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LOGISTIC EVALUATION OF AN UNDERGROUND MINE USING SIMULATION

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ABSTRACT

This paper describes a logistic study about an underground gold mine, belonging to AngloGold Ashanti, where four different layout options could be applied to the tunnels, and also different transportation strategies. Each evaluated layout had its own configuration for shaft and truck fleet. The study was made individually for each year of the mine operation life, determining the necessary transportation capacity to achieve the planned production at that year. Due to the very restrictive traffic options in the tunnels, a framework was developed to represent the tunnels and traffic rules in a discrete-event simulation model. The results identified the scenario with the lowest necessary transportation capacity to achieve the planned production.

1 INTRODUCTION

The underground mining is a very daunting challenge. In addition to all concerns about safety, the tunnel network has to be well planned in order to achieve feasibility to the mining operations. The excavation of galleries is an expensive and complex operation. So, the tunnel network has to be designed to minimize its extension, allowing the best possible traffic options.

The usual challenges in underground mining logistics are basically space restrictions. The truck size cannot be changed. It is limited by the gallery height and width. The gallery layout is not flexible, there are no alternative paths or shortcuts. Also, the distance from the bottom to exit increases along time. Despite these circumstances, the mine should keep a regular production rate.

A search for the best layout option to the tunnel network was the problem faced by AngloGold Ashanti, a gold mining company with operations in Brazil. In addition to the tunnel layout itself, the mine could have shafts in different positions, different transportation strategies with intermediary silos, and also different truck fleets. The goal was to find the best layout option to achieve the scheduled production using the lowest investment in trucks. The truck fleet should be sized for each one of the fourteen years of the mining operation. Since the underground traffic is a very dynamic process, it is very difficult to study with deterministic tools, and the discrete-event simulation was the chosen option.

The concern about underground traffic in mines is not new. It is also subject of simulation studies since the early days of this technique applied with computers. Hayashi and Robinson (1981) documented a simulation study regarding an underground railroad in a coal mine. They addressed traffic problems in detail, considering crossing lines, single lines and tunnel layouts. Their objective was also to achieve the best train configurations and dispatching strategies to sustain coal production with minimum resources. Nevertheless, the studied layout was rather simple: a line with one branch and six sidings.

The study conducted by Miwa and Takakuwa (2011) is also about a coal mine. They have evaluated an underground conveyor network, another option to retrieve minerals from the mine. In this case, the study was focused on the conveyor velocity, working under a predefined layout with two main conveyor branches. The objective was determine bottlenecks to the current operation, searching for ways to improve production. Wu et al. (2013) have developed a simulation study regarding tunnel visualization of underground mines, but the transportation and traffic were not discussed. A simulation study regarding underground mine equipment, including trucks, was conducted by Runciman (1997). In this case, not only the transportation, but also excavation and blasting operations were simulated with its main equipment in an schematic layout.

All of these studies had focus on evaluation of pre-existing systems with rather simple layouts. The contribution of this paper is to provide insight on simulating great underground tunnel networks used by trucks, and all dynamic problems they face regarding space restrictions.

When an underground mine uses trucks as the main transportation resource, the tunnel network may have traffic problems similar to a railroad network. Usually, the tunnels are large enough to allow only one truck to pass. Sometimes two. Traffic situations like passing or crossing are not easy inside the mine. Almost every tunnel has structures called "mucking bays" or "passing bays", which are strategically located spaces that can accommodate one truck, sometimes more than one. When a truck is in a tunnel and another comes from the opposite direction, one of them parks into the passing bay and allows the other to pass. This is similar to a single railroad line with a siding, like presented in Figure 1.

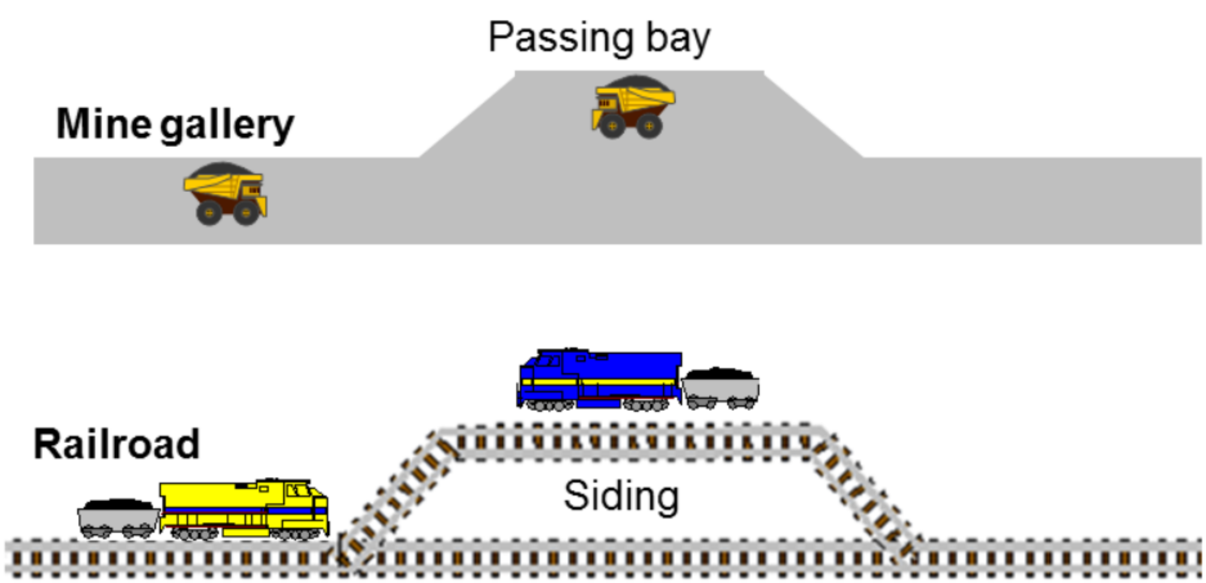

Figure 1: Comparison between crossing vehicles in a mine gallery and a railroad.

Since the traffic problems are similar, the solutions developed for railroad could also be applied to this case, with the necessary adjustments. Even the prioritization behavior is the same: loaded trucks should pass and empty trucks should wait. The chosen algorithm was the one proposed by Fioroni et al. (2008), which addresses the line/tunnel restrictions, crossing rules and traffic behavior. The following sections describe how this study was conducted.

2 THE UNDERGROUND MINE PROBLEM OVERVIEW

The underground mine used to support this study is located in Brazil, at the Minas Gerais state. The available scenarios to be evaluated are a combination of the following components:

- Tunnel layout
- Traffic directions
- Shaft loading position
- Intermediary silos: quantity and position
- Truck type and capacity

The trucks have three main tasks to accomplish: carry the gold ore to a shaft or hopper, carry waste to the shaft or hopper and carry waste to some mined out areas that need to be filled again. Trucks never go loaded to surface. The mine has a limited number of loaders, which is the same for all scenarios. The loading points are changed according to the production schedule, going deeper at the mine.

After internal discussions and studies, the AngloGold team has selected four scenarios to be evaluated with simulation:

2.1 Scenario 1: Original design

This scenario is the original design for the mine, with four main access tunnels named GAL, BAL, SER and FGS. The layout also has a ramp called Transport beginning at level 11. The fleet is a mix of trucks with capacity of 30 and 45 tons. It is considered the base scenario, used as a reference.

The schematic of the tunnel network is presented in Figure 2. Each color square is a mining point at the level, and a brown square means a passing bay position.

This scenario has a hopper at level 9 and the shaft is positioned at level 11, providing two unloading points to the trucks.

2.2 Scenario 2: Deeper shaft position

This scenario uses the same mix of trucks, but adds a new unloading position at level 16, providing more options to the trucks, minimizing congestions. It is also nearest to the bottom of the mine. The tunnel layout is the same of scenario 1. A rule is applied to this scenario: all extraction points under level 14 have to deliver the ore to the new hopper at level 16.

2.3 Scenario 3: Intermediary silos

This scenario uses the same tunnel network layout and unloading positions of scenario 1, but intermediary silos were added at levels 15, 18, 20 and 22. A fleet of 30-ton trucks is used to bring gold ore to these silos, and after that, a fleet of 60-tons trucks is responsible to convey it to the shaft position at level 11.

2.4 Scenario 4: Additional transport tunnel and traffic changes

This scenario adds a new transport tunnel to the scenario 1 layout, assigning it as unidirectional going down, and another pre-existing tunnel as unidirectional going up. The truck fleet mix is also the same as scenario 1, with 30 and 45 tons of capacity. This scenario layout is illustrated at Figure 3.

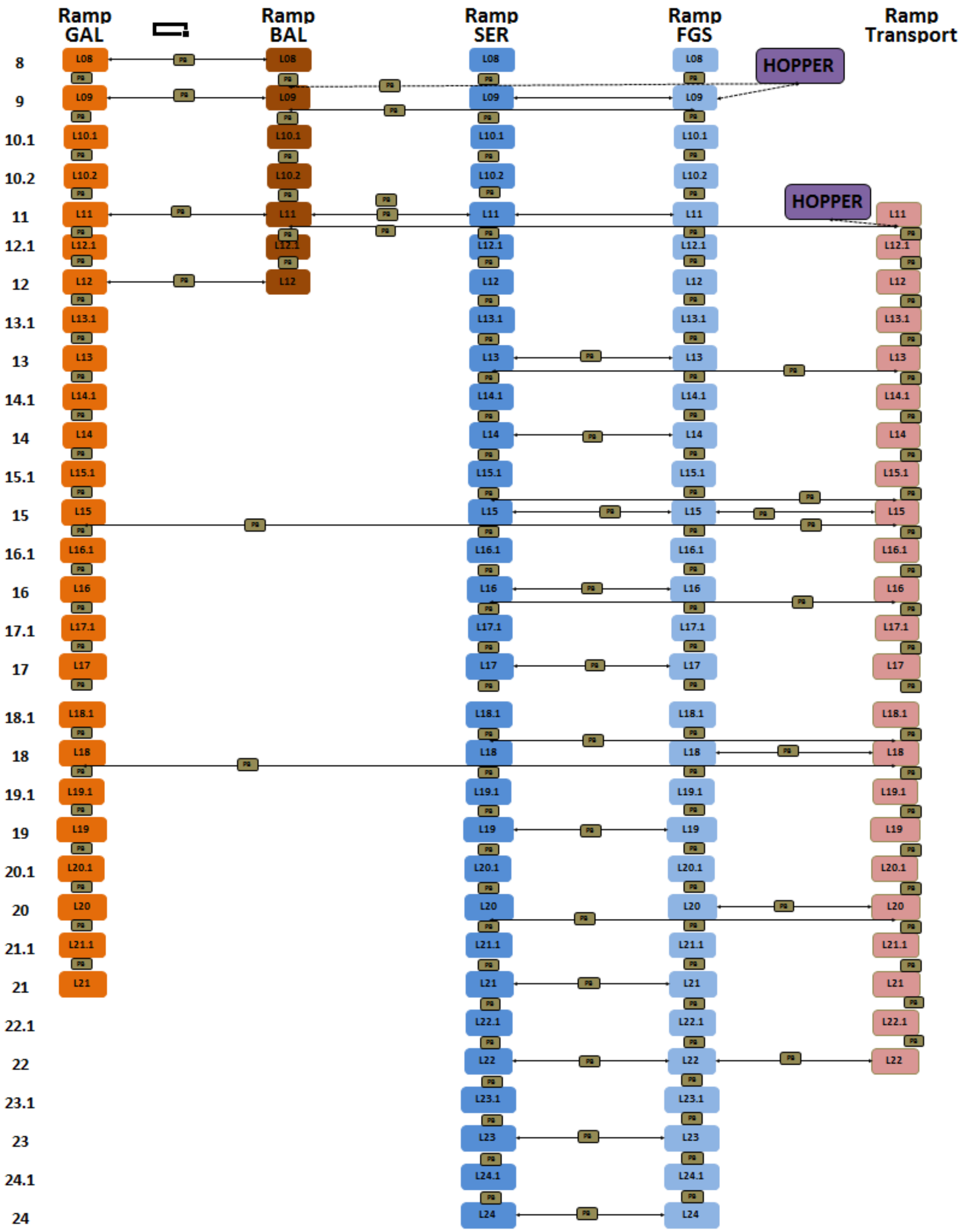

Figure 2: Tunnel schematics for the scenario 1, the base scenario.

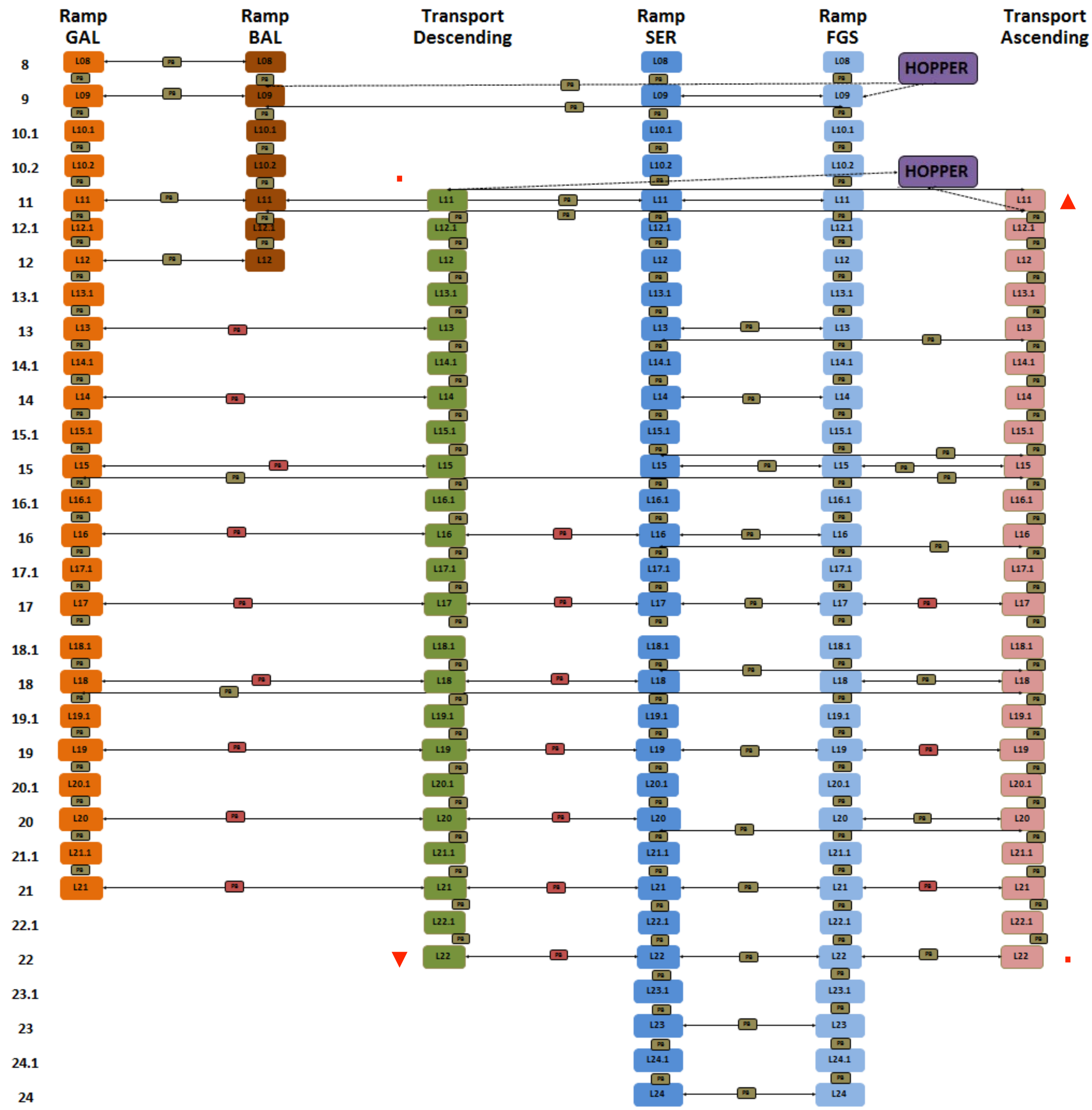

Figure 3: Tunnel schematics for the scenario 4, with an additional transport ramp.

3 MODELING THE MINE

The simulation tool chosen to build the models was Arena, from Rockwell Automation. The approach to model the tunnel network was the one described by Fioroni et al. (2013), the signal-oriented approach. It was chosen because the network had some particularities that should be addressed locally, and this approach allowed that. Situations like prioritization between trucks and the access to the hoppers required a local set of decisions different from the regular truck movement. This approach focuses on the signal intelligence, letting them decide if the truck is allowed to pass or not. Signals were distributed along the model network and each one of them had a different decision expression, considering the other signal's status, the nearby tunnels situation and other factors relevant to its specific location. At the real mine, they don't really have this many light signals, but the truck advance is decided visually or by radio instructions, resulting in the same behavior.

In this signal-based approach, the truck is "dumb". It only knows its destination and the route it has to follow, always moving ahead. Nevertheless, it has to obey the signals in its path. All intelligence to decide if the signal will be red (stop) or green (go) is implemented into the signal. A Boolean expression is associated to every signal, which check if the path is free and all particular conditions are complied, like priority and others. If a position requires a special decision regarding crossing or queues, it is also implemented in the Boolean expression at the related signals.

The model has considered more than 2000 individual positions where the truck could load, unload, park or wait for other trucks to cross. The animation structures of the tunnel network are presented in Figure 4, where the signals can be seen along the lines.

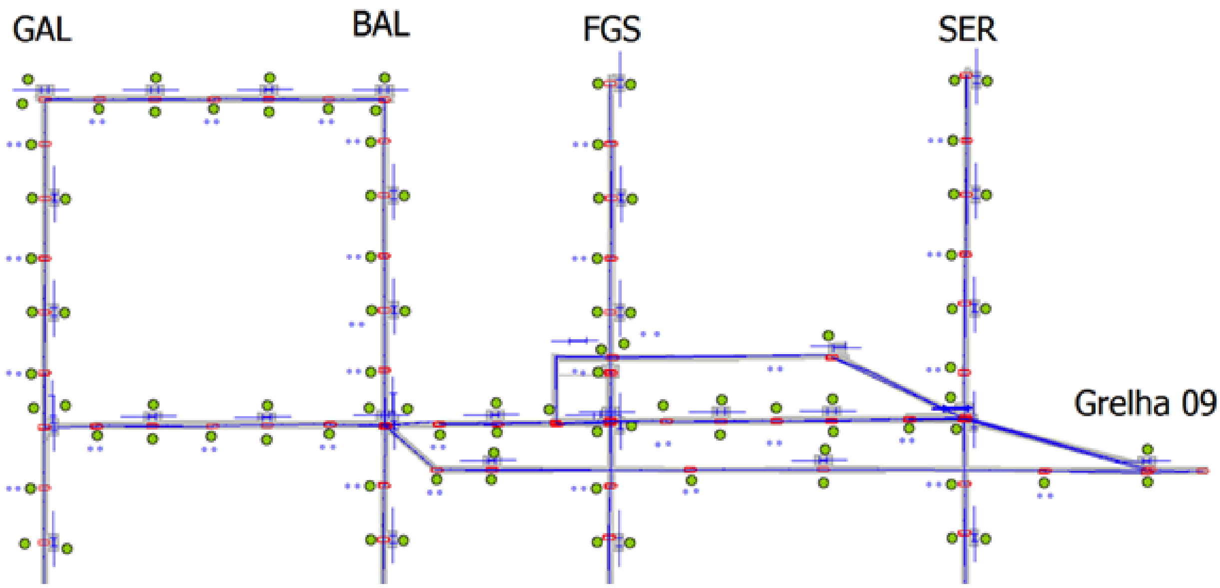

Figure 4: Partial view of model animation

The real network was too big to be represented, and great part of it was unimportant to the study. So, not all tunnels were represented. Only the ones relevant to the process and with truck circulation. It was simplified, by removing irrelevant connections and aggregating common points.

Also, it was assumed that the truck should use only one path/route between positions. This helped to simplify the model and give some "room" in the results, since at the real mine the trucks could avoid tunnels with more traffic, taking better decisions than the model. But it was not considered sufficiently relevant to affect the decision. The routes were mounted by AngloGold personnel, since they have more knowledge about the mine, and where the trucks should pass on every trip between positions. More than 10.000 routes were created, covering each possible origin-destination pair in the model.

An individual model has been built for each scenario, due to structural differences between them. Evidently, the route's list had to be updated for each model.

All trucks and loaders are affected by downtimes and maintenance, and every movement of the trucks has a chance to be affected by disturbing vehicles, impacting its travel time. Besides the priority in the mine is for the trucks, sometimes they may be affected by these vehicles, which are personnel transportation, tunnel maintenance equipment, cars, etc.

3.1 Model output

A set of KPIs were implemented in the model to help the system validation and comparison between scenarios. Specially travel and activities times and utilizations. Also, the scheduled production and simulated production were compared to confirm the goal achievement. A partial view of the output interface can be seen in Figure 5.

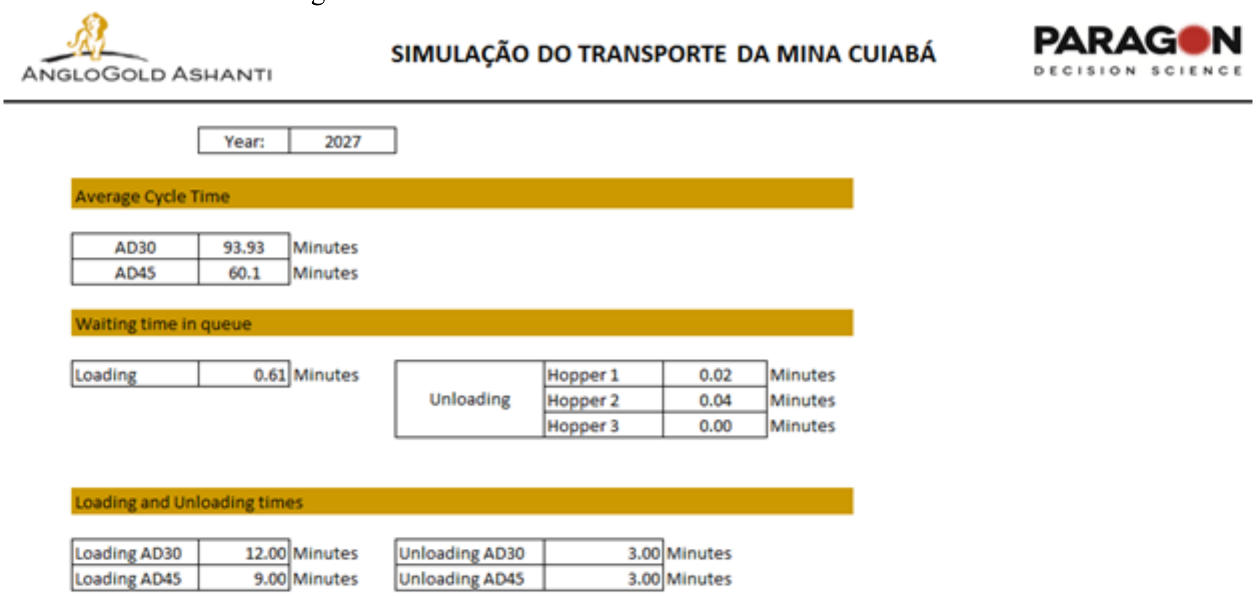

Figure 5: Partial view of the output interface.

In addition, the model output has included the number of trips performed at each route inside the mine, in order to provide the user useful information about potential traffic problems and the most problematic routes, as can be seen in Figure 6.

Origin	Destination	Number of trips
st545	st1939	4675
st1940	st726	4657
st145	st1939	3283
st109	st1939	2952
st139	st1939	2843
st127	st1939	2643
st1940	st290	2400
st133	st1939	2348
st31	st1935	2290
st1940	st272	2168
st1940	st254	2143
st907	st1939	2024
st1940	st284	1972

Figure 6: Usage count for each route at the tunnel network.

3.2 Model validation

The model was validated by comparing its results with deterministic calculations made for the base scenario (scenario 1). Also, all results were analyzed by the mining experts to check for coherency. The model behavior was evaluated with sensitivity experiments.

After that, AngloGold team approved the model to proceed with scenario experiments.

4 SCENARIO RESULTS

Several experiments were made with each scenario, to determine the optimal truck fleet at each year of operation. The objective was to find the lowest fleet, able to achieve 95% or more of the scheduled production.

In order to compare the scenarios, a new KPI was proposed, since the truck type was not the same for all scenarios and the direct comparison would not be possible. This KPI was named "Total Transportation Capacity" (TTC) and is a sum of capacities of all trucks of the two different fleets measured in tons, as presented below:

$$TTC = (F_1 * C_1) + (F_2 * C_2)$$

Where
F_1: Trucks of fleet 1
C_1: Truck capacity at fleet 1
F_2: Trucks of fleet 2
C_2: Truck capacity at fleet 2

The TTC was calculated for all scenarios and used to generate the chart presented in Figure 7 below.

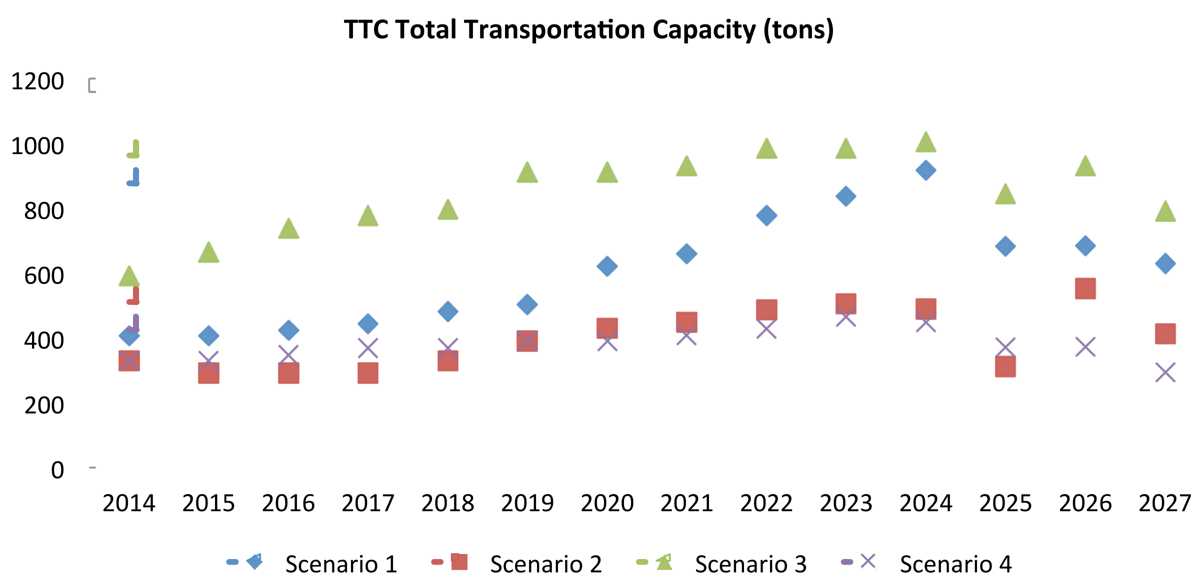

Figure 7: Comparison between scenarios.

Evaluating this KPI, scenario 2 and 4 performed noticeably better than 1 and 3. The production has a peak at 2024 and a reduction at 2025. It can be noted at the transportation capacity required for this year in all scenarios. The following year, 2025, isn't so demanding, requiring less trucks. These sudden changes in the number of trucks from one year to another are inconvenient and should be avoided.

In the comparison between scenarios 2 and 4, is possible to note that scenario 4 is more stable. It requires fewer changes in the number of trucks during the entire mine operation period. Table 1 below shows another KPI: the peak capacity required for each scenario.

Table 1: Peak capacity required for each scenario.

Scenario	Peak TTC (tons)
1	918
2	552
3	1004
4	466

By evaluating this KPI, the best is also scenario 4, which achieved the scheduled production for all years with the lowest TTC, meaning the smallest fleet.

5 CONCLUSIONS

By the results obtained and model behavior, is possible to conclude that the railroad algorithms and approach adopted were appropriate to represent an underground mine truck traffic behavior. All scenarios could be modeled and considered validated by the mine specialists. This is a relevant achievement, because to model restrictive movement is always a challenge. Not the restriction itself, but the entire decision process that has to be present to allow the truck or train to move in this structure.

This study has focused on the truck fleet as the main factor to decide which scenario was the best, but there are other factors involved, like the investment to implement the infrastructure required for each one of them. For the effect of this study, all scenarios were assumed to have similar investment levels, making them equal in this point of view.

One weak point in this study is the absence of a dispatch system in the model, which will probably exist in the real system. Besides it would not be perfect or optimal, this could allow the trucks to choose a better path or decide for a different destination depending on the present situation at the mine. In this case, however, as mentioned before, it was considered irrelevant to this study. In fact, the fleet determined with the model will be a little bit higher than the one necessary to the real system. On the other hand, the comparison between scenarios is not affected at all. All of them share the same weaknesses, which become irrelevant when comparing scenario data. They are all affected in the same way and in the same level, meaning the comparison is very reliable.

The Total Transportation Capacity KPI has proven to be useful, but also has the assumption that the truck cost is somewhat linear regarding its capacity. Depending on its price, the AD60 used in scenario 3 could be more interesting than AD45 used in scenario 4, being a better choice of scenario.

The conclusion is that this result pointed for the best technical decision. But the best business decision should be taken after adding costs to all this data. Costs that were not available for evaluation at the time of this study, but will certainly be considered for the AngloGold team decision.

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