RAILWAY PLANNING: AN INTEGRATED APPROACH USING DISCRETE EVENT SIMULATION

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ABSTRACT
In this paper, a discrete event simulator of a heavy haul railway, developed as an integrated tool for supporting operational, tactical and strategic planning, is presented. For operational planning, a better scenario for maintenance tracks, using the same stoppage time, is defined. For tactical planning, the capacity of two-track circulation lines is analyzed, considering real capacity for the year of 2016. Finally, an increase in railway capacity utilization is planned, considering a scenario with a higher number of cars with duplicated rail lines for strategic planning. The simulation tool was previously verified and validated with real data presenting an error inferior to 5% in results for all planning areas.

Keywords: Capacity; Railway; Simulation; Planning

1. INTRODUCTION

The proposed research deals with discrete event simulation in the three scopes of planning in a supply chain: strategic, tactical and operational. It is important to note that many complex systems have already been detailed and studied only with the use of discrete event simulation. For example, the dependencies between the performance of the supply chain and the ruptures of the stock were analyzed (Cigolini 2014). Another example is the study of logistic chains of iron ore and general cargo with modeling starting with the design of the product in the cargo terminals, the transportation via modal rail and the unloading in the port for ship loading (Faria 2015).

Other issues, however, can be solved through robust optimizations with multiple applications. First is the tactical planning of the supply chain (Almeida 2015). Another is the operational planning of iron ore mining (Pinto 2001). Moreover, there are the mathematical models assigned as independent sub-systems within an integrated system to determine optimal levels of inventory and costs and investments (Tsai 2013). There are also some studies that evaluate the supply chain in a centralized and decentralized way through the so-called "interactive agents" (Macal and North 2014).

The simulation, although not aimed at optimizing the obtained results, is able to represent in detail a real system, identifying problems, bottlenecks and deficiencies through the evaluation of scenarios based on deterministic or stochastic parameters (Banks 2014).

Heavy haul railways carry large volumes of loads and seek to use the maximum available capacity of the rail system to obtain scale economy. This type of rail is typically used for commodities such as minerals, coal, among others.

A railway can be characterized as a closed circuit in order to connect the load source and destination, which is usually a port or an industry, and is composed by multi-locomotive heavy haul trains (Zhuan and Xia 2008). A closed loop system is the interaction between a (open loop) system and a controller that checks and supervises the deviation of a variable from a target. Its scheme is defined as a multiple open loop with memory, repeatedly implementing control measures, computing each time based on the current traffic state and the actions taken in the past (Corman and Quaglietta 2015).

Railway capacity is frequently evaluated. At a given moment, however, its capacity may be resized and aligned to long term demand analysis. Heavy haul railways are capital intensive systems which require robust methods that simultaneously encompass interactions on operational, tactical and strategic levels.

The current study describes an innovative method for strategic capacity of railway planning, considering tactical and operational decisions. A discrete event simulation model was developed, encompassing general features of such systems. To demonstrate its functionality, the model was used to support strategic capacity planning on heavy haul railways of Vale (a multinational corporation engaged in mining and logistics) located in different continents: Vitória-Minas, Carajás (South America) and Nacala (Africa). An in depth a case study conducted on the Vitória-Minas Railway (VMR) railway is described.

The Vitória-Minas Railway (VMR) is one of the world's major heavy haul railways, with one of the world's highest productivity levels. Spanning 905 kilometers in total length, this system connects the iron ore mines in the state of Minas Gerais to the Port of Tubarão in the state of Espírito Santo, Brazil. The VMR also transports coal, general cargo and passengers. The

VMR has a two-way track railway, a denominated trunk line, and four single-track branches. Studies and analyses have been conducted using mathematical or analytical models with limited scope. However, they do not encompass the global effect of the logistics chain.
Using concepts described in Crainic and Laporte (1997) a discrete event simulation model was developed using Arena®. The model represents the closed-loop iron ore rail transportation and enables the analysis of important variables when facing an increase in capacity transportation in VMR. In addition, the model includes operational and tactical decisions. It enables short-term analysis, such as the daily maintenance of the railway, port facilities and loading terminal operations and medium-term planning issues such as rail capacity.
This paper is organized as follows: in section 2 the literature of strategic, tactical and operational planning on heavy haul railways is revisited. Then, in section 3 the developed methodology using discrete event simulation is described. In section 4 a case study is presented on VMR. The results are presented in section 5, preceding the conclusion.

2. METHODS

Simulation studies in the railway sector are not new, since the use of this technique provides great security in supporting investment decisions, which are usually substantial.
Extensive literature is available on models and algorithms for railway simulations. The use of discrete event simulation in railway dynamics is a widespread tool. Currently there are many others that can be used in this area. Here the most relevant works for our research and those used to develop the VMR simulator are presented. The research conducted by some authors (Cordeau et. al. 1998), (Crainic and Laporte 1997) (Fogliatti et al. 2007) (Kamrani et al. 2014) brings a comprehensive review of major studies related to optimization, sequencing and planning, with main focus on railways.
The use of simulation to support investment decisions has been used since the 90s in North American and European railways companies, where the railways have great influence (Lewellen and Tumay 1998) and (Hooghiemstra and Teunisse 1998). The evolution of simulation software has increased since then. It can be noticed that there is a group of specialized software for railways like SIMPROCESS (Swegles 1997) (Dalal and Jensen 2001), RailSys (Anand and Anayi 2010), SIMUL8 (Marinov 2009) (Wales 2015), SIMONE (Middelkoop and Bouwman 2011), OpenTrack (Nash and Huerlimann 2004) and ROMA (Corman and Quaglietta 2015). In addition, general software is used for rail purposes. Arena software has been used for many different applications but also in rails (Bontekoning 2006) (Faria 2016) (Fioroni et. al. 2008) (Meireles 2010). Although Arena is not a specific package for railways, it has a variety of features that allow its use in different railway analyses or in specific studies in rail yards (Sinay et. al. 2008) (Abbot and Marinov 2014) (Ricci 2016) or in studies of other areas (Pinto 2015) (Ceciliano 2007). However, such studies of rail yards are conducted with a high level of abstraction, since their activities are operational and require a careful study of processes involving the system to determine its routine work.
Joborn et al. (2004) divides planning into three levels: strategic (long term), tactical (medium term) and operational (short term). The developed simulator is a tool aimed to support decisions in these three areas of planning.
The analysis carried out in each of these levels can be summarized as described below:

- Strategic analysis: some indicators provided by the simulator served as guidelines for the long-run planning sector. The objective is to plot strategic plans such as: viewing track network projects; expanding, doubling or tripling stretches; insertion of new dumpers in the discharge at the port or new loading silos in the mines and location of facilities (terminals, workshops, among others); the acquisition of resources, such as locomotives and wagons; improved asset productivity; and even pricing policies.
- Tactical analysis: at this level, the specifics of policies and operational assumptions are generally updated on a monthly basis and with a one-year horizon maximum. The simulator makes it possible to establish the efficient allocation and use of resources to enable better system performance, since it details the premises used.
- Operational analysis: in the short-run planning, the simulator is able to quickly and accurately respond "what if?" everyday questions. In other words, it is possible to test the effects of transportation of iron ore, passengers or general cargo on the supply chain, when, for instance, there is a scheduled maintenance in the port and in mining equipment, or when there is a railway accident, or an unscheduled interdiction on railway, among others.

For the case study in question, a computer model of the chain logistics from the loading terminals or mines to the port (Tubarão Port) was built. These points were interconnected by the railway (VMR). The methodology for developing simulation projects for discrete events that was used is found in Banks et al. (2000). The concept of developed templates (Abbott and Marinov 2014) was also used, applying the tool: Software Arena.

3. CASE STUDY

VMR is a heavy haul railway with a daily distribution of close to 106 trains. For this cargo volume, it is necessary to have train schedule management in order to reduce as many delays as possible on the railway line

in maneuver yards, loading terminals and unloading trains. As shown by Crainic and Laporte (1997), rail planning must encompass three main levels: strategic (long term), tactical (medium term) and operational (short term). All of these have planning levels of specific goals according to modelling analyses, however, there is a limitation when it comes to the formulations of interconnected models. For example, a strategic location model will hardly offer responses to the required volume for a daily train schedule.
Due to the progress in simulation models, these merging models are becoming increasingly possible to be built. The simulator presented here has the feature of simultaneously joining these three levels considering the operation of the railroad as a whole.
The conceptual model developed based on the diagram is shown in Figure 1.

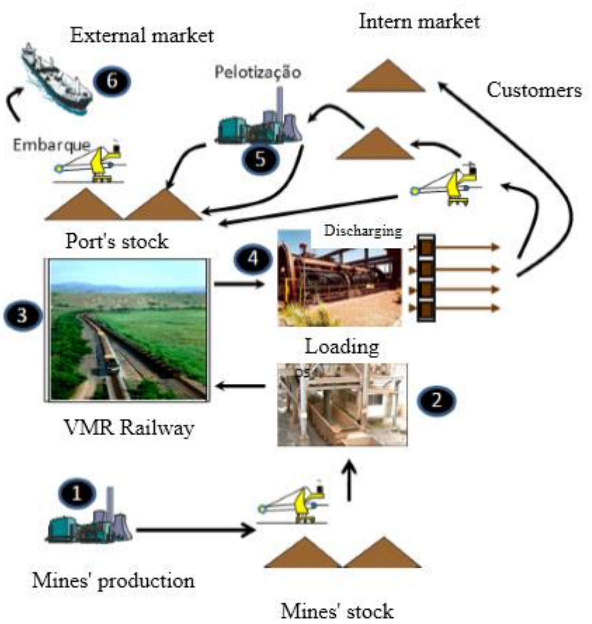

Figure 1: Scope of the implemented model

Regarding the distribution of empty lots that leave Port of Tubarão heading for the mines, their allocation was based on the availability and performance of the loading points. This allocation is performed at the OCC and is based on mine schedules. An algorithm was required to best represent these distributions. Its development may be summarized as follows: the step 1, the loading points request the loading of iron ore for external and internal markets and the step 2, a decision-making algorithm is used to analyze the distribution based on six sequential priority evaluations:

- Evaluation 1 (Distribution on the branch line): As previously mentioned, the VMR contains four branch lines where the loading points are concentrated. The algorithm determines which branch line has the greatest delay in relation to the schedule and allocates a distribution to balance the service percentage.
- Evaluation 2 (Maximum amount allocated by loading stretch): The algorithm determines the maximum amount of lots each branch line is capable of receiving.
- Evaluation 3 (Maximum queues per loading point): The algorithm determines the maximum number of empty lots that can be allocated to a given loading point.
- Evaluation 4 (Preventive and corrective maintenance): Preventive and corrective maintenance limits the receiving of empty lots on the branch lines in evaluations 2 and 3.
- Evaluation 5 (Assessment of the loading point): The lots are distributed as a function of the service percentage at the most-delayed loading point (summing the external and internal markets).
- Evaluation 6 (Identification of loads headed for internal or external markets from the loading point): The algorithm follows the same logic by evaluating the service percentage in following the schedule and by assigning priority to the internal market and to whichever destination is the most delayed.

4. ANALYSIS AND RESULTS

As previously mentioned, there were several planning analysis at three levels: operational (short term), tactical (medium term) and strategic (long term) using the discrete event simulator developed. The goal is to justify the importance of applying this tool to support decision-making in different areas.
An important process while developing a simulation model is the calibration and acceptance of the developed models (Marinov 2009). Those can be obtained by two distinguished ways: by the comparison between real and achieved results or by using analytical techniques when not possible to get operational data.
All analyses described below were performed using an Intel® Core ™ i7-5600U CPU@2.60 GHz computer with 4.00 GB (RAM) on a 64-bit operational system. Furthermore, the size of the simulation has spin duration of one year, with a number of 50 replicates and warm-up set to ten days. On average, the processing time of these simulation rounds are close to ten minutes.

4.1. The operational planning:

The simulator is capable of responding fast and accurately to "what if" questions. It is possible to test the effects of the iron ore on the logistic chain when, for instance, a port or a machine has planned maintenance, or some railway accident happens. It is also possible to test the best way to dissipate a "blister effect" caused by an event or by the increase of unavailable wagons in the system.
One of the objects of analysis of the model developed in the short-term is daily maintenance planning. The planning of preventive maintenance of a permanent route is essential to eliminate and avoid errors or

alterations that could affect the performance of the rail network.
Thus, the developed mesh simulator is able to assist the operational planning area, or short-term view, considering the frequency of trains circulating in determined stretches, with their peculiarities, such as the best time and duration of permanent way maintenance tracks, with regard to the impacts on capacity and average transit time.
For this purpose, a VMR mesh section divided into single and double stretches, called BH Branch, is analyzed. It can be seen in the following Figure 2:

Figure 2: BH Branch layout

For this analysis, the hypothetical frequency of iron ore, passenger and general cargo trains were inserted. The impact on the transit time variables and maximum capacity of BH Extension was found by varying the pathway where maintenance could be performed, but values for monthly total stoppage time, i.e were kept the same.

- Scenario 1: four weekly track maintenances with duration of six hours.
- Scenario 2: three weekly track maintenances with duration of eight hours.
- Scenario 3: two weekly track maintenances with duration of twelve hours.

The detailed information about the results obtained from the scenarios described above is presented in the following Table 1 and Table 2:

Table 1: Single Line Table Caption

Variable (average)	Weekly tracks maintenances		
	Scenario 1	Scenario 2	Scenario 3
Lots/day: iron ore	24,64	24,38	24,31
Trains/day: iron ore	11,40	11,31	11,27
Cycle: iron ore	8,14	8,23	8,34

Table 2: Average trains/day pairs (iron ore, general cargo and passengers) – BH Branch with maintenances

Local	Weekly tracks maintenances		
	Scenario 1	Scenario 2	Scenario 3
Yard VP8	24,76	24,61	24,61
Stretch VP8_VP7A	24,76	24,61	24,61
Yard VP7A	24,76	24,61	24,61
Stretch VP7A_VP7	21,69	21,55	21,59
Yard VP7	18,62	18,48	18,56
Stretch VP7_VP6	18,62	18,48	18,57
Yard VP6	18,62	18,48	18,57
Stretch VP6_VP5	17,82	17,68	17,73
Yard VP5	17,01	16,87	16,90
Stretch VP5_VP4	17,01	16,87	16,90
Yard VP4	17,01	13,24	13,29
Stretch VP4_VP3	13,32	13,24	13,29
Yard VP3	13,32	13,24	13,29
Stretch VP3_VP2	13,32	13,24	13,29
Yard VP2	13,32	13,24	13,29

According to these outputs, it is possible to conclude that the performance of four weekly permanent road track maintenances, each one lasting 6 hours, allows a greater implementation of the volume of iron ore with a smaller cycle. Besides, it brings a larger railway capacity in pairs of trains per day.
Yet, analyzing the main indicators (average lots/day and average cycle of iron ore), there were statistical parameters to validate the data of completed replication and considering a 90% confidence interval, these are stable and representative, Table 3 and Table 4.

Table 3: Analysis of statistical parameters of the variable “average lots/day” of iron ore

Parameter	Weekly tracks maintenances		
	Scenario 1	Scenario 2	Scenario 3
Lower Control Limit	25,56	25,56	25,30
Upper Control Limit	23,74	23,21	23,32
Standard deviation	1,03	1,33	1,12
Average	24,65	24,38	24,31
Error	3,70%	4,83%	4,08%

Table 4: Analysis of statistical parameters of the variable “cycle” of iron ore

Parameter	Weekly tracks maintenances		
	Scenario 1	Scenario 2	Scenario 3
Lower control limit	8,35	8,45	8,54
Upper control limit	7,94	8,00	8,13
Standard deviation	0,24	0,26	0,23
Average	8,14	8,23	8,34
Error	2,58%	2,76%	2,48%

4.2. Tactical planning

The annual budget cycle is performed based on the results of the scenario generated by the simulator. Some pointers are given with high details, such as the cycles at the loading points, the Port cycle and the equipment’s indicators (physical availability, utilization and effective rate). These pointers will be practical guidelines for the medium term planning sector to use them for more effective use of available resources.

One of the applications of the simulator in medium term decisions is by defining railway capacity. This is analyzed by the current operating characteristics such as the transit time, the definition of permanent line track maintenances, the unavailability of the network, the licensing times for trains, among others. To demonstrate the applicability of the simulator at the tactical level, an analysis of the division capacity of single parts and duplicate parts will be performed.

4.2.1. Analysis of the capacity of two-track circulation lines

For this analysis, a random section where the railway is doubled was selected to verify the dynamic capacity generated by the simulator when setting up the operating efficiency factor (k). It was emphasized that all data inputs were obtained using National Land Transport Agency ANTT Network Statement (ANTT 2016). The capacity results obtained by simulation were compared to ANTT Network Statement in order to verify the adherence of the model.

The following analysis includes the evaluation of the Resplendor railway section. For these capacity analyses of the two-track lines the following parameters are used as simulation assumptions, Table 5:

Table 5: Simulation assumptions of two-track lines analyses

Variable	Values	Unit
Number of replications	100	unit.
Duration of replications	30	day
Statistical distribution: iron ore train starting	Normal (32,4)	minute
Statistical distribution: general cargo train starting	Normal (2.18,0.22)	hour
Statistical distribution: passenger train starting	Uniform (1)	day

The Table 6 presents the main data obtained from the simulation model. Considering a 95% confidence interval, it is noted that the simulated outputs of the variable railway capacity present an accuracy of 0.53, a standard deviation of 0.41 and an error 1.31% margin. That is, such parameters indicate a proper statistical variability of the results of this simulation model.

Table 6: Outputs simulation – Resplendor railway section

Variable	Simulated outputs	Unit
Annual capacity	209,32	millions of tons
Total empty trains	1.177,98	unit
Total loaded trains	1.196,23	unit
Trains/day	40,57	pair
Operational efficiency	63,03	%
Coefficient *k*	96,15	%
Transit time: empty trains	2,60	hour
Transit time: loaded trains	2,69	hour
Speed of empty trains	25,97	km/h
Speed of loaded trains	25,09	km/h

4.3. The strategic planning

According to Crainic (1997), to increase long-term volume within 5 to 10 years, investments will be necessary in order to expand system capacity. These can be the need of duplicating or triplicating the existing lines, a new car dumper to the Port, a new silo at the loading station, or an alternative to improve productivity such as increased number of wagons for trains and increased average weight at the loading station, among many other possible alternatives. Besides, some indicators given by simulated outputs such as the total cycle, the Port unloading cycle and needed GDE lots will be the guidelines for the long term planning sector to siege the need of multiannual rolling stock. The simulator also provides the average

queue generated with the system, therefore making it easier to verify possible bottleneck points as well as critical points. Using this, investment possibilities must be proposed by the analyst based on generated outputs and global links at the logistic chain.
To analyze the VMR logistics chain, rounds of simulations were held in order to verify the impacts on the main rail indicators. This was compared by changing the number of wagons for the transport of ore and by altering assumptions related to the Port of Tubarão.

4.3.1. The impact of the change in the number of cars on the system

In this item, the impact of the change in the number of freight wagons for the transport of iron ore in VMR is verified by the main indicators which are calculated in the simulation model.
The below Figure 3 presents the impact of the increase in the number of GDE's wagons (horizontal axis), responsible for transporting iron ore, in compliance with the volume and wagons cycle (time for the wagon to complete a full cycle: Port - Mine - Port).
These indicators are fundamental for the design of rolling stock, mainly in the strategic horizon or long-term. In the simulation model, a "target" volume is inserted (red line in Figure 2), i.e. the volume (relative to an interval of four months) that is expected to be completed during replication scenarios (number of GDE's wagons: "X axis").

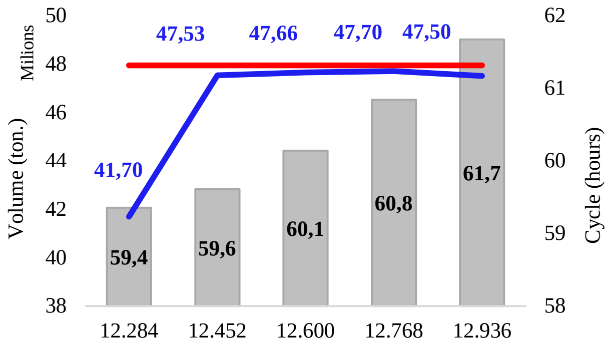

Figure 2: Volume influence of the system cycle

This analysis verifies that for the variable "volume" (blue line in the graph), the more wagons inserted in the railway, the closer the line gets to "target" volume, but the wagons cycle inceases (gray bars in Figure 2).
However, it must be noted that from the scenario of 12.768 wagons, even when more wagons are inserted, the volume doesn't change. The same does not occur with wagon cycle, which increases considerably over the scenarios.
Thus, one can conclude that the bottleneck to achieve the "target" volume is not the shortage of rolling stock. Therefore, 12.768 GDE's wagons would be the ideal number to carry out the transportation of iron ore, once it reaches 99.5% by volume. This type of analysis is essential to assist the strategic areas in verifying the amount of assets required for the implementation of the long-term projected volume.

4.3.2. Increased capacity with the duplication of single parts

The increase of transportation demand over the years may result in a rail capacity deficit and thus disable the growth in transported volume. Therefore, the long-term planning area is responsible for envisioning increasing capacity over the years.
It is said that some investment projects are strategic, such as the expansion of patios where long trains are not able to make the crossing with other trains. The construction of new crossing yards at points where there is a "bottleneck" in the rail network improves the permanent path, allowing an increase in speed and, consequently, reduces the transit time between consecutive sections. Doubling single portions is also an alternative for increasing railway capacity.
A comparison analysis was carried out to estimate what would be the ability to increase the BH Branch stretch to duplicate it fully (Hypothetical scenario) at the expense of current installed capacity, as shown in Table 7 and Table 8.

Table 7: Comparison of Current scenario versus BH branch duplicated scenario

Variable (average)	Current scenario	Hypothetical scenario
Lots/day: iron ore	24,64	26,20
Trains/day: iron ore	11,40	12,16
Cycle: iron ore	8,14	8,88

Table 8: Comparison of Current scenario versus BH branch duplicated scenario: average trains/day pairs (iron ore, general cargo and passengers):

Local	Current scenario	Hypothetical scenario
Yard VP8	24,76	31,40
Stretch VP8_VP7A	24,76	31,40
Yard VP7A	24,76	31,40
Stretch VP7A_VP7	21,69	27,47
Yard VP7	18,62	23,54
Stretch VP7_VP6	18,62	23,54
Yard VP6	18,62	23,54
Stretch VP6_VP5	17,82	23,26
Yard VP5	17,01	22,99
Stretch VP5_VP4	17,01	22,99
Yard VP4	17,01	19,18
Stretch VP4_VP3	13,32	19,18
Yard VP3	13,32	19,18
Stretch VP3_VP2	13,32	19,18
Yard VP2	13,32	19,18

It is inferred that an analysis with high investment expenditure, such as a duplication of rail segments, must be better analyzed. The balance point where spending on investment is equal to the obtained revenue is called break-even.

In this example, the breakeven point occurs where the cost of the project is equal to the increasing cost of train cycles due to increased stopped train time (stopped trains in a queue in backyards of intersections or stopped trains queue in the crossing yards that give access to the BH Branch) by not carrying out the duplication.

5. CONCLUSIONS

This paper presents a simulator developed to analyze the behavior of a heavy haul railway considering strategic, tactical and operational planning levels. The goal of a highly efficient heavy haul railway is to maximize the use of loading points and to follow the schedules to meet demand while taking into account the entire integrated logistics chain: mine, railway and port. Thus, the long-term planning department has a robust tool that allows for the analysis of new expansion projects. The short-term planning department has a tool to address the various logistical issues that arise daily.

The high sensitivity of the system to various sources of interference in train circulation, including their scheduled and corrective stops, bottlenecks and queues require modelling algorithms that can properly represent these behaviors.

The algorithm developed to direct the trains was observed to be highly adequate in its goal to maximize occupation at the loading points in order to fulfil the pending requests at these locations. The algorithm automatically reduces the capacity at a point where preventive or corrective maintenance is being performed and adjusts by providing other points with greater demand and where no maintenance is being performed.

By achieving the primary objective of this study, the long-term planning departments will have a tool to assess the demands of new expansion projects, and the short-term planning departments will also be able to address the many “What if?” questions that arise daily.

The various tests of this model in its current development phase allow for its use in many applications:

- Determining the adequate number of railcars to achieve a given transportation volume;
- Identifying potential bottlenecks in the face of increased transport volume;
- Evaluating the impact of projects to improve the loading, unloading, and train assembly and disassembly terminals;
- Assessing the impact of projects to increase the network circulation capacity (e.g., duplication, triplication, inclusion of new crossings);
- Assessing the impacts of scheduled maintenance programs of loading and unloading equipment and railroad tracks;
- Assessing the impact on engineering projects to decrease the duration of corrective maintenance of loading and unloading equipment and railroad tracks;
- Determining the adequate percentages of two-lot and three-lot trains going uphill and downhill because having additional three-lot trains in loading, unloading, assembly and disassembly yards leads to an increase in the residence time at these yards. In turn, the train trips will be faster as a result of less-intense traffic in the network. Therefore, the simulator is capable of determining, based on the many simulation runs, the best configuration of the percentage of these trains under the simulated scenario conditions.

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