reach the dump site. On the other hand, the total unloading time is equal to the sum of queuing time, positioning time, and unloading time. The total hauling time when empty is the time taken to reach the open-pit, while the delay time of trucks (queuing time) is the time of delay that a dump truck spends waiting for an excavator to provide service or load. The optimal cycle time is the actual time required to complete one cycle, including all delays, such as queuing, waiting for clearing and relocation, as well as other delays:

$$T_{oc} = T_{ac} - T_{del}, \quad (6)$$

where:

T_{oc} – optimal cycle time;

T_{ac} – actual time;

T_{del} – delay time.

2.4. Productivity calculation

2.4.1. Digger's actual productivity

The productivity of the excavator and shovel can be calculated by the Equation (7) to give the number of BCM/hour and is determined as follows:

$$\text{Productivity} = \frac{\text{One truck load}}{\text{Actual loading time}} \cdot (1 - \text{Delay factor}) \cdot 60. \quad (7)$$

Optimal productivity includes only relocation and clearing, and no waiting time. For an excavator, productivity is calculated by Equation (8) as follows:

$$\text{Productivity} = \frac{\text{One truck load}}{\text{Optimal loading time}} \cdot (1 - \text{Delay factor}) \cdot 60. \quad (8)$$

2.4.2. Availability and utilization

The availability and utilization rates can be calculated by Equations (9) and (10), which are based on downtime loss and available hours:

$$\text{Availability} = \frac{\text{Net available time} - \text{Down time loss nett}}{\text{Net available time}}; \quad (9)$$

$$\text{Gross utilization} = \frac{\text{Utilized hours}}{\text{Available hours}} \cdot 100. \quad (10)$$

2.4.3. Equipment productivity

The productivity of excavators, shovels and dump trucks can be calculated by the following Equation:

$$\text{Production} = P_o \cdot T_c \cdot A_v \cdot U_t, \quad (11)$$

where:

P_o – productivity, tons/hour;

T_c – scheduled time, hours/unit time (for example, 22 hours/day);

A_v – availability (decimal);

U_t – utilization (decimal).

3. Results and discussion

3.1. Loading and hauling time calculation

As the main research purpose is to optimize loading and hauling, the problems that occur during loading and hauling of different grades of ore and waste can be solved.

3.1.1. Total loading time for excavator and shovel

The excavator and shovel first bucket time, recorded on the site, is shown in Table 3. First bucket time for the shovel and excavator is presented, showing start time, end time and first bucket time compared to the average for all.

Table 3. First bucket time of the excavator and shovel

No.	First bucket time of excavator			First bucket time of shovel		
	Start	End	T_{fb}	Start	End	T_{fb}
1	9:04:00	9:04:41	0:00:41	3:00:01	3:00:34	0:00:33
2	9:07:03	9:07:39	0:00:36	3:03:31	3:04:53	0:01:22
3	9:10:33	9:11:05	0:00:32	3:07:02	3:07:26	0:00:24
4	9:18:20	9:19:04	0:00:44	3:10:12	3:11:18	0:01:06
5	9:23:11	9:24:15	0:01:04	3:15:20	3:15:50	0:00:30
6	9:30:00	9:31:35	0:01:35	3:20:30	3:21:57	0:01:27
7	9:33:08	9:34:11	0:01:03	3:23:41	3:25:04	0:01:23
8	9:35:08	9:35:56	0:00:48	3:30:10	3:31:34	0:01:24
9	9:40:07	9:40:55	0:00:48	3:42:11	3:42:53	0:00:42
10	9:57:01	9:58:11	0:01:10	3:45:01	3:46:00	0:00:59
Average			0:00:54 = 0.9 min			0:00:59 = 0.98 min

Equations (1) and (2) allow for the calculation of the actual average number of passes (7), on the basis of which the excavator loading time is determined. The total time of excavator loading is 4.02 minutes. Therefore, the actual loading time recorded on the site is equal to the actual loading time calculated by the average number of passes (5). In addition, the actual loading time of the shovel is calculated using Equations (1) and (2), where the actual loading time is 2.9 minutes.

The cycle times for excavator and shovel are shown in the appendix (recorded cycle times), where the initial and average cycle times for excavator and shovel are recorded.

The actual loading time recorded on the site is equal to the actual loading time calculated from the average actual number of passes, as shown in Table 4.

3.1.2. Optimal loading time for excavator and shovel

The optimum number of passes for the excavator can be calculated as follows: the maximum truck capacity (tons or kg) per pass is equal to the number of passes per loading.

In BMSC, the optimal loading capacity for the truck is 20 BCM (bank cubic meters), which means 43 tons, and the bucket capacity for the TERREX RH40 excavator is 9700 kg. Then the number of passes is equal to 5, and the optimal loading time for the excavator is equal to 2.98 minutes.

The optimum number of passes for the shovel can be calculated as follows: the number of passes per loading is equal to the optimal truck load capacity (tons or kg) per pass.

Table 4. Actual loading time of excavator and shovel

Material: waste	Digger: PE04				Digger: PE01			
No.	Loading time Start	Loading time End	T. taken	Passes	Loading time Start	Loading time End	T. taken	Passes
1	8:05:31	8:08:47	0:03:16	6	3:20:13	3:22:39	0:02:26	5
2	8:10:05	8:14:27	0:04:22	9	3:23:03	3:25:36	0:02:33	6
3	8:16:11	8:19:53	0:03:42	6	3:26:07	3:29:27	0:03:20	4
4	8:21:50	8:25:56	0:04:06	8	3:29:50	3:33:50	0:04:00	4
5	8:29:11	8:33:21	0:04:10	7	3:34:17	3:36:26	0:02:09	4
6	8:36:10	8:40:00	0:03:50	6	3:37:20	3:40:27	0:03:07	6
7	8:43:03	8:46:57	0:03:54	8	3:43:31	3:45:57	0:02:26	6
8	8:48:01	8:52:18	0:04:17	7	3:47:22	3:49:41	0:02:19	5
9	9:01:03	9:04:23	0:03:20	6	3:51:14	3:54:02	0:02:48	6
10	9:07:10	9:12:04	0:04:54	7	3:55:01	3:59:00	0:03:59	4
Average			0:03:59 = 3.98 min	7			0:02:55 = 2.92 min	5

On the other hand, the optimal load capacity in BMSC for a truck is 20 BCM, which means 43.75 tons, and the bucket capacity for the TERREX RH40 excavator is 10300 kg. Then, the number of passes is 4. Passes and the corresponding optimal loading time of a shovel are determined by equations 1 and 2. It is equal to 2.42 minutes.

3.1.3. Dump truck cycle time

The length of time it takes a dump truck to complete one cycle is the cycle time. This process includes time for loading, maneuvering, hauling (full and empty), positioning, and queuing time. There are several methods for determining loading time, including the number of shovels, dragline or loader passes per loading and the resulting loading time. One of the simpler and reasonably accurate methods is Equation (3), as the time of loading the dump truck by the excavator is equal to 3.64 minutes. For a shovel, the time of loading the dump truck is equal to 2.4 minutes. The average loading time for excavator and shovel is given in Table 5 and Figure 3.

Table 5. Time for loading dump truck by an excavator

No.	Truck No.	Loading time by an excavator (min)
1	22	2.95
2	22	3.02
3	22	3.80
4	22	3.07
5	22	4.67
6	22	3.35
7	22	3.85
8	22	2.95
Average		3.53

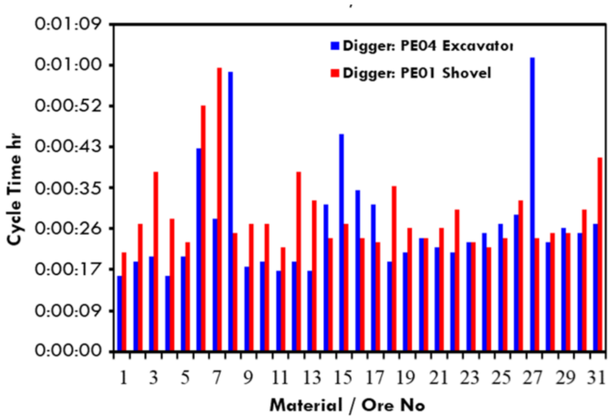

Figure 3. Cycle time of the excavator and shovel

The average loading time by the excavator and shovel, defined as the average loading time of digger, is 2.965 min.

3.1.4. Turning, positioning and unloading time

Positioning, turning, and unloading times are shown in Table 6. Positioning time at the loading position also depends on the type of haulage unit and operating conditions, as shown in Table 7. Accurate positioning of trucks at the correct angle and in the same relative position considerably improves the operator's timing and speeds up shovel operation.

In BMSC, the normal queuing time is given in Table 8.

3.1.5. Hauling time for a loaded truck

The hauling time of a loaded truck is the time required for a dump truck to reach the dump site and can be calculated by Equation (4).

Table 6. Positioning time and unloading time

Load No.	Truck No.	Positioning time	Unloading time
1	22	0.20	0.73
2	22	0.32	0.50
3	22	0.60	0.62
4	22	0.38	0.58
5	22	0.35	0.37
6	22	0.18	0.50
7	22	0.25	0.47
8	22	0.23	0.62
Average		0.31	0.55

Table 7. Positioning time at the loading area

Load No.	Truck No.	Positioning time
1	22	0.50
2	22	0.17
3	22	0.57
4	22	0.20
5	22	0.97
6	22	0.27
7	22	0.32
8	22	0.50
Average		0.43

Table 8. The average queuing time

Load No.	Truck No.	Queuing time
1	22	Idle
2	22	1.22
3	22	0.10
4	22	1.18
5	22	0.08
6	22	2.88
7	22	0.13
8	22	0.48
Average		0.87

The hauling time in Bisha is given in the appendix (hauling time when loaded) with an average value for all. Table 9 summarizes the hauling time for the mine, which depends on distance and speed.

Table 9. Summary of hauling time for the mine sides

Hauling areas	Hauling time when loaded		
	Distance, m	Speed, km/hr	Time, min
Pit floor	239	10.1	1.53
Ramp 01	612	14.4	2.63
Ramp 02	293	14.3	1.24
Flat haul	250	21.4	0.71
ROM ramp	294	16.1	1.10
ROM flat haul	167	17.2	0.66
Dumping area	17	3.4	0.54

3.1.6. Total actual cycle time

Total actual cycle time includes loading time, total hauling time when loaded, total unloading time and total hauling time when empty. Total loading time includes the sum of times for queuing, positioning and loading, which is equal to 4.265 minutes. Total hauling time when loaded is the time taken to reach the dump area; it is 8.46 minutes. Total unloading time is the sum of times for queuing, positioning and unloading, which is equal to 0.86 minutes. Total hauling time when empty is the time required to return to the open pit in an empty state, which is equal to 6.18 minutes. Total actual cycle time of a dump truck is then 19.765 minutes.

The return time of the hauling unit is the time taken to return to the loading site without any material or empty, which is recorded for a truck of 22 trucks and is given in the appendix (return time for truck 22) with an average value for all.

3.1.7. Delay time for trucks

Queuing time is the time delay that a dump truck spends waiting for an excavator to provide service or load, and the average queuing time for trucks to queue at the loading point is based on a sample of operations as shown in Table 10. The average of normal queuing time and high queuing time is 1:55:4 (1.91 minutes).

Table 10. High queuing time

No.	High queuing time	
	Queuing time for Track 1	Queuing time for Track 2
1	2:09:00	2:07:00
2	3:09:00	2:46:00
3	2:20:00	2:17:00
4	2:47:00	3:45:07
5	3:08:00	2:39:00
6	3:45:00	2:26:00
7	2:44:00	3:30:10
8	3:12:02	4:20:00
Average	2:56:08	2:58:09
Average		2:57:80

3.1.8. Optimal cycle time

Optimal cycle time (T_{ac}) is the actual time required to complete one cycle including all delays, such as queuing, waiting for clearing and relocation, and other delays, which can be calculated by equation 6 and is equal to 17.855 minutes.

3.2. Actual productivity

3.2.1. Digger's actual productivity for excavator and shovel

The digger's actual productivity for the excavator can be calculated by Equation (7) and is equal to 230.35 BCM/hour.

The delay factor is the delay time of 60 minutes, while the waiting time is 9.12 minutes, and 5 minutes for relocation and 60 minutes for clearing. The actual loading time is considered and includes the first bucket time, as well as the first bucket time, which includes the positioning time. The shovel productivity can be calculated by Equation (7) and is equal to 310.68 BCM/hour.

When calculating actual dump truck productivity, the delay factor is excluded because the waiting time and delay time are included in the actual cycle time. The truck productivity is 60.71 BCM/hour, as calculated by Equation (7).

Sensitivity analysis is performed to determine the impact of waiting time and delay factor on productivity. The coefficient of determination [21] is measured to assess the relationship using the following Equation:

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[[n\sum x^2 - \left(\sum x\right)^2][n\sum y^2 - \left(\sum y\right)^2]\right]}}, \quad (12)$$

where:

n – total number of observations;

Σx – total of the first variable value;

Σy – total of the second variable value;

Σxy – sum of the product of first & second value;

Σx^2 – sum of the squares of the first value;

Σy^2 – sum of the squares of the second value.

Consequently, the coefficient of determination is r^2.

It is obviously noted from Figure 4 that actual productivity is affected by the waiting time. It has been found that a 10% increase in waiting time results in a 2.5% decrease in actual productivity. Sensitivity analysis shows that the relationship is purely linear with a coefficient of determination equal to 1.

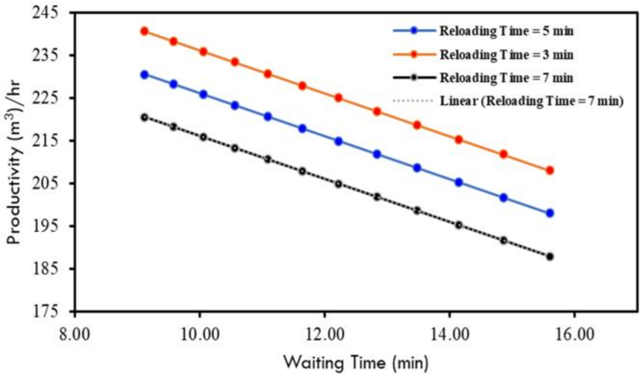

Figure 4. Impact of waiting time on productivity

Figure 5 demonstrates how variations in the delay factor values also have an impact on productivity. In this regard, it is seen that a 25% increase in the delay factor would result in a 10% decrease in productivity. The reduction in productivity is due to the temporary excavator relocation on the site.

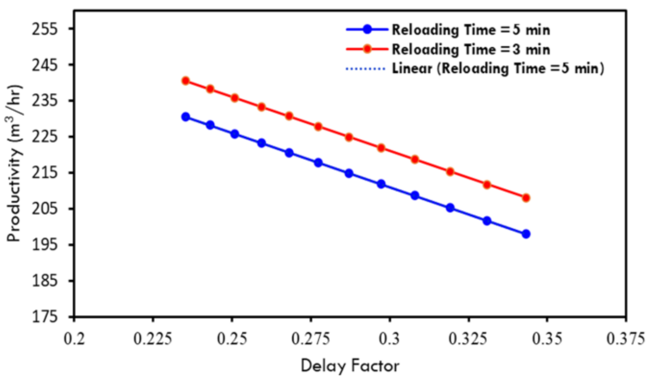

Figure 5. Impact of delay factor on productivity

3.2.2. Optimum productivity

With optimal productivity, the relocation and clearing are only included, and the waiting time is excluded. For the excavator, the productivity is calculated using Equation (8) and is equal to 369.26 BCM/hour.

For the shovel, the productivity is calculated by Equation (8) and is equal to 454.71 BCM/hour.

For the dump truck, the optimal productivity is only based on the normal queuing time at the optimal cycle time after excluding the delay factor and is equal to 67.21 BCM/hour.

3.3. Availability and utilization

Availability and utilization rates can be calculated using Equations (9) and (10), which are based on downtime loss and the available hours. According to the 2021 record, the availability and utilization of equipment are given in Table 11.

Table 11. Availability and utilization

In 2021	Excavator	Shovel	Dump truck
Availability	85%	85%	85%
Utilization	81%	81%	81%

Gross utilization is calculated by Equation (10), which is based on the BMSC of mine planners, using utilized 18 hours and the scheduled 22 hours. The gross utilization is equal to 81%.

3.4. Equipment productivity

3.4.1. Actual productivity

The actual productivity, availability and utilization of excavators and dump trucks are taken into account. Actual productivity includes all waiting time and delay time.

The excavator productivity is determined by Equation (11) and is equal to 3489.1 BCM/day. For shovels, the actual productivity is equal to 4705.87 BCM/day. Total value of digger productivity using three excavators and two shovels is 19879.07 BCM/day.

For the dump truck, productivity is equal to 921.69 BCM/day. The total dump truck productivity is equal to 23042.37 BCM/day.

3.4.2. Optimal productivity

Normal or optimal productivity takes into account the optimal productivity, availability and utilization of excavators and dump trucks, which include a fixed time that is considered as cycle time delay. The digger equipment productivity for excavators has been determined: excavator productivity is 5667.2 BCM/day and shovel productivity is 6828.2 BCM/day.

In this case, there are 3 excavators and 2 shovels, and the total productivity of the diggers is 30658 BCM/day.

4. Conclusions

The optimization of loading and hauling in open-pit mining is of great importance, as it is a critical part of all mining processes that affect the production rate and mining profitability. Open-pit mines are getting larger, which leads to a high production rate of materials, so loading and hauling have become one of the main parts of the mining process. The overall material handling expenses are reduced by selecting the appropriate equipment when planning material handling. The mining fleets should be carefully matched to the mining environment and planned production schedule.

The average total loading time of the excavator and shovel is recorded on the site as bucket time. Using the actual average number of passes, the actual time has been determined and compared to that recorded on the site with the cycle time, calculated for the shovel and excavator. Several passes for both excavator and shovel are calculated to determine the optimal loading time; the average time for positioning, turning and unloading is recorded; truck positioning and operator's time; speed is improved. The actual and optimum productivity is determined for the shovel and excavator to move to availability and utilization, which are based on downcast time loss and the available hours. Checking the actual cycle time and the optimal one during hauling and loading, optimization is applied to enhance productivity and reduce loss time.

When assessing the loading and hauling time, which is represented by excavator and shovel cycle times, the total loading time for excavator and shovel are 3.98 and 2.92 minutes, respectively, while the optimal time are 2.98 and 2.42 minutes, respectively. The result shows that the difference between total and optimal time for excavator and shovel ranges from 25.76 to 16.15. Sensitivity analysis shows that actual productivity depends on waiting time: a 10% increase results in a 2.5% decrease. A 25% increase in the delay factor results in a 10% loss due to the temporary excavator relocation on the site.

Author contributions

Conceptualization: MM, EG; Data curation: AG; Formal analysis: MB, AE; Funding acquisition: MM; Investigation: MB; Methodology: MM, EG; Project administration: MM, MB; Software: MB; Supervision: MM, HA; Validation: EG; Visualization: AE; Writing – original draft: MM; Writing – review & editing: HA, AG.

All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

Authors would like to express their gratitude to colleagues of Taif University (Taif, Saudi Arabia) for their research support.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Оптимізація часу циклу навантаження та транспортування самоскидами при відкритому видобуванні корисних копалин

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Мета. Надання гірничодобувним підприємствам з відкритого способу видобутку практичних стратегій та ідей щодо оптимізації циклів навантаження та перевезення самоскидами, що зрештою призведе до підвищення продуктивності та економічних переваг.

Методика. Використовуючи фактичну середню кількість проходів, визначали фактичний час і порівнювали його із записаним на місці часом циклу, розрахованим для ковша та екскаватора. Для визначення оптимального часу навантаження розраховується кілька проходів як екскаватора, так ковша; фіксується середній час на позиціонування, поворот та розвантаження; розташування вантажівки та час оператора. Фактична та оптимальна продуктивність визначається для переходу екскаватора в режим готовності та використання, які ґрунтуються на зменшенні втрат часу та наявних годин.

Результати. Визначено, що загальний час циклу видобування відкритим способом становить 19.765 хвилин, що складається із загального часу завантаження, часу транспортування для повного завантаження, загального часу вивантаження та загального часу повернення порожнього транспорту, що становить 4.265, 8.46, 0.86 та 6.18 хвилин відповідно. Аналіз чутливості показує, що фактична продуктивність залежить від часу очікування: збільшення на 10% призводить до зменшення на 2.5%, причому збільшення коефіцієнта затримки на 25% призводить до втрати 10% через тимчасове переміщення екскаватора на майданчик.

Наукова новизна. Досягнуто скорочення загального часу циклу видобутку за рахунок оптимізації часу навантаження мережі транспортних доріг, підвищення продуктивності та часу розвантаження і повернення автосамоскидів на основі обробки результатів аналітичних розрахунків та фактичних спостережень.

Практична значимість. Поєднуючи теоретичний аналіз із практичними міркуваннями та урахуванням специфіки конкретного об'єкта, стаття покликана забезпечити комплексну та застосовну основу для оптимізації часу циклу роботи самоскидів при відкритому видобуванні корисних копалин, що призведе до підвищення ефективності та рентабельності гірничих робіт.

Ключові слова: *час циклу роботи, самоскид, час завантаження, відкритий спосіб видобування, мінімізація, час вивантаження, сталий розвиток*

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