Journal of Mining and Environment (JME) Vol. 16, No. 3, 2025, 997-1007

Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

Enhancing Transportation Fleet Efficiency in Open-Pit Mining via Simulation: a Case Study

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Article Info

Received 23 September 2024
Received in Revised form 9 December 2024
Accepted 29 December 2024
Published online 29 December 2024

DOI: 10.22044/jme.2024.15094.2889

Keywords

Mining haulage optimization
Simulation modelling
Dynamic truck allocation
Open-pit mining
Operations

Abstract

Efficient loading and hauling systems, with trucks and shovels as the primary transportation machinery, are essential for optimizing mining operations. This study introduces a simulation-based approach to enhance the utilization of the hauling system in an Abbasbad copper mine in Iran. A dynamic truck allocation model is proposed to overcome the limitations of fixed allocation methods. In this approach, trucks are assigned to loading equipment based on the real-time throughput data, prioritizing equipment experiencing the highest production delays. The simulation results demonstrate that this flexible allocation model improves productivity, achieving a 13% increase in waste material handling compared to the fixed allocation scenario. These findings indicate that the proposed framework to significantly improve the efficiency and productivity of haulage systems in mining operations.

1. Introduction

Open-pit mining projects require substantial capital investment, and incur significant operating expenses, with approximately 50% of these costs attributed to material transportation and handling [1-3]. Mining equipment plays a crucial role in the success of mining operations [4]. Optimizing equipment utilization is therefore crucial [5]. The truck-and-shovel system is widely employed in open-pit mining due to its high production efficiency, flexibility, relatively low operating and capital costs, and ease of maintenance [6]. However, managing a transportation fleet in this environment is complex, involving intricate traffic routes, equipment instability, limited crushing capacity, and constrained unloading points. Moreover, variations in ore grade at work fronts and various technical and economic constraints further complicate fleet management. effective fleet allocation and utilization are thus essential for mining managers, to maximize production, reduce costs, and ensure mineral quality aligns with production planning objectives [7].

As the number of loading and unloading points increases, designing an efficient transport fleet becomes increasingly complex, making simulations invaluable. Simulations are widely used in both open-pit and underground mining to optimize material loading and hauling systems, and to improve overall mining operations, mine planning, and production scheduling [1]. This computer-based technique replicates the behavior of an operating system over time, facilitating a deeper understanding and optimization of system performance [8]. Simulation methods are generally categorized into a discrete event simulation, Monte Carlo simulation, continuous simulation, and

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virtual reality models [9]. Among these, discrete event simulation is particularly prominent across various industries, as it enables effective modeling and performance analysis of complex systems [9].

This study proposes a novel approach for flexible truck allocation in the transportation fleet simulation of the abbasabad copper mine. The current fixed allocation system is compared with a flexible allocation method, and demonstrating significant improvements in waste management and transportation efficiency have been shown. Utilizing the DSim mining transportation fleet simulation software—applied for the first time in Iran—this research explores innovative strategies to optimize fleet performance. Unlike prior studies that primarily focus on fleet size optimization, this research emphasizes maximizing the efficiency of the existing fleet. In addition, while prior research often centers on fixed or generic flexible allocation models, this approach identifies a specific flexible allocation method that yields superior results across multiple scenarios.

The remainder of this paper is organized as follows. Section 2 reviews related work on short-term open-pit scheduling. Section 3 defines the problem solved using by the optimization model. Section 4 introduces the proposed optimization model. Section 5 describes the real-scale open-pit mine case study and the analyzed scenarios. Section 6 presents and discusses the results of the case study and concludes the study, while outlining directions for future work.

2. Related Works

Ataeepour and Baafi (1999) were the first to use the ARENA simulation model to analyze excavator-truck operations in mining, treating all trucks in the mine as identical in terms of capacity, engine power, performance curves, and other key characteristics [10]. Later, Wang et al. (2006) introduced a momentary dispatching principle for open-pit mines under macroscopic control, successfully implemented it in large-scale mine. This method demonstrates advantages over traditional dynamic programming approaches and fixed manual scheduling [11]. Chanda et al. (2010) compared computer simulation, artificial neural networks (NN), and multiple regression (MR) models for predicting hauling cycle times, concluding that the NN and MR models provided superior predictive accuracy compared to simulation alone [12]. In a further development, Tarshizi et al. (2015) applied discrete event simulation in an open-pit coal mine to improve truck-shovel efficiency, minimize the environmental impact of transportation, and increase production levels using the GPSS/H software for implementation [13].

Azadi et al. (2015) employed simulation techniques with the Arena software to model the transportation system of Songun copper mine. By introducing new methods, the efficiency of the current mine fleet was increased. The actual mine conditions were modeled with five flexible allocation scenarios [14]. Shahin et al. (2020) used discrete event simulation with Arena software to model the Mehdiabad lead and zinc mine, identifying bottlenecks in loading and hauling operations and proposing strategies to improve fleet performance [15]. In a related study, Hadizadeh et al. (2021 applied the Arena software to compare flexible dispatching with fixed allocation methods. They found that flexible dispatching increased production rates by 20%, boosted productivity by 25%, and reduced idle time by 20%. Additionally, the application of a firefly meta-heuristic algorithm revealed that a mixed fleet of 35-ton and 100-ton trucks was the most effective in terms of productivity and cost efficiency [16]. Recently, Ashtiani et al. (2023) developed a simulation model to determine identify the optimal type and size of truck fleets to improve the operational efficiency and productivity in mining. Their findings demonstrated that heterogeneous fleets outperformed homogeneous ones in meeting production targets and reducing fuel consumption, while smaller trucks offered a greater handling flexibility, and minimized downtime during breakdowns. This study considered factors such as fleet type and size, truck breakdowns, fuel consumption, and production rates to optimize fleet performance and material flow in mining operations [17].

3. Simulation Modelling

Preliminary studies on the fleet are conducted as preparation for the simulation. After collecting and analyzing the required data, the simulation is executed using the DSim software. Once the model is validated, the simulation outputs are thoroughly reviewed. The simulation process involves several key steps: defining the purpose of the simulation, data collection, and model construction. The model is then verified and validated to ensure its accuracy. Following validation, experimentation is conducted, culminating in a final analysis of the results.

3.1. Simulator description

The Delphos open-pit simulator (DsimOP) is a powerful planning tool designed to estimate the production capabilities of a mining plan based on three fundamental components: the mine layout (including loading and unloading fronts and routes), the fleet of loading and transportation equipment, and strategic plan that specifies the desired quantities to be transported from each front to various potential destinations. Using these components, the Dsim open-pit performs a comprehensive simulation of the material handling processes.

One of the main advantages of the Dsim open-pit simulator is its user-friendly interface, which facilitates rapid setup and evaluation of different scenarios. This functionality allows for efficient retrieval of critical metrics, such as the productivity of key equipment and production rates per cycle. The simulator also accounts programmed interference such as shift changes or breaks, that can impact one or more pieces of loading or hauling equipment.

Importantly, Dsim simulates the loading equipment in a "semi-static" manner, enabling the assignment of equipment to different work fronts during the simulation. The transfer of equipment between these fronts is represented as a time delay during which equipment is unavailable. However, the actual movement of equipment to other fronts is not modeled as part of the transport network [18, 19].

3.2. Inputs of simulator

Data collection is a fundamental stage of simulation, with one of the critical aspects being the timing of activities, which is gathered from Mine Number 4. Building the simulation model requires several key data points including machine specifications such as type, model, and capacity, as well as the time needed for excavators to complete loading activities.

In addition, data on the Time required for Repairs (TTRs) and the Time Between Failures (TBFs) for the fleet of excavators, trucks, and crushers is crucial. The simulation also requires detailed data on roads and mine topography as well as scheduled breaks such as dinner, lunch, and shift changes. Moreover, it is essential to include loading and maneuvering times, truck speeds and fuel consumption, as well as maintenance schedules for all equipment involved in the operation.

Due to the frequent breakdowns of critical equipment such as excavators and crushers, these operational factors are incorporated into the simulation software. The time between the equipment breakdowns and the duration of repairs can be represented either as an average or distribution function. Figure 1 graphically illustrates the concepts of Mean Time Between Failures (MTBFs) and Mean Time to Repair (MTTR), providing a basis for evaluating system reliability by analyzing both uptime and downtime.

The Mean Time Between Failures (MTBFs) refers to the average duration between two consecutive system failures, measured from the moment the system begins operation until it fails again. The mean Time To Repair (MTTR) indicates the average time required to repair the system, and restores it to its operational status following a failure. Mean Time to Failure (MTTF) indicates the average operational duration of a system before experiencing a failure, during which the system is considered 'active.'

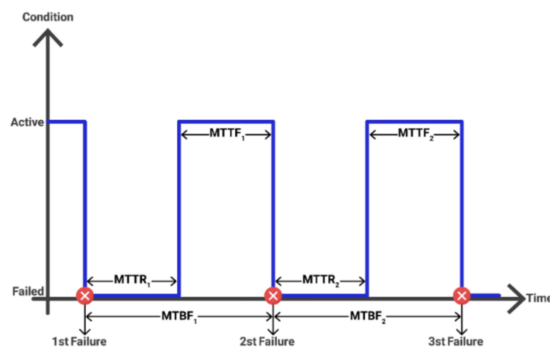

Figure 1. The concept of average repair time and time between failures [13].

4. Case Study

This research focuses on the Abbasabad copper mine, located approximately 145 km along the Shahroud-Sabzevar highway in Semnan Province. Currently, the primary mining activities is waste removal. Recent suggest the mine contains approximately 40 million tons of resources and approximately 28 million tons of reserves, with a cutoff grade of 0.1. the stripping ratio is 4:1. In 2021, the production figures were 398,944 tons of ore and 4,253,974 tons of waste.

The Abbasabad copper mine is located in northeastern Iran, in the far eastern part of the Semnan Province, between the towns of Shahroud and Sabzevar. It is situated within the central Iranian zone, specifically in the north-eastern section. The Abbasabad area is bordered by the Miami fault to the west and an internal fault to the east, separating the central Iran zone from the Alborz-Binaloud structural zone [20] (see Figure).

This region comprises two distinct sedimentary sequences. The first sequence indicates an advance during the middle Eocene, followed by regression from the upper Eocene to Oligocene. The second sequence reflects another advance spanning from the Eocene to the upper Oligocene, followed by a regression continuing from the earlier phase. Excluding the Quaternary units, the youngest rock unit identified in this area is a conglomerate [21].

At the Abbasabad copper mine, operations are divided into two work shifts: day and night. The day shift is primarily focused on extensive mineral loading, while the night shift is dedicated to cleaning the workfront and extracting tailings and deep andesite-basalt material. The total effective working time for the system under study is 1,200 minutes, covering both shifts.

The loading and hauling fleet at the Abbasabad copper mine consists of 28 trucks and 12 excavators. The trucks are produced by local manufacturers, whereas the primary loading equipment is sourced from Komatsu. Table 1 details the specifications of the fleet and crushers used at the Abbasabad copper mine.

Figure 2. Abbasabad copper mine.

Table 1. Specifications of fleet and crusher.

Type	Model	Capacity	Number
Truck	Benz2629	17 [t]	4
	Benz2624	17[t]	14
	Dump truck 7540A	30 [t]	10
Excavator	Volvo E380D	1.5-2.5 [m^3]	2
	Komatsu PC400-8	1.9 [m^3]	5
	Komatsu PC490-11	1.12-3.1 [m^3]	3
	Hyundai 330	1.44 [m^3]	2
Loader	Tiraje ZL50	3 [m^3]	2
	Liugong ZL50	3 [m^3]	1
Crusher	Jaw crusher Zenit	150 [t]	1
	Jaw crusher Hamkar	150 [t]	1
	Pebble crusher Tekno Tak	100 [t]	1
	Roller crusher Nahadin Sanaat Alvand	35 [t]	1

4.1. Acquisition of data from mine site

Data collection at the mine was carried out a six-day period, forming the basis for subsequent modeling efforts.

4.2. Data inputs

Random probability distribution functions are derived using the R and EasyFit software to convert the data into a format suitable for the software input. Table 2 presents the time distribution functions of the excavators. Similar time functions are measured for other mining equipment, and the best-fitting distributions are selected for use in the simulation. A p-value less than the significance level (α = 0.05) indicates rejection of the null hypothesis, implying that the data do not fit the specified distribution.

Table 2. Distribution function of repair time of excavator.

TTR distribution function		
Hyundai 330-2	**Hyundai 330-1**	**Komatsu 400**
Gen. Gamma (0.95652, 2.0351, 90.972)	Johnson SB (-0.88716, 0.6622, 441.35, -64.175)	Rayleigh (167.85)

Table 3. Distribution function of time between failures of excavator.

BF distribution function		
Hyundai 330-2	**Hyundai 330-1**	**Komatsu 400**
Weibull (0.52866, 81.242,12.0)	Gen. Logistic (0.51482, 97.984, 131.45)	Frechet (1.07,17.801)

Table 4. Function of repair time and between failure of trucks.

TTR distribution function	TBF distribution function
Uniform(a = 13.232, b = 58.768)	Uniform (a = 685.23, b = 730.77)

In Table 5, the average repair time and average time between failures for the fleet are given.

Table 5. Average repair time and average time between failures for the fleet.

Type	MTTR	MTBF
Komatsu 400	3:30:00	57:30:00
Hyundai 330-1	4:20:00	249:28:00
Hyundai 330-2	3:15:00	150:45:00
Trucks	1:00:00	24:00:00
Crusher	1:42:06	7:51:59

The EasyFit software is used in this research to fit and select the appropriate distribution. The fitted curves for the fleet and crusher time data are shown in Figures 3-10.

Figure 3 shows the distribution function diagram for the repair time of the Komatsu 400 excavator, which follows a Rayleigh distribution.

Figure 4 shows the distribution function diagram for the repair time of the Hyundai 330-1 excavator, which follows a Johnson SB distribution.

Figure 5 presents the distribution function diagram for the repair time of the Hyundai 330-2 excavator, which follows a Gen.Gamma distribution.

Figure 6 shows the distribution function diagram for the time between failures of the Komatsu 400 excavator, which follows a Frechet distribution.

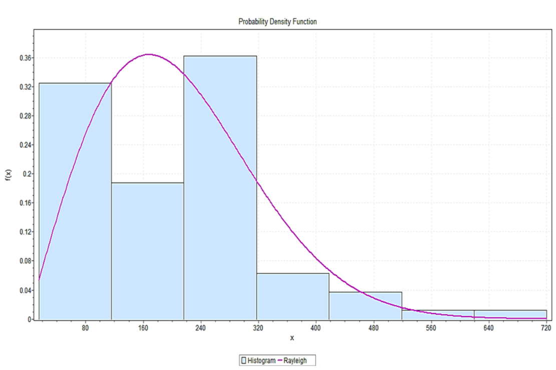

Figure 3. Distribution function for repair time of Komatsu 400 excavator.

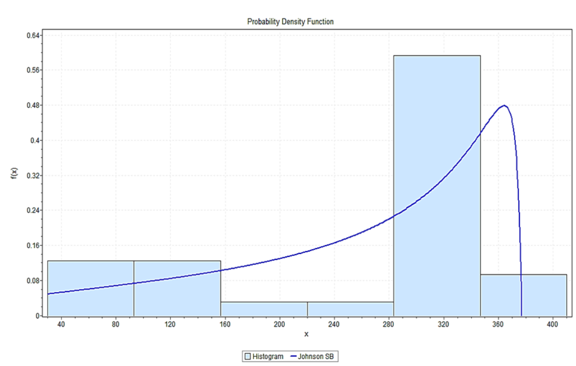

Figure 4. Distribution function for the repair time of the Hyundai 330-1 excavator.

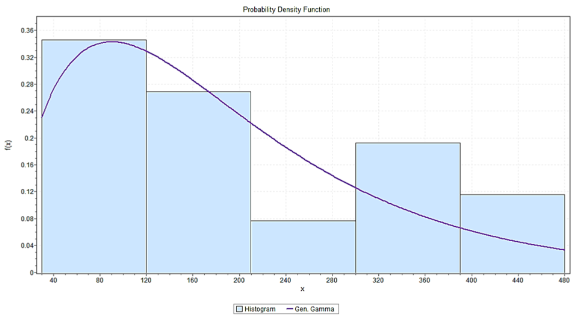

Figure 5. Distribution function of Hyundai excavator repair time 330-2.

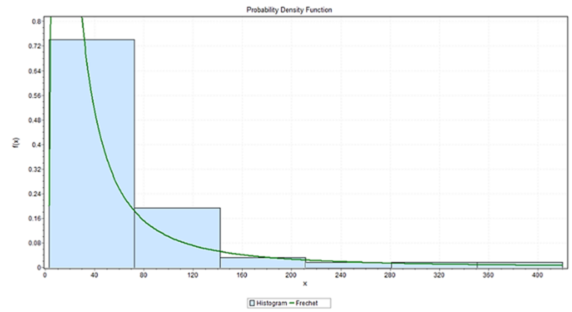

Figure 6. Distribution function of time between failures of Komatsu 400 excavator.

Figure 7 shows a graph of the distribution function for the time between failures failures of Hyundai 330-1, which distribution is Gen.Logistic.

Figure 8 shows the distribution function for the time between failures of the Hyundai 330-2 excavator, which follows a Weibull (3P) distribution.

Figure 9 shows that the fatigue life (3P) distribution is suitable for modeling the crusher's repair times.

Figure 10 indicates that the Wakeby distribution is the most suitable function for modeling the time between failures of the crusher.

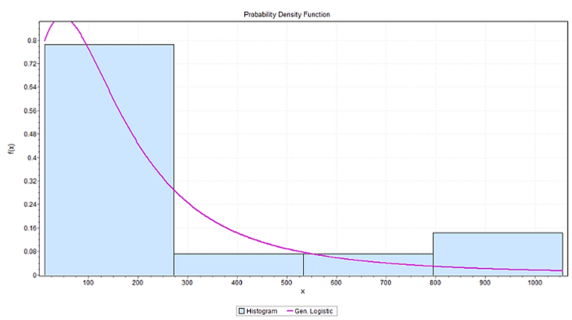

Figure 7. Distribution function of time between failure of Hyundai 330-1 excavator.

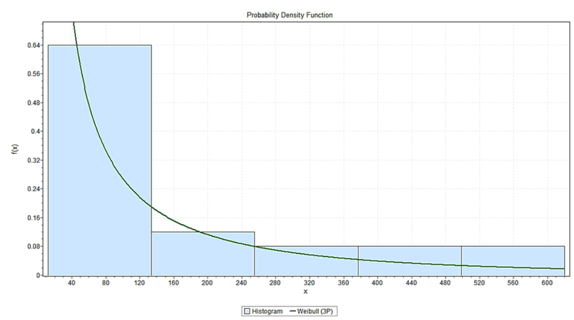

Figure 8. Distribution function of time between failure of Hyundai 330- 2 excavator.

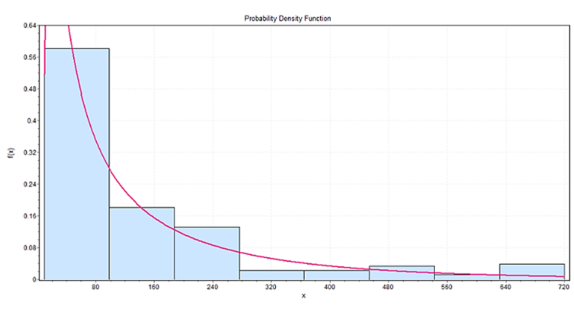

Figure 9. Distribution function of crusher repair time.

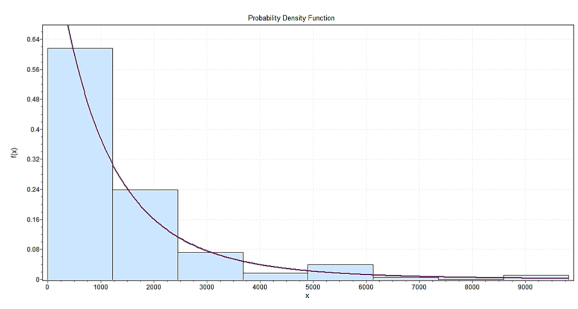

Figure 10. Distribution function related to the time between failures of crusher.

4.3. Mine site configuration in simulation software

Figure 11 presents a schematic model of sector No. 4 of the Abbasabad copper mine, featuring four mining faces-P4032, P4034, P4035, and P4036- where loading equipment loads trucks.The model identifies three primary destinations for material discharge: the primary crusher, waste dump, and mineral stockpile. Additionally, it highlights several support facilities including a truck shop and designated truck parking areas (parking lot 1 and parking lot 2).

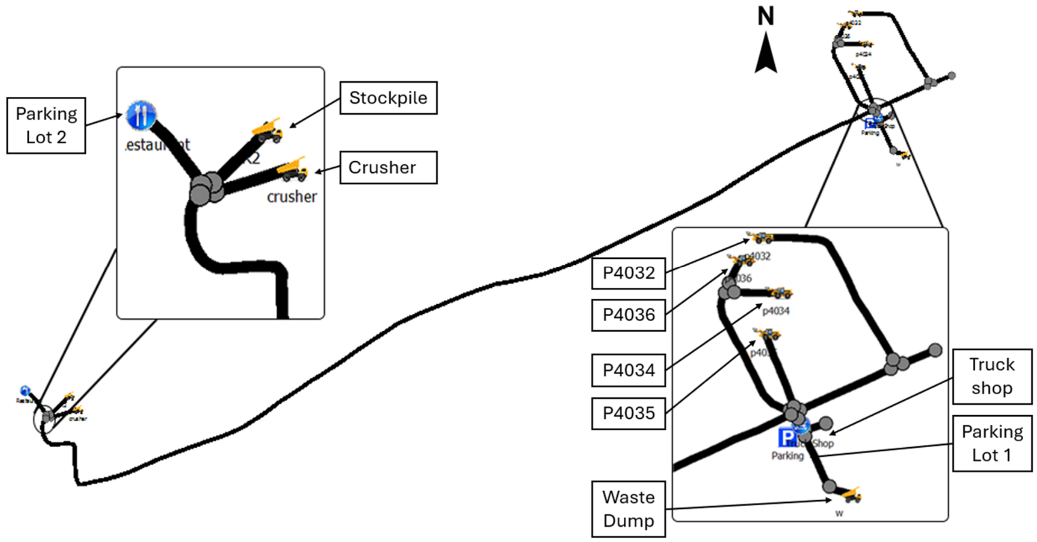

Figure 11. Schematic representation of the loading and hauling system at Abbasabad copper mine.

5. Results and Analysis

Unlike static approaches, which allocate trucks based on predefined schedules or arbitrary criteria; this model dynamically adapts to fluctuations in operational conditions in real time. It specifically prioritizes equipment experiencing the highest production delays, ensuring that trucks are allocated to frontworks with the greatest need. This approach minimizes idle times and maximizes operational efficiency. By improving throughput and enhancing overall system flexibility, the model allows for better resource utilization and more responsive operations, particularly in complex mining and transportation fleet. Furthermore, its ability to continuously adjust allocation decisions as conditions evolve marks a significant advancement over conventional methods, providing a more adaptive and robust solution for optimizing truck and equipment proportion. By applying the algorithm in a practical setting, valuable insights are provided into how it can be optimized for real-world mining operations, offering a refined approach that enhances production outcomes and can inform further research in truck allocation methodologies. The flexible method provides an improved solution rather than a fully optimized one. This approach is designed to enhance material production by allowing each truck to be loaded by multiple loading units, which helps each unit to better achieve its respective production target. This flexibility promotes a more balanced workload across equipment, leading to improved production efficiency even if the solution is not mathematically optimal.

The current transportation system is validated to accurately reflect actual production at the mine site. Following validation, the model is used to assess various scenarios for optimal truck fleet allocation to loading equipment, aiming to maximize production.

5.1. Validation

To validate the model effectively, it is essential to ensure that the simulation outputs closely match the actual production data. In this study, the total tonnage produced by each excavator and the tonnage transported between the origins and destinations are compared with real system data to validate the simulation results. Tables 6 and 7 provide a detailed comparison of the actual data and simulation outputs including the corresponding error rates (in percentages These results confirm the validity of the simulation model, demonstrating its applicability under various conditions. Specifically, Table 6 shows that waste is sourced from P4036 and P4035, while ore is extracted from P4032. Additionally, both ore and waste are sourced from P4034, with R2 serving as the discharge point for the ore.

Table 6. Validation of the model with the production tonnage of each excavator in [t].

Excavator	Real production [t]	Simulated production [t]	Relative difference %
Komatsu 400	4079.4	3838	-5.09%
Hyundai 330-1	6955.05	7102.2	2.11%
Hyundai 330-2	10045.17	10498	4.51%

Table 7. Validation of the model with tonnage between origin and destination.

Origin	Destination	Real production [t]	Simulated production [t]	Relative difference
P4032	R2 Stockpile (R2)	4375.37	4134.33	-5.509%
P4035	Waste Dump (W)	10045.17	10498	4.507%
P4036	Waste Dump (W)	5087.150	5244.73	3.09%
P4034	Stockpile (R2)	345.55	345	-0.15%
P4034	Waste Dump (W)	1226.02	1216.14	-0.805%

5.2. Production using fixed truck allocation to loading equipment.

Table presents the allocation of excavators to the mining faces.

Table 8. Allocation of excavators to mining faces.

Excavator	Mining face	Destination
Komatsu 400	P4032	Stockpile (R2)
Hyundai 330-1	P4034	Stockpile (R2)
Hyundai 330-1	P4034	Waste Dump (W)
Hyundai 330-2	P3035	Waste Dump (W)
Hyundai 330-1	P4036	Waste Dump (W)

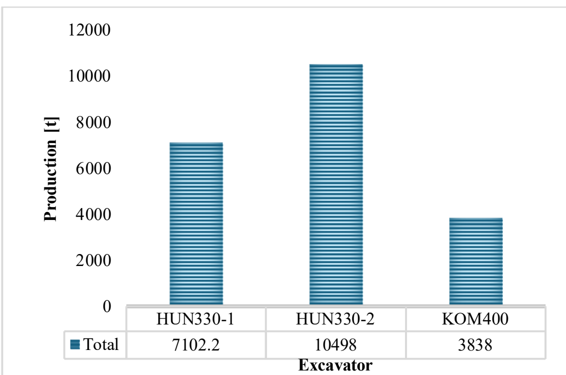

Figure 12. Actual production by excavator.

Figure shows the total production of each excavator. The Hyundai 330-2 excavator leads in terms of total tonnage, which is attributed to its larger fleet of trucks and greater capacity. Conversely, Komatsu 400 shows significantly lower production, primarily due to an average downtime approximately three times longer than that of the other excavators.

Figure shows a breakdown of production by origin and destination. Owing to efficient truck allocation, the production at these mining faces closely matches the software's predicted outputs.

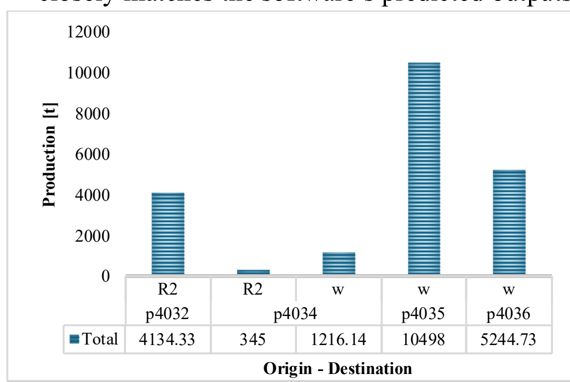

Figure 13. Actual production by origin and destination.

5.3. Production using flexible truck allocation to loading equipment

This scenario analyzes the current state of the system utilizing a flexible truck allocation to loading equipment. The results show that the production of Komatsu and Hyundai 330-2 excavators decreased compared to the fixed truck allocation, with average failure rates of 3 and 0.7 times higher than those of other excavators, respectively.

Consequently, the system allocated more capacity to the Hyundai 330-1 excavator. Figure 14 shows simulated production by excavator, while Figure displays the simulated production by origin and destination.

Table 9. Comparison of actual vs. simulated production by material.

Type of material	Actual production [t]	Simulated production [t]	Percentual difference %
Waste	16358.34	18497	13.07%
Ore	4720.92	2220	-52.97%
Total	21079.26	20717	-1.71%

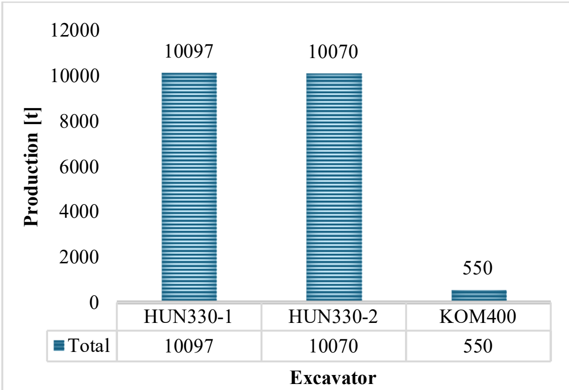

Figure 14. Simulated production by excavator.

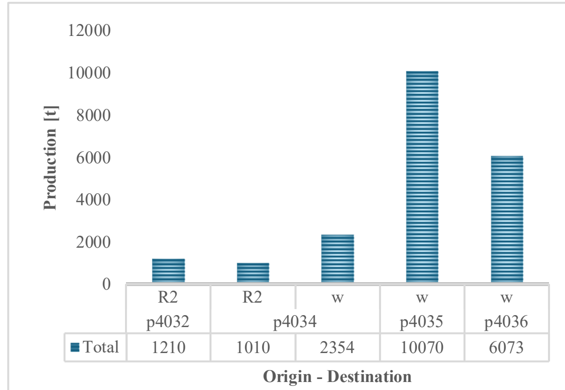

Figure 15. Simulated production by origin and destination.

6. Conclusions

The scenario analysis examines the tonnage produced by each excavator and the tonnage transported between origin and destination, both critical parameters in mining calculations. The defined scenarios (fixed and flexible) aimed to improve the performance of the loading and hauling fleet through a comprehensive analytical approach. Mine planning typically aims to maximize profit, enhance ore extraction, increase the value of marketable products, or extend a mine's operational life. However, in many mines, allocation systems are primarily based on mineral production. In developing countries like Iran, characterized by supply and demand heterogeneity and inflation, the focus often shifts away from prioritizing mineral exploitation and precious metals. Instead, the emphasis is on prolonging the mine's life to maintain profitability during the peak mineral price periods. The management team at the Abbasabad copper mine aims to achieve consistent profits by increasing waste beyond designed tonnage levels, ensuring continued mining activity even during low mineral price years while realizing economic savings. The simulation results indicate that this flexible allocation model improves productivity with a 13% increase in waste material handling compared to the current fixed allocation scenario. This approach minimizes idle times and maximizes operational efficiency by improving throughput and system flexibility. It allows for better resource utilization and more responsive operations, especially in transportation fleets. The ability to adapt allocation decisions in real time provides a significant advancement over conventional methods, offering a more flexible and robust solution for optimizing truck and equipment allocation. Practical application of the algorithm offers valuable insights into real-world optimization, enhancing production outcomes and informing further research. While not fully optimized, the flexible approach promotes balanced workload distribution and improved production efficiency.

Several recommendations can be made for the loading and hauling fleet at the Abbasabad copper mine, which could be considered as a new approach for future studies:

1- Investigating fleet failure

2- Combine scenarios

3- Analyzing fleet loading and hauling costs

4- Examining traffic routes within the mine

5- Examination of bottleneck in the mining process

Acknowledgments

The authors thank the Advanced Mining Technology Center (AMTC) and the DELPHOS mine planning laboratory of the university of Chile for providing the use of an academic license for the Delphos simulator open-pit (DSimOP) software used in this work.

This work was partially funded by the Advanced Mining Technology Center (AMTC) of the university of Chile, through the PIA/Basal program grant AFB230001 from the Chilean National Research and Development Agency (ANID).

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افزایش کارایی ناوگان حمل و نقل در معدنکاری روباز با رویکرد شبیه سازی: مطالعه موردی

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ارسال ۲۰۲۴/۰۹/۲۳، پذیرش ۲۰۲۴/۱۲/۲۹

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چکیده:

بهینه‌سازی عملکرد سیستم‌های حمل و نقل معادن روباز که عموماً شامل کامیون‌ها و شاول می‌باشند، برای بهینه‌سازی عملیات معدنی حیاتی هستند. این مطالعه رویکردی مبتنی بر شبیه‌سازی را برای بهبود بهره‌وری سیستم حمل‌ونقل در معدن مس عباس‌آباد ایران معرفی کرده و یک مدل تخصیص دینامیک کامیون به‌منظور رفع محدودیت‌های موجود در روش‌های تخصیص ثابت ارائه می‌دهد. در این رویکرد، کامیون‌ها بر اساس داده‌های واقعی تولید به تجهیزات بارگیری اختصاص می‌یابند، به‌طوری‌که اولویت تخصیص به تجهیزاتی داده می‌شود که بیشترین تأخیر در تولید را دارند. نتایج شبیه‌سازی نشان می‌دهند که این مدل تخصیص انعطاف‌پذیر نه تنها بهره‌وری را بهبود بخشیده، بلکه جابجایی مواد باطله را نسبت به سناریوی تخصیص ثابت، ۱۳ درصد افزایش می‌دهد. این یافته‌ها حاکی از آن است که چارچوب پیشنهادی می‌تواند به‌طور چشمگیری کارایی و بهره‌وری سیستم‌های حمل‌ونقل در عملیات معدنی را ارتقا دهد.

کلمات کلیدی: بهینه‌سازی حمل و نقل معدنکاری، مدل‌سازی شبیه سازی، تخصیص پویای کامیون، عملیات معدنکاری روباز.