INGENIERÍA INDUSTRIAL
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El Teniente:
Integrated Mine-Mill Transportation Model

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Agenda

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    2. Integrated Operations Center
    3. Early Alert System
- Mining Sectors Forecast:
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General Context

1. El Teniente

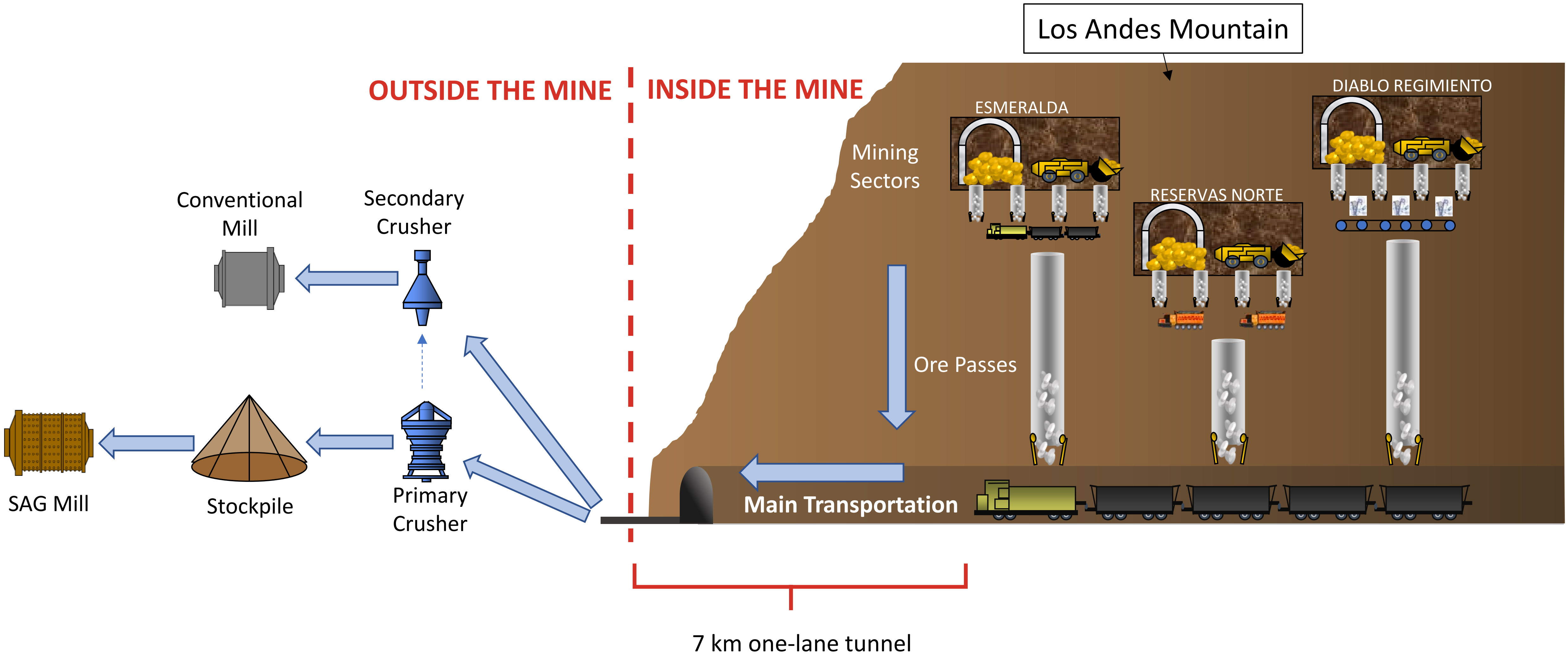
- Owned by Codelco, the world's largest copper producer. Codelco produces more than 1.8 million metric fine tonnes (mft) of copper/year.
- El Teniente is the world's largest underground mine, with over 3,000 km of development to date.
- Is a copper underground mine that has been operated for more than 100 years and currently processes 150,000 tonnes per day (t/day) in order to produced 400,000 mft per year.
- The main operations of the industrial complex of the Division are the mine, the main transportation (Teniente 8), the concentrator (Colón) and the smelter (Caletones).
- The Division has 18 productive sectors where three of them represents more than 75% of the ore produced (Esmeralda, Diablo Regimiento and Reservas Norte).
- The main transportation consist of a railway system, that has a cycle time of 1,5 hours from the crushers to the ore passes and back (10 km average).

1. El Teniente

Main Transportation:

- The material extracted among the sectors is taken to the ore passes. When a ore pass has enough material to fill a train (1,500 tons) a trip is declared to the main transportation.
- Trains pick up the ore produced from the ore pass (inside the mine) and carry on to the dumping zone (outside the mine).
- The main transportation has eight trains operating simultaneously, 2 of them are exclusively for fine mineral (crushed inside the mine) and the other 6 for coarse mineral (crushed outside the mine).
- An average shift has 8 hours where it can perform up to 40 trains laps in total.

1. El Teniente



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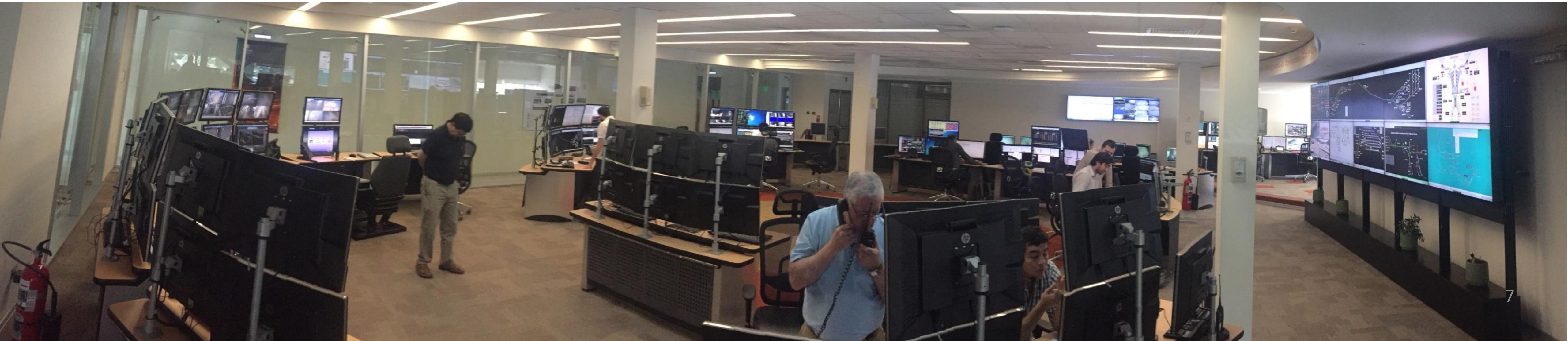
2. Integrated Operations Center

- In 2016 El Teniente creates an Integrated Operations Center (CIO) that join operators form all the Division to improve the coordination and communication among them.
- The responsible of the CIO has to analyze short-term strategies in the main transportation to synchronize the productive chain.
- In particular the CIO communicates all the Mining Sectors with the main transportation (Teniente 8) to carry as much material as possible and maximize the ore processed in the mill.



3. Early Alert System

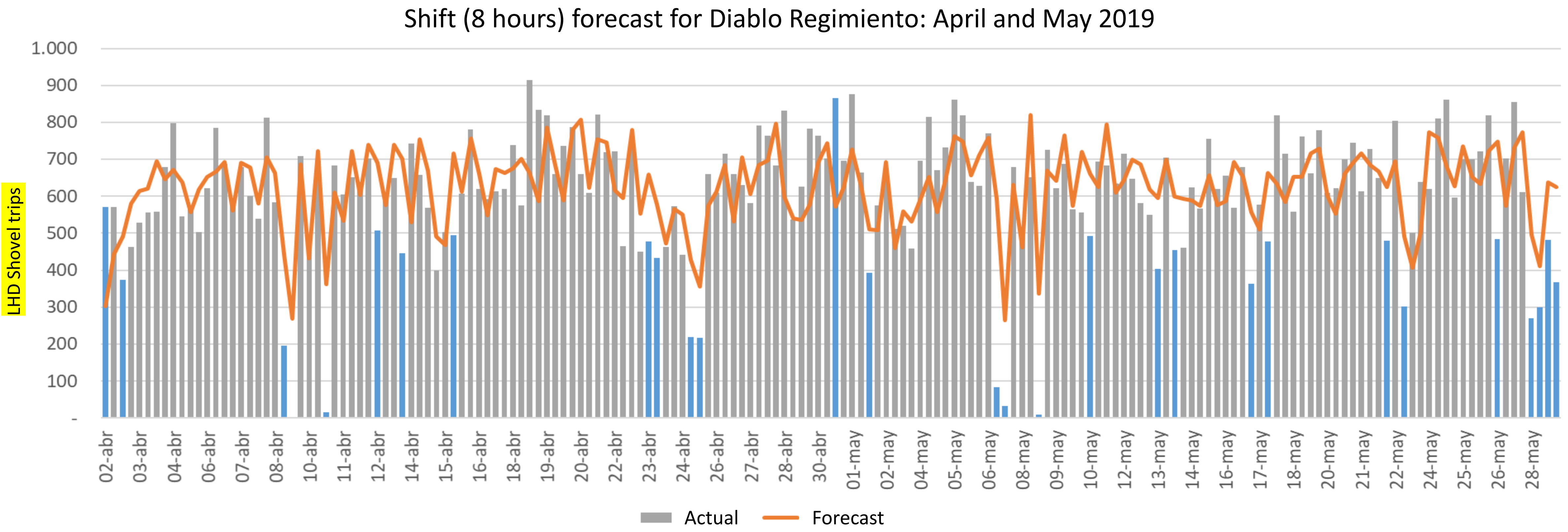
- An Integrated Mine-Mill Transportation Model is created in order to support the decisions making in the CIO.
- The model run at the beginning of the shift, and forecasts the next 8 hours (duration of the shift) the performance of the Division.
- Forecasts the LHD shovel trips for the main Mining Sectors and maximize the material transported among the trains and gives the best coordination between the trains to obtained the corresponding laps.
- The model allows the CIO responsible to take advantage early for possible temporary bottlenecks or contingencies created along the shift.

Mining Sectors Forecast

1. Variables

- The model forecasts the next 8 hours (one shift) the ore produced from each mining sector of the Division among all the available LHD shovels.
- It gives the timing when each ore pass has enough material to fill a train (trip).
- It considers the three main Mining Sectors of the Division (ES, DR and NN), and for each one generates a forecast.
- The variables considered are:
  - ❑ LHD Shovels availability
  - ❑ Production for the last 8 hours
  - ❑ Mining Program (tons to transport in the shift)
  - ❑ Distribution of the mineral between the ore passes in the last shift
  - ❑ Capacity of the equipments (different types of shovels and minecarts)
  - ❑ Maintenance of the equipments
  - ❑ Mean productivity per hour
  - ❑ etc.

2. Results for Diablo Regimiento



Variation Coefficient of Actual LHD Shovel trips (cycles): 28.0%
Mean Precision: 80.5%

3. Interface

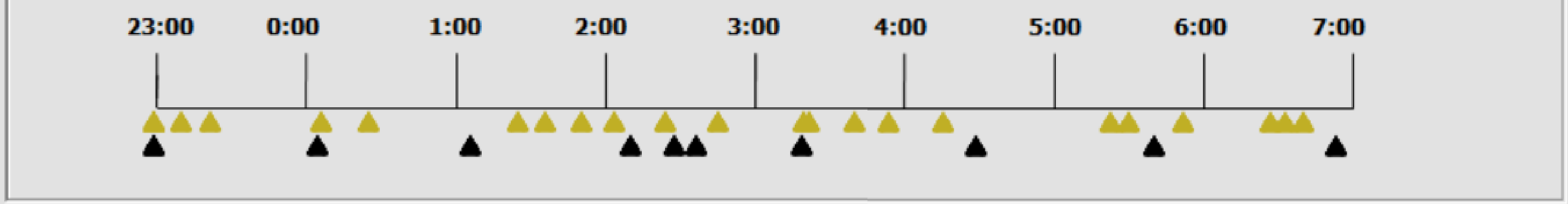
Forecast for Mining Sectors

	23:00 - 0:30	0:30 - 2:00	2:00 - 3:30	3:30 - 5:00	5:00 - 6:30
Coarse Ore	10 Entregas	3 Entregas	5 Entregas	3 Entregas	4 Entregas
	11-123OP40	GTI2-3OP60	3-4 2OP60	11-123OP40	OP14
	OP14	OP26	OP17H	OP24	OP22
	OP17H	OP27	OP22	OP27	OP26
	OP22		OP24		OP27
Fine Ore	3 Entregas	1 Entregas	4 Entregas	1 Entregas	1 Entregas
	OP21	OP21	OP21	OP21	OP21
	OP21		OP21		
	OP21		OP29		
			OP31		

	Forecast		PAM
Total de Entregas Turno:	30	(8)	32,9
Total de Entregas Grueso:	21	(6)	24,2
Total de Entregas Fino:	9	(2)	8,7
Reservas Norte:	8	(0)	7,5
Diablo Regimiento:	7	(2)	5,6
Esmeralda:	7	(3)	8,9
Otros Sectores:	6	(3)	7,8
Dacita:	2	(0)	3,2

Time Line for Trips completions in Ore Passes

☑ Esmeralda ☑ Reservas Norte ☑ Diablo Regimiento ☑ Otros Sectores



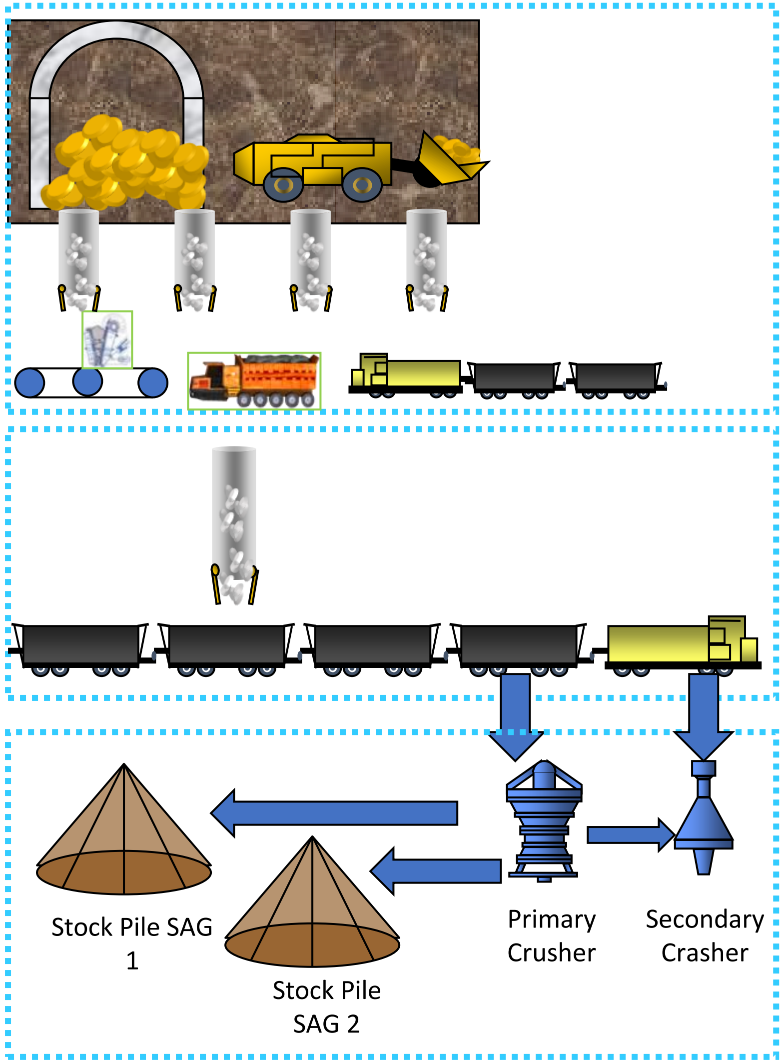
Main Transportation Model

1. Introduction

- The main transportation consists of 8 trains that carry material from the ore passes (which declare trips as it accumulate 1,500 tons) to the dumping zone (primary crusher or secondary crusher depending if the mineral is crushed or not).
- It has 2 trains exclusively for fine mineral (crushed inside the mine) and the other 6 for coarse mineral (crushed outside the mine).
- The railroad network for the 8 trains has one-lane tracks.
- The main problem of coordination between the trains is the main tunnel, which is 7 km length.
- The train dispatcher must send the trains from the dumping zone to the ore passes with the less interference as possible, and he has no tool to support him.

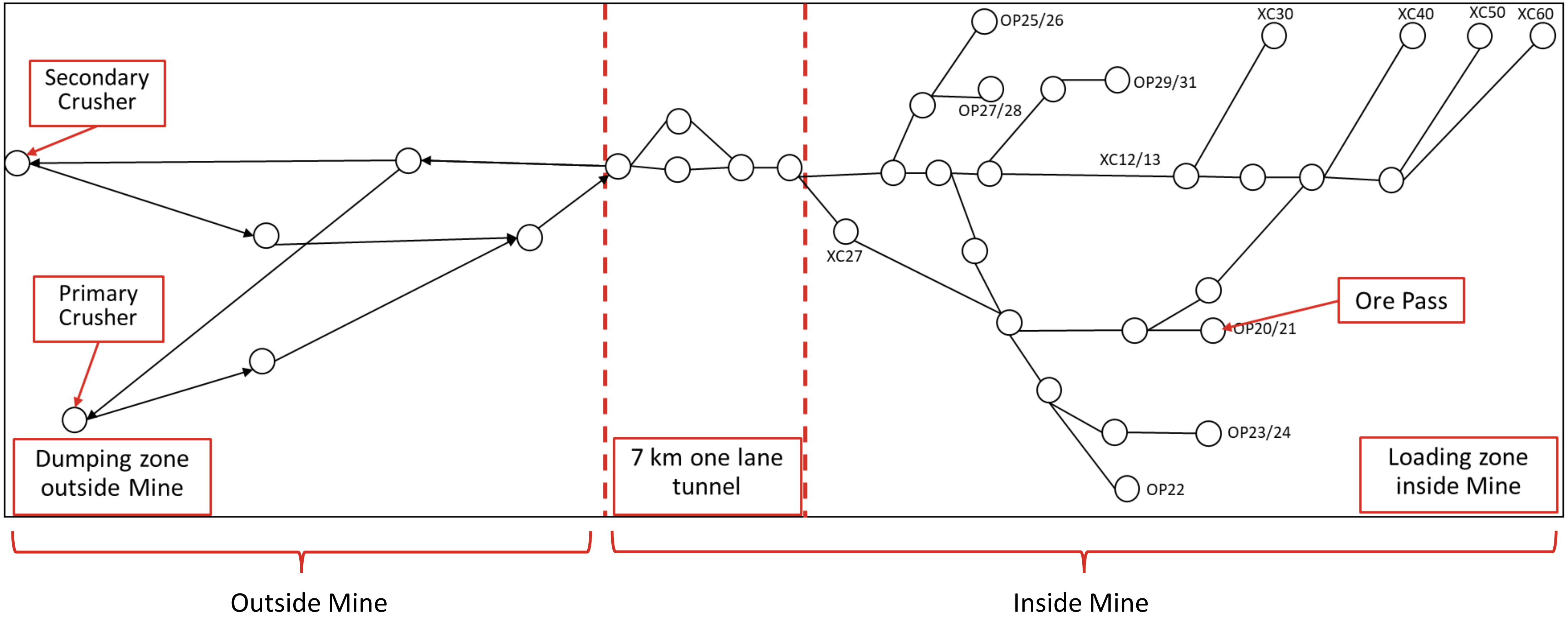
2. Algorithm

- Given the predicted timing of trips at each ore pass the model maximizes the mineral transported.
- The model consider:
  1. Permanency time on a railroad
  2. Waiting time for trips
  3. Loading/Unloading times
  4. Operational waitings
  5. Bigger Unloading times depending on the crusher and mill conditions (rate and availability)
  6. Restriction on the hour of the last lap (trains can’t enter the mine one our before the ends of the shift)
  7. Etc



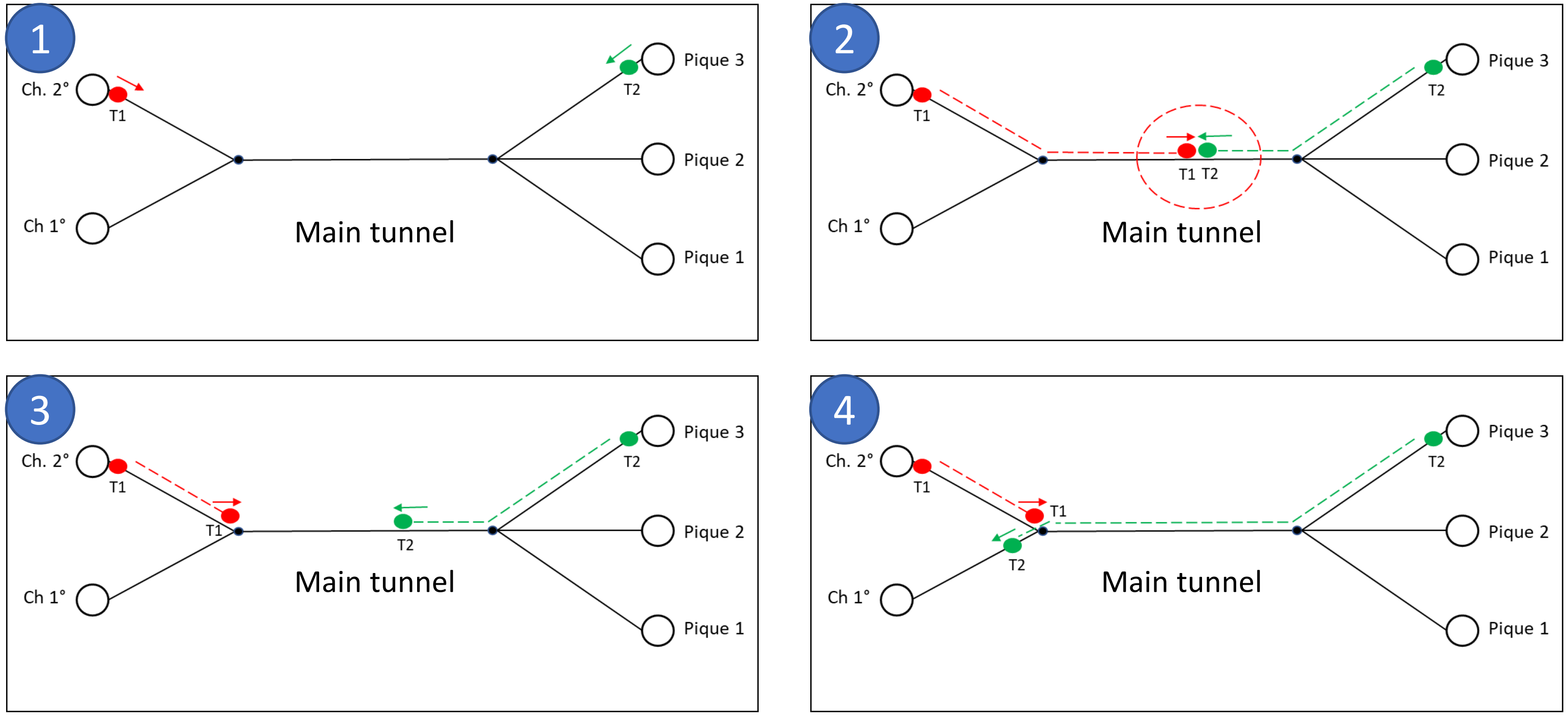
2. Algorithm

- It was modeled as a Discrete Event Simulation.
- The railroad network was discretized into 37 nodes with permanency time depending on the direction of the train.



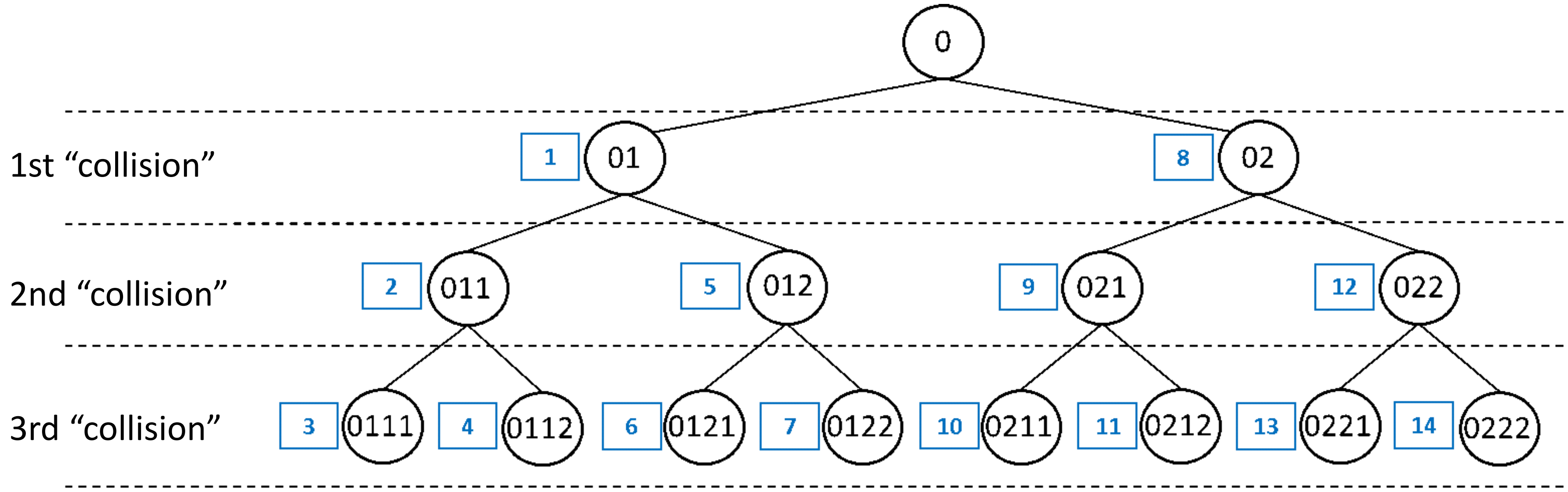
2. Algorithm

- Every train travel through the network until it encounters with another train in the opposite direction.
- The dispatcher must decide which train has to wait and which one has to move in order to avoid a “collision” resolving between 2 possible worlds (branch). Once the “collision” was avoided, the trains continue their route until the next “collision”.
- The problem was modeled as a Binary Decision Tree inspired on Branch and Bound.



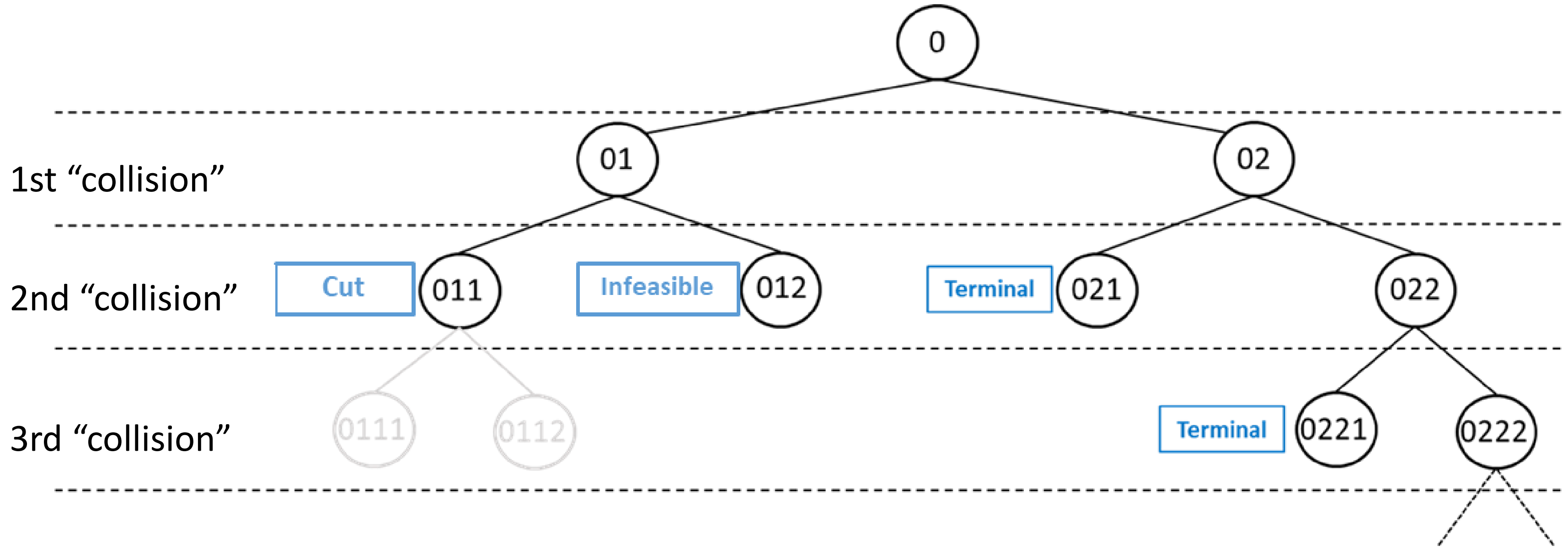
2. Algorithm

- Each possible “collision” between trains creates 2 branches of the tree. In one of them a trains wait on a node where doesn’t interfere with the other one, and in the other branch occurs the opposite.
- A branch of the tree ends when every train ends all their routes without interference among them (feasible solution).
- For an average shift, around 40 “collisions” occurs for each branch (10^{12} branches), that means 1,200 years for the algorithm to cover all the tree if there is no bound.



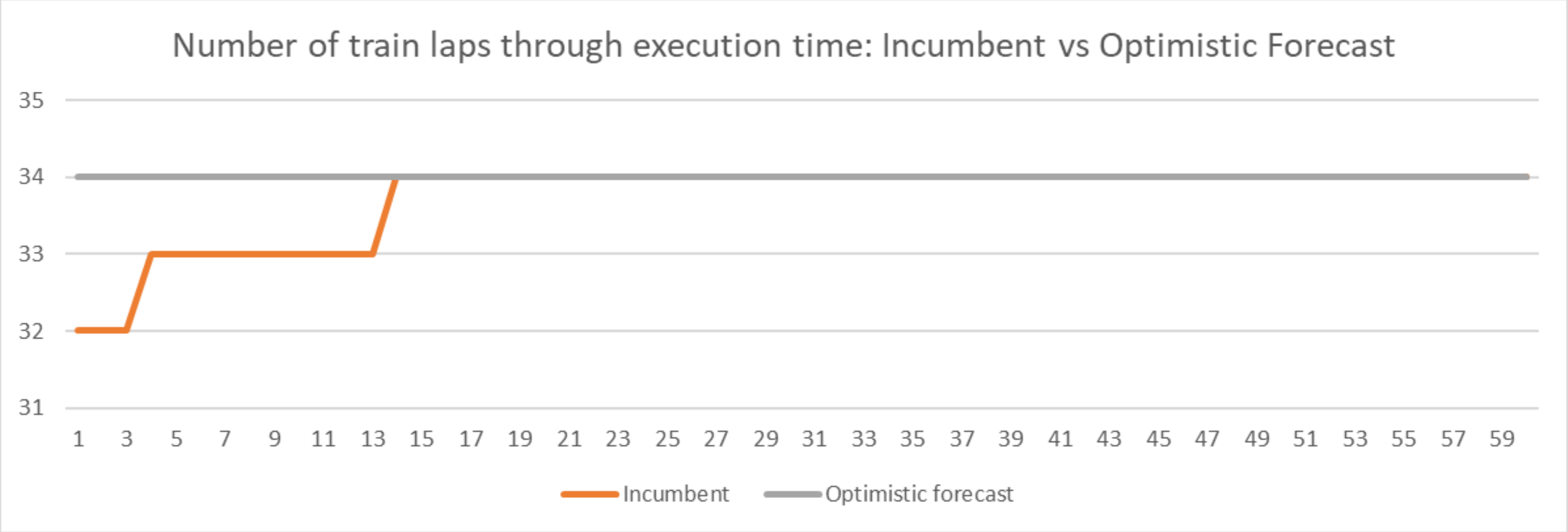
2. Algorithm

- On every node of the tree the model forecast the maximum number of laps that it can be done if there is no interference among the trains (optimistic forecast).
- Every solution obtained in the tree bound the branches where the optimistic solution is worst than the best solution obtained (incumbent).
- The model also bound infeasible solutions (branches where the waiting train doesn't have any segment of route where it doesn't interfere with the train that has to move).



2. Algorithm

- Solutions in less than 10 minutes are needed, therefore we developed a strategy to go over the tree.
- In order to reduce the probability of local solutions, the model travel sequentially a predefined number of nodes through equidistant branches.
- Also the algorithm runs in parallels threads to maximize the performance of the computer.
- Each thread starts on a different branch of the tree and shared the incumbent between them. Once a thread had finished it reassigned to another branch.
- The results for one instance ran with 32 threads:



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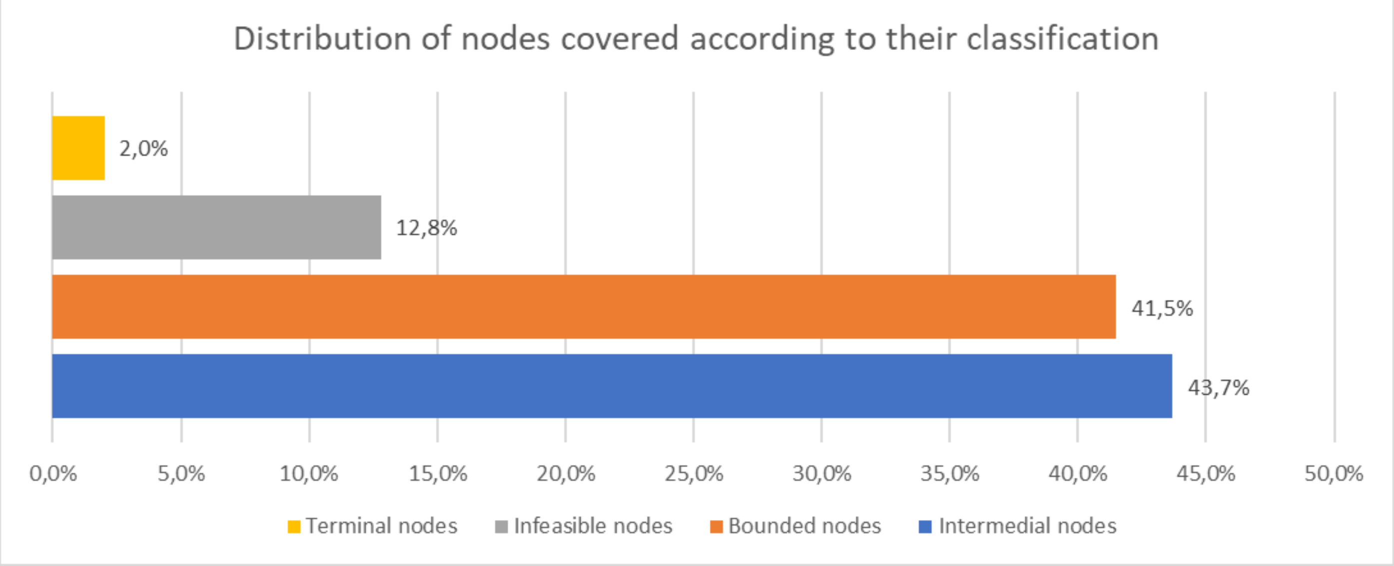
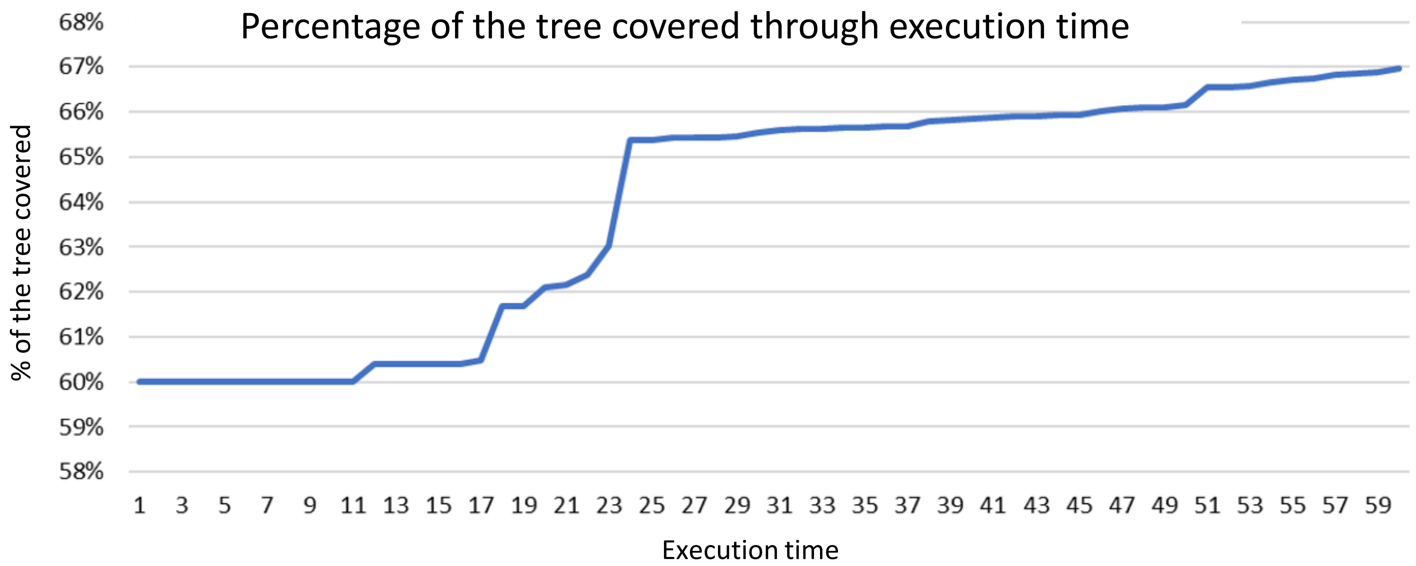
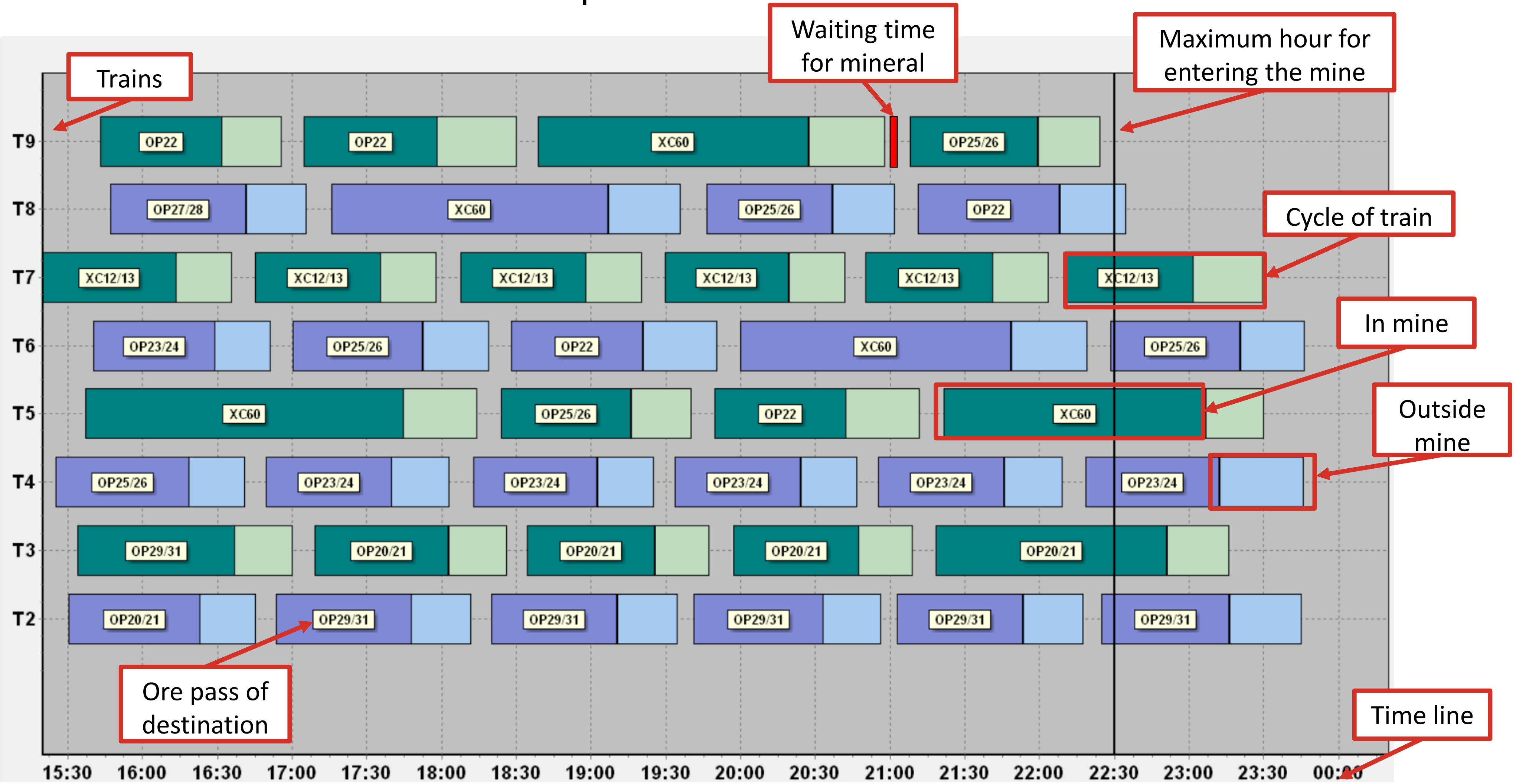




- The algorithm runs for an hour and had created 2 millions of nodes.
- Estimated size of the tree:
  - Average of 50 collisions on terminal nodes.
  - The node of the incumbent was on level 46.
  - $\sum_{i=0}^{50} 2^i \approx 2{,}25\ x\ 10^{15}$ nodes.
  - It's needed 26,000 year to creates fully a tree of this size.
- In a shift where the main transportation is the bottleneck of the productive chain (the mining sectors declared more trips than laps the train can do), the algorithm do from 1 to 3 laps over the dispatcher solution or from 2.8% to 8.5%.

3. Interface

Results interface for the main transportation model



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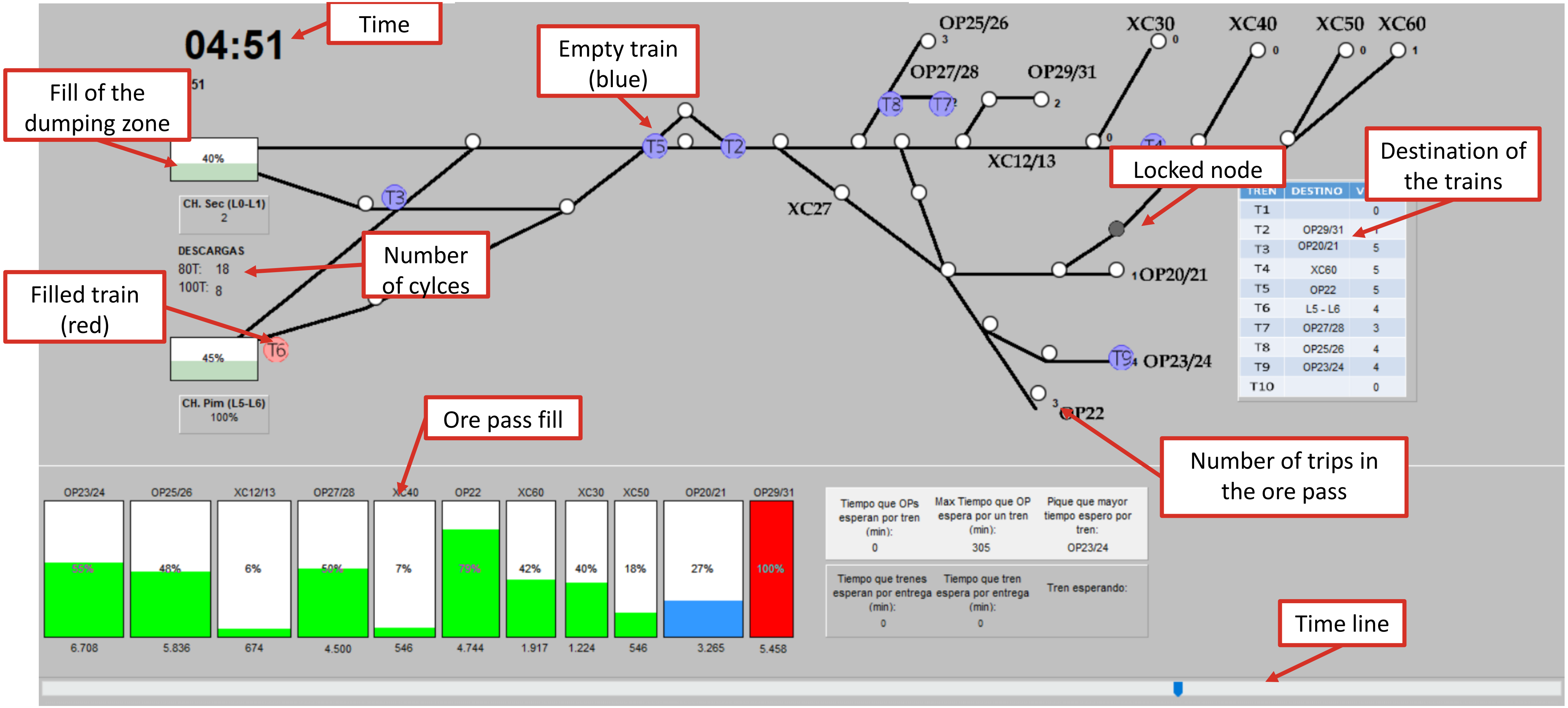

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