Operational Excellence in Mining through Optimization Math Models and Simulation Systems

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Abstract

This study presents a comprehensive analysis of optimizing mining haulage operations through the development and application of mathematical models and simulation techniques. Motivated by the need to enhance efficiency, reduce operational costs, and maximize productivity in the mining sector, this research introduces a dynamic truck allocation system that is informed by real-time operational data. The core of the investigation revolves around achieving an optimal Match Factor (MF) of 1, which indicates a perfect balance between the number of trucks and shovel availability, thus minimizing wait times and maximizing operational throughput.

The conclusions drawn from the simulation results demonstrate the effectiveness of the proposed models in identifying the optimal fleet size that minimizes mining costs and maximizes productivity. Through detailed analysis, it was revealed that maintaining the equilibrium of truck deployment not only reduces unit mining costs but also significantly enhances production output. The study highlights the critical importance of understanding queue dynamics and their impact on operational efficiency, providing actionable insights for mining operations to optimize their haulage systems.

By employing rigorous mathematical modeling and simulation, this research offers a novel approach to shovel-truck allocation, contributing valuable perspectives to the field of mining engineering. Based on Jorge Lozano's Mining Engineering thesis at the Universidad Nacional de Ingeniería (Lozano 2019), this paper stands as a testament to the potential of mathematical and simulation methodologies in addressing complex operational challenges in the mining industry, paving the way for future advancements in mining logistics optimization.

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1 Hypothesis

The hypothesis of this research is that, given a closed system (shovel-truck haulage circuit), with a fixed number of servers (shovels), the optimal number of trucks occurs when the minimum mining cost is found. This is possible when the Match Factor is equal to 1; that is, the system has reached its maximum productivity. This condition will be used to estimate the optimal number of trucks and will show the technical-economic behavior of a productive system. This behavior will allow for the evaluation of the operation's feasibility. The partial results of this chapter have been presented by the author (Lozano, 2019).

2 Mathematical Model Optimization

Imagine a shovel-truck system, where mining phases and unloading destinations exist. Then, consider that there are m shovels and n trucks in the system. The m shovels are assigned to different mining phases with the goal of meeting a production quota K, where the production $P(m)$ must always be greater than or equal to $K(m)$. Here, the question arises: how many trucks are needed? It can be estimated with the Match Factor formula, considering an MF of 1. However, this overlooks the nature of the haulage system, i.e., its economic behavior. If a system starts operating without trucks, it will have a high mining cost due to lack of production. But as trucks enter the system, the waiting time at the shovels decreases, thus increasing productivity and reducing mining cost. This makes sense, but to what extent? The answer will provide a study on the behavior of queues and waits at the shovels.

2.1 Optimal Math Factor

To understand the economic behavior of the system in terms of queues and waits, consider the function $WSh(n)$, which represents the shovel waiting hours as a function of the trucks, decreasing with the number of trucks. On the other hand, given the nature of the servers, there is always a queue in a system; having a queue is not always bad. Initially, when there are no trucks, there are no queues, but as the number of trucks increases, there is a possibility of an increase in queues. This increase is governed by the function $QSh(n)$. Among the two functions $WSh(n)$ and $QSh(n)$, the significant impact is the waiting time of the shovels.

Let $P(n)$ be the tonnage mined, representing the mine's production for n trucks in operation. This function is defined as shown in equation 1:

$$P_n = \sum_{i=1}^{m} \left(\frac{H_i f_c}{t_{c_i} + t_{s_i} + t_{e_i}} \right) \tag{1}$$

Where:

- H_i: nominal operation time of Shovel i
- t_{c_i}: average loading time of Shovel i
- t_{s_i}: average squaring time of trucks at Shovel i
- t_{e_i}: average waiting time of Shovel i
- f_c: truck load factor.

From equation 1, it is seen that the average waiting time t_{e_i} of shovel i is inversely proportional to production, supporting the notion that an increase in the truck fleet decreases delays and increases production. To calculate the limit of $P(n)$ when n tends to be very large, the result is that $P(n)$ is bounded, i.e., it has a theoretical maximum, which equals $\sum_{i=1}^{m}\left(\frac{H_i f_c}{t_{c_i}+t_{s_i}}\right)$. For a system with a single shovel and a single destination, as will be seen later, it is feasible to reach this production; but in a system of m shovels and multiple destinations, it is only a maximum limit, since the interaction of multiple variables adds additional delay time, which is congestion. As mentioned in the previous paragraphs, the wait at the shovel determines the mine's production.

Given this result of dependency between $P(n)$ and $WSh(n)$, the function $WSh(n)$, represented by the sum of all the shovels' waiting times, is determined as shown in equation 2:

$$WS_{h_n} = \sum_{i=1}^{m}\left(\frac{H_i t_{e_i}}{t_{c_i}+t_{s_i}+t_{e_i}}\right) \tag{2}$$

The importance of this function is that it provides a relation with the mine's production $P(n)$, but its relation with the queues is still unknown. To demonstrate this relation, the following is defined:

The nominal operation time of a shovel equals the total operation time plus the waiting time. Therefore, according to this, the following equation 3 is defined:

$$H_i = E_i + (t_{c_i} + t_{s_i})\#_i \tag{3}$$

Where $\#_i$ is the number of cycles of shovel i in time H_i. From this equation, the number of cycles is found by rearranging equation 3 as shown in equation 4

$$\#_i = \frac{H_i - E_i}{t_{c_i} + t_{s_i}} \tag{4}$$

Then, given that the number of cycles $\#_i$ occurred in time H_i, the service rate per hour for the m shovels is given by equation 5.

$$s_m = m \cdot \frac{\sum_i \left(\frac{H_i - E_i}{t_{c_i} + t_{s_i}}\right)}{\sum_i H_i} \tag{5}$$

Similarly, the arrival rate of trucks to the shovels is estimated. Starting by defining t_{n_j}, as the nominal haulage time, i.e., the time it takes for truck j to be loaded at a shovel i: haulage time, loading, squaring, unloading, and returning empty. This time can be estimated using the mine's topography and the truck manufacturer's *rimpull* curves. On the other hand, t_{q_j} is defined as the queue time. Then, the haulage cycle time t_{cc_j} is determined using equation 6.

$$t_{cc_j} = t_{n_j} + t_{q_j} \tag{6}$$

Equation 6 shows the real cycle time due to the queue effect for a truck j on a particular route. If this truck j completes k_j cycles in an operation time H_j, then it can be expressed with equation 7.

$$\sum_{k_j=1}^{k_j} tcc_{jk_j} = \sum_{k_j=1}^{k_j} tn_{jk_j} + \sum_{k_j=1}^{k_j} tq_{jk_j} = H_j \tag{7}$$

Generalizing equation 7 for n trucks in operation results in equation 8.

$$\sum_{j=1}^{n} H_j = \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} tn_{jk_j} + \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} tq_{jk_j} \tag{8}$$

However, for a particular route, the nominal haulage time does not change. Thus, equation 8 simplifies to yield equation 9.

$$\sum_{j=1}^{n} H_j = \sum_{j=1}^{n} k_j t_{n_j} + \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} t_{q_{jk_j}} \tag{9}$$

From equation 9, the component $\sum_{j=1}^{n} k_j t_{n_j}$, which is the total nominal time, can be expressed in equation 10:

$$\sum_{j=1}^{n} k_j t_{n_j} = tx_{-q} \sum_{j=1}^{n} k_j = tx_{-q} K \tag{10}$$

Where tx_{-q} is the average nominal haulage time of the system, and K is the number of haulage cycles of it. This average time does not include queue time. Now, from equations 9 and 10, the number of cycles is determined, expressed as follows:

$$K = \frac{\sum_{j=1}^{n} H_j - \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} t_{q_{jk_j}}}{tx_{-q}} \tag{11}$$

From equation 11, the number of system cycles occurring in $\sum_{j=1}^{n} H_j$ operational hours of the system is known. Then, the number of cycles per hour arriving at the shovels is determined by equation 12, representing the arrival rate of trucks to the shovels.

$$a_n = n \cdot \left(\frac{\sum_{j=1}^{n} H_j - \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} t_{q_{jk_j}}}{tx_{-q} \sum_{j=1}^{n} H_j} \right) = n \cdot \left(1 - \frac{\sum_{j=1}^{n} \sum_{k_j=1}^{k_j} t_{q_{jk_j}}}{\sum_{j=1}^{n} H_j} \right) = n \cdot \left(\frac{1 - Q_n}{tx_{-q}} \right) \tag{12}$$

Finally, for a homogeneous system of shovels and trucks, equation 5 becomes equation 13, representing the service rate of the shovels.

$$s_m = m \cdot \frac{\sum_i \frac{H_i - E_i}{t_{c_i} + t_{s_i}}}{\sum_i H_i} = m \cdot \frac{\sum_{i=1}^{m} H_i - \sum_{i=1}^{m} E_i}{(t_{c_i} + t_{s_i}) \sum_i H_i} = m \cdot \left(1 - \frac{\sum_{i=1}^{m} E_i}{\sum_i H_i} \right) = \frac{m(1 - E_m)}{t_{c_i} + t_{s_i}} \tag{13}$$

For a homogeneous system of trucks and shovels, it can be said that the arrival rate of n trucks to the m shovels and the shovels' service rate is equivalent to equations 12 and 13, respectively. Therefore, equation 14 is proposed, showing the balance between trucks and shovels where the rates are equivalent.

$$n \left(\frac{1 - Q_n}{tx_{-q}} \right) = \frac{m(1 - E_m)}{tc_i + ts_i} \tag{14}$$

This equivalence leads to reconsidering the system's MF_{nm}. Thus, the following equation, which is the quotient between the truck arrival rate and the shovel service rate, is presented in this way:

$$MF_{nm} = \frac{n(tc_i + ts_i)}{mtx_q} \tag{15}$$

Now, with the result of equation 13, we develop equation 16, representing the MF in terms of the percentage of waits, queues, and the average haulage time with and without queues, defined as follows:

$$MF_{nm} = \frac{n(tc_i + ts_i)}{mtx_q} = \left(\frac{1 - E_m}{1 - Q_n} \right) \left(\frac{tx_{-q}}{tx_q} \right) \tag{16}$$

Additionally, it is known that the following relationship expressed in equation 17 is fulfilled, since k cycles have occurred throughout the operation:

$$ktx_q = ktx_{-q} + kq \tag{17}$$

Furthermore, it is known that the average haulage time, including queues, multiplied by the number of cycles, equals the total operational hours. Thus, equation 17 can be transformed into the following expression:

$$\sum_{i=1}^{n} H_i = \frac{tx_{-q}}{tx_q} \sum_{i=1}^{n} H_i + \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} tq_{jk_j} \tag{18}$$

Solving for the average haulage time ratio from equation 18 presents the following relationship.

$$\frac{tx_{-q}}{tx_q} = \frac{\sum_{i=1}^{n} H_i - \sum_{j=1}^{n} \sum_{k_j=1}^{k_j} tq_{jk_j}}{\sum_{i=1}^{n} H_i} = 1 - Q_n \tag{19}$$

Applying the result of equation 16 to equation 19, the final formula for the *MF* is obtained:

$$MF_{nm} = \frac{n(tc_i + ts_i)}{mtx_q} = \left(\frac{1 - E_m}{1 - Q_n}\right)\left(\frac{tx_{-q}}{tx_q}\right) = 1 - E_m \tag{20}$$

Equation 20, which is the *Match Factor*, provides the possibility to evaluate the productivity of a mine; that is, if the MF is less than 1, it means that the system has a deficit of trucks, and if it is greater, it means there is an excess of trucks. Consequently, the goal is to find the equilibrium point when the MF equals 1.

Now, if we solve for the waiting time as a function of the queue from equation 20, it is expressed as shown in equation 21.

$$E_m = 1 - \frac{n(tc_i + ts_i)(1 - Q_n)}{mtx_{-q}} \tag{21}$$

According to equation 21 and the equilibrium condition of the MF, a system is in equilibrium when the MF equals 1. Then, at this point, there exists a number of trucks n_0 in such a way that there is neither a deficit nor an excess of trucks. In other words, the service rate of the shovels equals the arrival rate of the trucks, and strictly speaking, the waiting time equals zero. This n_0 can be calculated as follows:

$$n_0 = \frac{mtx_{-q}}{(1 - Q_{n_0})(tc_i + ts_i)} \tag{22}$$

For a heterogeneous system of shovels and trucks, these formulas apply directly. For the case study, we will start from the case of homogeneous and heterogeneous systems of shovels and trucks. As seen in equation 20, the close relationship between the queues of trucks at the shovels, their waiting time, the number of trucks, the service time of those, and the average haulage time, and how these parameters define the productivity of a system. This productivity finds its maximum expression when the MF equals 1, when the system's equilibrium point is found. This is equivalent to finding the optimal number of trucks, i.e., n_0.

If we pay attention to equation 20, where the MF is expressed, it is seen to depend on the queue percentage of the system, the waiting percentage, the number of trucks, and the service times of shovel and truck haulage. Thus, it is possible that more than one MF equals 1, meaning it is within the possibilities that two or more fleets of trucks present this value, since it depends not only on the trucks but also on the routes of the destinations. And not necessarily does a single solution exist. It may be that for n_0 the MF is 1, but it is also possible for a different n_0, given it depends on the behavior of the queues and waits.

For this reason, a different equation is needed, but one that is closely related to the MF, the unit mining cost, umc_n.

2.2 Optimal Unit Cost

The mining cost $MC(n)$ is defined by the following equation:

$$MC_n = \sum_{i=1}^{m} Ch_i H_i + \sum_{j=1}^{n} Ch_j H_j + GAmn \tag{23}$$

Where Ch_i is the unit cost of a shovel i and Ch_j is the unit cost of a truck j. Additionally, GA represents additional costs such as drilling and blasting. Equation 23 summarizes the loading, hauling, and other costs the operation assumes to move the total production. The loading cost component is a constant function since it represents the cost of operating the m shovels in the system, while the system's hauling cost represents an increasing function due to the increase in trucks. Therefore, to estimate the unit mining cost, it is necessary to determine the production shown in the following equation:

$$P_n = \frac{fc(1 - E_m)}{t_{c_i} + t_{s_i}} \sum_{i=1}^{m} H_i \tag{24}$$

The production P_n has a maximum, which for a homogeneous system equals

$$\frac{fc}{t_{c_i} + t_{s_i}} \sum_{i=1}^{m} H_i.$$

Taking this result into account and equations 20 and 21, we obtain the unit mining cost expressed in equation 25.

$$umc_n = \frac{\sum_{i=1}^{m} Ch_i H_i + \sum_{j=1}^{n} Ch_j H_j + GAmn}{\frac{fc(1-E_m)}{t_{c_i}+t_{s_i}} \sum_{i=1}^{m} H_i} \tag{25}$$

The denominator of the function umc_n has a feasible maximum since it is the production, then, past this point, any increase in trucks would produce the same or less in production but an increase in cost. On the other hand, under this maximum, we will have an increase in the unit mining cost, so, there is a minimum point of the function umc_n.

A more specific explanation is when the number of trucks tends to zero, the unit operation cost is very high due to the high waits of the shovels and the low production. As trucks enter the system, production increases and the unit mining cost decreases up to a certain point, since even if the number of trucks is increased, the shovels' production has reached its maximum limit. That is, the waits are as minimal as possible and the marginal increase in mining cost is produced because the queues of trucks in the system start to increase.

There exists, then, an acceptable queue length that originates a marginal increase in production and from that point onwards, any increase in trucks does not add value to the system. Thus, the problem reduces to finding the operation's equilibrium point (number of trucks), where the unit mining cost is the minimum. It has been seen that to find the minimum unit mining cost, it is necessary to find the maximum feasible production limit, which mathematically is equal to

$$\frac{fc}{t_{c_i}+t_{s_i}}\sum_{i=1}^{m}H_i.$$

Equation 22 provides the optimal number of trucks to achieve an MF equal to 1, but it expresses that it depends on associated wait and queue times. Therefore, it can be affirmed that, given a system of m shovels and n trucks, the maximum production occurs for an n_0 and at this point, there is a minimum unit mining cost as shown in equation 26.

$$umc_{n_0} = \frac{\sum_{i=1}^{m} Ch_i H_i + \sum_{j=1}^{n_0} Ch_j H_j + GAm_{n_0}}{\frac{fc}{t_{c_i}+t_{s_i}}\sum_{i=1}^{m} H_i} \tag{26}$$

From all the above, it is concluded that, for a number of trucks n_0, the maximum production and the minimum limit of the unit mining cost are found. Therefore, this n_0 is the optimal number of trucks that makes the system work at its maximum productivity; this n_0 occurs when the MF_{nm} is equal to 1. This can be mathematically expressed as shown in equation 27.

$$\forall S(m,n,r(x,y,z),d), \exists n_0 \left[P_{n_0} = \max_n P_n \wedge umc_{n_0} = \min_n umc_n\right] \rightarrow MF_{nm} = 1 \tag{27}$$

Where $S(m,n,r(x,y,z),d)$ is a hauling system of m shovels, n trucks, r transport routes, and d destinations.

3 Simulation

3.1 Methodology

In this chapter, the methodology to be used for developing the transportation systems will be described. Generally, a program representing the hauling system will be constructed. This computer program is based on generating transactions over time, which, for the current case, will represent the trucks. Each transaction will be generated following some frequency distribution or a measure of central tendency. That is, each mine route segment will have an average hauling time or a distribution function representing it. This transport time will be modeled according to the trucks' speed, gradients, and rolling conditions.

Trucks will travel the mine's routes, which for the program will be time transactions. It is known that each truck must arrive at a loader or dumping site at some point. If the truck arrives at the loading or unloading system, it will inquire if it is busy. If so, the system will control the queue, and only when the system is unoccupied, the truck can enter and be served. When the loading system finishes serving a truck, it will inquire whether the load is mineral or waste. For this, the system has a distribution of material by tonnage which will control the destination of the material. When a truck returns from the dumping site or the crusher, it will be assigned based on an algorithm, whose objective function is to minimize queues and maximize shovel coverage. This algorithm functions as a dynamic *Match Factor* and works in real-time, taking information from queues at each loading front.

In general terms, trucks are simulated, and the transport cycle is optimized with the aforementioned algorithm; all this with the objective of finding the best production for a specific reality.

3.2 Truck Dynamic Allocation

To study the behavior of a hauling system with simulation, it's important to define what we want to achieve. In this particular case, an objective is already given, which is to meet planned production; also, the decision-making tools that have been mathematically demonstrated: the *Match Factor* and the Minimum Mining Cost. But when analyzing a system of m shovels and d unloading destinations, the question arises: how to assign the empty trucks and why should we use some tools to assign them? We must use a tool to assign trucks because in real life, there are not always fixed routes to the shovels (if this were the case, optimization would not make sense). What does exist is a possible combination that originates the MF to be equal to 1, meaning that the arrival rate of trucks is equivalent to the service rate of the shovels, and at this point, the minimum mining cost and maximum productivity are found as demonstrated in the previous chapters.

The assigned tool will be the concept of *Match Factor* (MF) but in a dynamic form, that is, at every required moment of the simulation or when the truck requires it. It is known that the MF reflects the productivity of a system, hence it will seek the highest possible productivity for each assigned truck with the goal that in the global sum, the best production is achieved for a particular number of trucks.

Thus, a truck returning from a dump area has the opportunity to go to "m" service locations, but only a limited set of solutions will ensure that it is served in the shortest possible time.

To identify which route is the most suitable, a specific route will be analyzed, and the result generalized. For example, if a truck wants to decide which shovel to go to, it would need to know some factor indicating where. This factor could be the result of the following reasoning: it would be ideal for a truck to arrive at the shovel and be served just in time, that is, without queuing and without the shovel waiting.

Considering the above, the factor CP is defined, which measures the total service time of the shovel versus the total hauling time to it from a given point in the mine. It is defined as follows:

$$CP_i = \frac{(\#Q_i * (t_{c_i} + t_{s_i}) + k_i * (t_{c_i} + t_{s_i}))}{t_i} \tag{28}$$

Where:

- $\#Q_i$: Current queue or number of trucks in queue at Shovel i.
- t_{c_i}: Loading time of Shovel i.
- t_{s_i}: Squaring time at Shovel i.
- t_i: Transport time to Shovel i.
- i: Shovel in question.
- k_i: Trucks en route assigned to Shovel i.

The following values and meanings of CP_i are considered:

- $CP_i = 1$: Means the truck will arrive just in time without queuing and without causing the shovel to wait. That is, the *Match Factor* is equal to 1 at that moment.
- $CP_i > 1$: The truck will queue.
- $CP_i < 1$: The shovel will wait.

If there is a set of CP_i, such that i belongs to the set $[1, m]$ and m belongs to the positive integers, then, how do we choose where to send the truck at a given time of the simulation?.If within the set CP_i, there exists a value of $CP_i = 1$, then the solution has been found;

otherwise, the set of solutions must be divided into two subsets: those belonging to the interval $[0; 1[$ and those belonging to the interval $]1, +\infty[$.Then the sets are defined as:

- $P = \{CP_i | 0 < CP_i < 1\}$ for all $MF(i)$ that belongs to the positive rational numbers. This set is composed of the destinations where the shovel waits.
- $V = \{CP_i | CP_i > 1\}$ for all $MF(i)$ that belongs to the positive rational numbers. This set is composed of the destinations where the assigned trucks will queue.

Then, the minimum function of P ($\min(P)$) is calculated. This ensures that for this set, the $\min(P)$ is the solution of the greatest waiting time that can occur in the mine. The minimum function of V ($\min(V)$) is also calculated. This ensures that for this second set, the $\min(V)$ is the solution of the least waiting time that can occur in the trucks. It is logical that the route to be chosen will be the one that maximizes shovel coverage as a system. Three possibilities can be found, such as that:

- Only the set P exists, then the solution will be the function $\min(P)$. In this case, the system will assign resources to the shovel with the least

  coverage so that in this way, it increases the system's coverage sustainably.
- Only the set M exists, then the solution will be the function $\min(M)$.
- Both sets P and M exist. In this case, it is better to invest resources in maximizing shovel coverage by choosing the function $\min(P)$.

This result provides us with the possibility to decide which shovel to send the truck to maximize the overall system coverage. In all cases, it is evident that there will be a queue since the system seeks to maximize the global coverage of the same and in this way maximize production. The queue is part of the optimization and, depending on the mining plan, will have an acceptable value that ensures a given shovel coverage and that this ensures planned production.

3.3 Advance Model Implementation

I have employed an advanced model to simulate a prototype mine, showcasing the comparison between simulated outcomes and real data regarding production and operational efficiency. This approach enables us to assess the simulation's accuracy and its applicability in optimizing transportation and mining productivity, highlighting the significance of aligning simulated results with operational realities to enhance decision-making and planning in the mining sector.

3.3.1 Real vs Simulated Analysis

In table 1 shows the comparison between the simulation results and the actual data in terms of the number of trucks and tons per day (tpd) of various rock types. The compliance percentage indicates how close the simulated results were to the actual ones. A compliance below 100% suggests an underestimation in the simulation, while a compliance above 100% indicates an overestimation.

Production	Units	Simulation	Actual	Compliance
# Trucks	#	24	24	100%
Moved Rock	tpd	212,745	212,343	100.18%
Mined Rock	tpd	205,736	205,446	100.14%
Ore to the Crusher	tpd	88,546	85,376	103.71%
Stock	tpd	7,930	7,282	108.89%
Dumping Site	tpd	75,537	76,693	98.4%
TSF	tpd	38,422	38,990	98.5%

Table 1: Production

In Table 2, the operational efficiency of the transportation system is compared, including the waiting time of trucks and the duration of stops (Hang Time). A compliance above 100% in 'Queue Time Truck-Shovel' reflects that the simulation overestimated the waiting time compared to reality.

Overall Efficiency	Units	Simulation	Actual	Compliance
Queue Time Truck-Shovel	%	6.4	6.9	93%
% Queue Time Mine	%	8.6	8.6	100%
Hang Time	%	34.7	34.6	100%
Queue*Hang	%	2.98	2.97	100%

Table 2: Overall Efficiency

Table 3 shows the productivity and cycle times for the loaders and shovels. A compliance above 100% indicates that the simulation was conservative, and the actual productivity exceeded expectations. Actual cycle times greater than simulated suggest possible inefficiencies not considered in the simulation.

Loading System	Units	Simulation	Actual	Compliance
Shovel 1 Productivity	tph	3,195	3,500	91%
Shovel 2 Productivity	tph	3,189	3,435	93%
Shovel 3 Productivity	tph	2,990	3,290	90%
Hang Time Shovel 1	%	36	37	97%
Hang Time Shovel 2	%	35	29	120%
Hang Time Shovel 3	%	39	34	114%
Shovel 1 Cycle	min/cycle	2.98	3.25	92%
Shovel 2 Cycle	min/cycle	2.96	3.22	92%
Shovel 3 Cycle	min/cycle	2.97	3.35	89%

Table 3: Loading System

Table 4 evaluates the productivity and cycle times in material transport. An actual productivity higher than simulated by 10% demonstrates that the transportation was more efficient in practice than in the simulation, which is an important data for future planning and improvements of the system.

Transportation System	Units	Simulation	Actual	Compliance
Productivity	tph	487	539	90%
Transport Cycle	min/cycle	29.83	29.84	90%
Queue at Shovel 1	min/cycle	1.78	1.84	97%
Queue at Shovel 2	min/cycle	2.35	1.99	118%
Queue at Shovel 3	min/cycle	1.99	1.89	105%

Table 4: Transportation System

3.3.2 Mining Cost and Risk Analysis

Figure 1 shows how the mining cost reaches a minimum when the number of trucks is in the range of 19 to 25, which is the optimization zone and evidences the formulation exposed in equation 27.Figure 2 shows how the queue evolves, and the range of 19 to 25, which is the optimization zone, reaches a maximum of 2 min per cycle and then becomes exponential, which explains the increase in unit cost shown in figure 1.

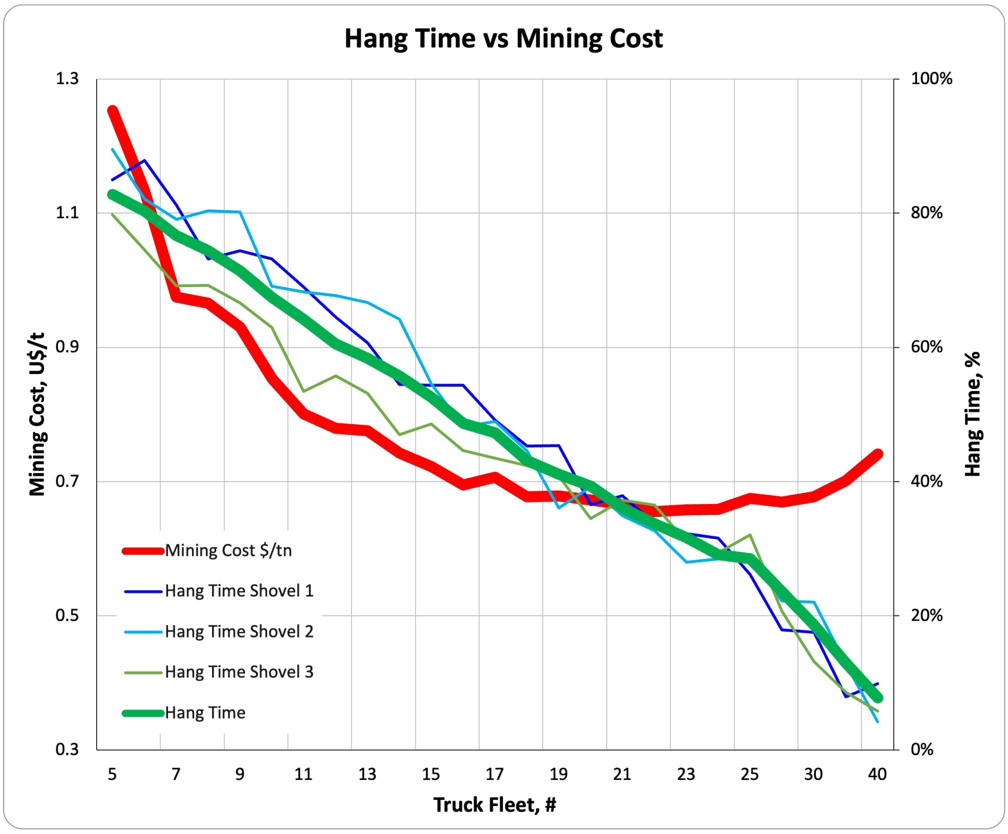

Figure 1: Mining Cost vs Hang Time

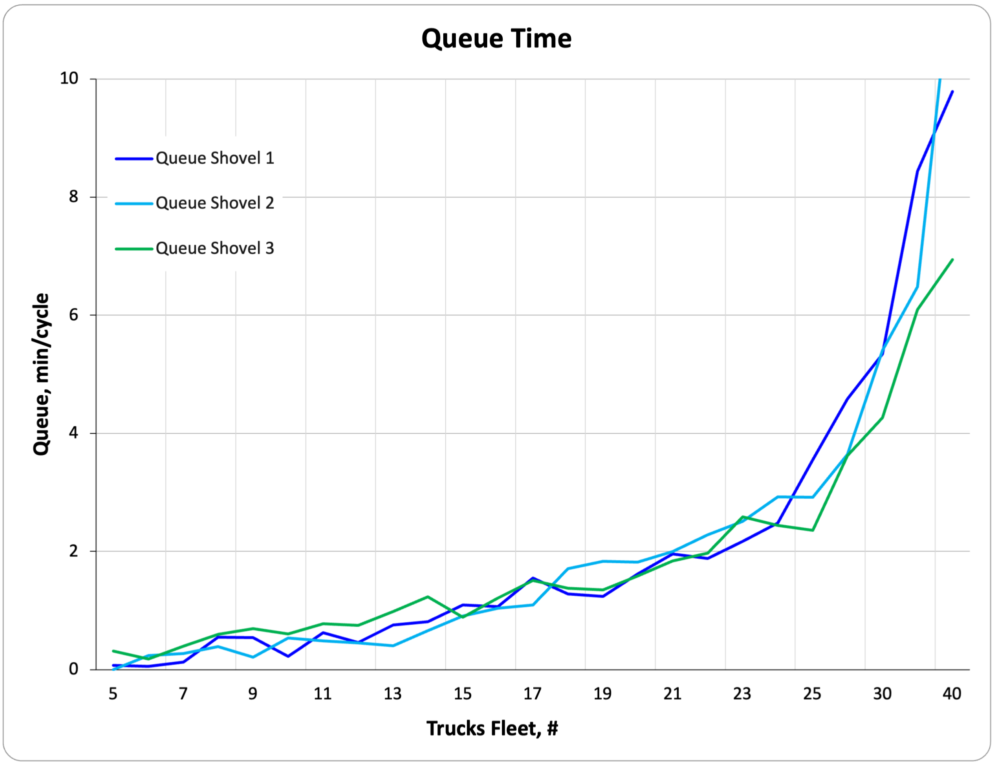

Figure 2: Queue vs Trucks

4 Conclutions

The conclusions drawn from this paper underscore the critical role of optimized shovel-truck allocation and the use of mathematical models and simulation in enhancing mining haulage operations. The study systematically addresses the challenge of minimizing mining costs while maximizing productivity through a balanced deployment of trucks, ensuring that the Match Factor (MF) equals 1. This equilibrium point signifies neither a deficit nor an excess of trucks, aligning the service rate of shovels with the arrival rate of trucks, effectively reducing waiting times to zero.

Key findings from the simulation results reveal that:

1. The optimal number of trucks, where mining costs reach a minimum and productivity is maximized, lies within a specific range, demonstrating the precision of the mathematical models developed.

2. The queue dynamics and their impact on mining operations highlight the importance of maintaining an optimal fleet size to avoid exponential increases in unit costs.

3. The relationship between truck queues, shovel wait times, and overall system productivity provides valuable insights for making informed economic decisions and managing operational risks.

In essence, this paper contributes to the field by offering a methodical approach to truck allocation in mining haulage operations, backed by empirical data and mathematical rigor. It presents a comprehensive framework for achieving operational efficiency and cost-effectiveness, paving the way for future research and practical applications in mining logistics optimization.

5 Disclaimer

It's important to highlight that 100% of the formulas presented in this research have been developed by the author based in Lozano 2019 research. However, it's pertinent to mention that the responsibility for the correct formulation and development of these equations rests solely with the author.

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