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## **SIMULATION MODELLING OF VITÓRIA-MINAS CLOSED-LOOP RAIL NETWORK**

**Summary.** This paper presents a closed loop simulation model that represents the mining logistics chain of the Vitória Minas Railway (VMR), Brazil. The simulator includes the loading process, circulation of loaded trains, unloading of ores for external and internal markets and the distribution of empty trains for new loads. General cargo and passengers trains are also included in the model, which, along with the queues formed in the circulation and the preventive and corrective maintenance of rolling stock, tracks and equipment, interfere with the transportation of iron ore. The primary objective of the iron ore transport is to meet the daily loading and unloading schedules and minimize queues by maximizing the operations at the loading and unloading points. The VMR simulator developed uses macro-mesoscopic approach with Monte Carlo simulation. To validate the simulator, we used actual data of the railway and compared with reality. We obtained a very good adhesion to the value of 2.9% for the validation scenario (Scenario 1) and 3.4% for the scenario with reducing the number of lots of wagons (Scenario 2). We concluded with this simulation that it is possible to reduce the number of GDE wagons without reducing the current level of productivity of the rail system.

## **MODELAGEM DE SIMULAÇÃO DO CIRCUITO FECHADO DA FERROVIA VITÓRIA À MINAS**

**Resumo.** Este artigo apresenta o modelo de simulação do circuito fechado da rede logística de minério de ferro da ferrovia Vitória À Minas (VMR), Brasil. O simulador inclui o processo de carregamento, circulação dos trens carregados, descarregamento para os mercados externos e internos e a distribuição dos trens vazios para novos carregamentos. Os trens de carga geral e de passageiros também foram incluídos no modelo, bem como suas filas de formação e as manutenções preventivas e corretivas do material rodante, que interferem no transporte do minério de ferro. O principal objetivo do transporte de minério de ferro é atender as programações de carregamento e descarregamento e minimizar as filas maximizando as operações nos pontos de carregamento e descarregamento. O simulador VMR desenvolvido utiliza uma abordagem macro-mesoscópica de simulação de Monte Carlo. Para validar o simulador, foi utilizado dados da ferrovia e comparado com a realidade. Obtivemos uma aderência muito de 2,9% para o cenário de validação (cenário 1) e 3,4% para o cenário com a redução do número de lotes de vagão (cenário 2). Concluímos que com esta simulação é possível reduzir o número de lotes de vagões GDE sem reduzir a produtividade da ferrovia.

## 1. INTRODUCTION

The railways of heavy haul type have the characteristic to carry a large volume of load using the maximum capacity of the rail system. This type of rail is typically used for large commodities such as mineral resources, coal, among others. Due to its large volume of cargo, rail can be characterized as a closed circuit in order to meet the load source and destination, which is usually a port or an industry. This has resulted in long heavy haul trains with multi-locomotives [20]. 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 [7]. It also defines a closed loop scheme as a multiple open loop with memory, repeatedly implementing control measures, computed each time on the basis of the current traffic state and the actions taken in the past. The whole investigation is conducted on the Vitória-Minas Railway (VMR). The Vitória-Minas Railway (VMR) is one of the world's major heavy haul railways, with some 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 with the Tubarão seaport 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.

The predicted changes at the loading centre due to an increase in iron ore volume in future years, create a great need for studies and analyses by the systems long-term planning departments. These departments often use mathematical or analytical models to scale their projects; however, they do not encompass the global effect of the logistics chain.

Therefore, a simulation model was developed to represent the closed-loop iron ore rail transport to analyze many variables in the face of an increase in transport volume or the inclusion of new projects in the VMR. For this purpose, a Monte Carlo discrete events simulation was used.

Arena® Software was founded by Systems Modelling (USA) in 1993, based on the combination of the simulation package CINEMA and the SIMAN programming language, allowing the integrated vision of animation and simulation system. In 2000, Rockwell purchased the Systems Modelling and this boosted further development in terms of language and interface [15]. The main objective of this simulation model is to provide a tool to answer questions like "What if" in the three levels of planning a cargo railway, i.e., strategic, tactical and operational planning.

The paper is organized as follows. Section 2 discusses the literature. Section 3 presents the conceptual model for VMR simulator. Section 4 presents the software architecture and the test-case. Section 5 concludes the paper and gives direction of future research.

## 2. LITERATURE REVIEW

An extensive literature is available on models and algorithms for railway simulations. The use of simulation discrete event in railway dynamics is a widespread tool and currently there are several tools that can be used in this area. Here we present the most relevant works for our research and used to develop the VMR simulator. Research conducted by [6] and [8] bring a comprehensive review of major works related to optimization, sequencing and planning and whose main focus is on the railways.

Simulation studies to support investment decisions have been used since 90ths in North American and European railways companies, where the railways have great influence in the transport of these countries [13] and [11]. Since then, the evolution of simulation software increase. Software implemented to study railway related problems are: RailSys [2], SIMUL8 [14], SIMONE [16], Open Track [17] and ROMA [17]. Also, Arena software has been used for used to study rail related applications [4], [10] and [15]. Although Arena is not a specific package for railway this has a variety of features that allow its use in different railway analyses or the specific studies in the rail yards [19]. However, such studies of the rail yards are conducted with a high level of abstraction, since their activities are extremely operational and require a careful study of the processes involving the system to determine its routine work.

The Test Cases adopted differ in terms of complexity and refer to a Line (only the Railway), a Terminal Area (or a Station), or an Integrated System. Table 1 categorizes some academic works that use railways Discrete Event Simulation, in alphabetic order.

Table 1

## Dynamic railway traffic control approaches

Reference	Title	Main Objective	Railway Site	Test Case	Simulation Software
[2]	Improving punctuality of train traffic on western main line of Swedish railway network: simulation approach	Development of railway software	Swiss railway	Line	RailSys
[3]	Introduction to simulation	Describe various concepts about simulation	Not applicable	Not applicable	Not applicable
[4]	Hub exchange operations in intermodal hub and spoke networks	Work about the main references in intermodal freight transport from Europe	European railways	Line	Not applicable
[7]	Planning models for freight transportation	Work about the main references on railways	Not applicable	Not applicable	Not applicable
[6]	A survey of optimization models for train routing and scheduling	Work about the main references on routing and optimization	Not applicable	Not applicable	Not applicable
[10]	Concurrent simulation and optimization models for mining planning	Development of railway model	Brazilian railway	Integrated System	Arena
[11]	The use of simulation in the planning of Dutch railway services	Aid to decision-making on investment in European railways	European railways	Line	Not applicable
[13]	Network simulation of a major railroad	Aid to decision-making on investment in North American railways	North American railways	Line	Not applicable
[14]	A mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a rail network	Development of terminal area model	Portuguese railway	Terminal area	SIMUL8
[15]	Simulation modelling of Vitória-Minas closed-loop Rail Network	Development of railway model	Brazilian railway	Integrated System	Arena
[16]	SIMONE: large scale train networks simulations	Development of railway software	Not applicable	Not applicable	SIMONE
[17]	Railroad simulation using Open Track	Development of railway software	Swiss railway	Line	Open Track
[19]	Railroad yard logistic to improve capacity	Development of terminal area model	Brazilian railway	Terminal area	Arena
[7]	Closing the loop in real-time railway control: Framework design and impact on operations	Widen the knowledge on how automatic real-time rescheduling tools	Dutch railway	Line	ROMA

To choose a simulation software we cannot consider only technical specifications, but also other external features, for example, the affinity of railway operators with the simulation package, as well as the software availability. Even with the improvements of rail software, some difficulties may be cited for the development of a railway simulation such as [12]: large areas to be modeled, traffic dispatching decisions often depend on human decision, which makes the system more dynamic, or decisions to prioritize traffic any composition depend on whether or not delay with respect to the planned, the simulations in railways constantly need information from your transient state where the user can intuitively and interactively interfere in the modeled system due to a non-stationary system. To improve this understanding, micro and macro knowledge of the process is necessary.

### 3. THE CONCEPTUAL MODEL FOR VMR SIMULATOR

VMR is considered as heavy haul railway with a daily distribution close to 106 trains. For this cargo volume, a train schedule management is necessary to reduce as much as possible delays on the railway line, in the yards of manoeuvres, loading terminals and trains unloading. As shown by [8], rail planning must meet three principal levels, the 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 this interconnection models, for example, a strategic location model will hardly offer responses to the required volume for daily train services.

The conceptual model developed here is based on (Fig. 1).

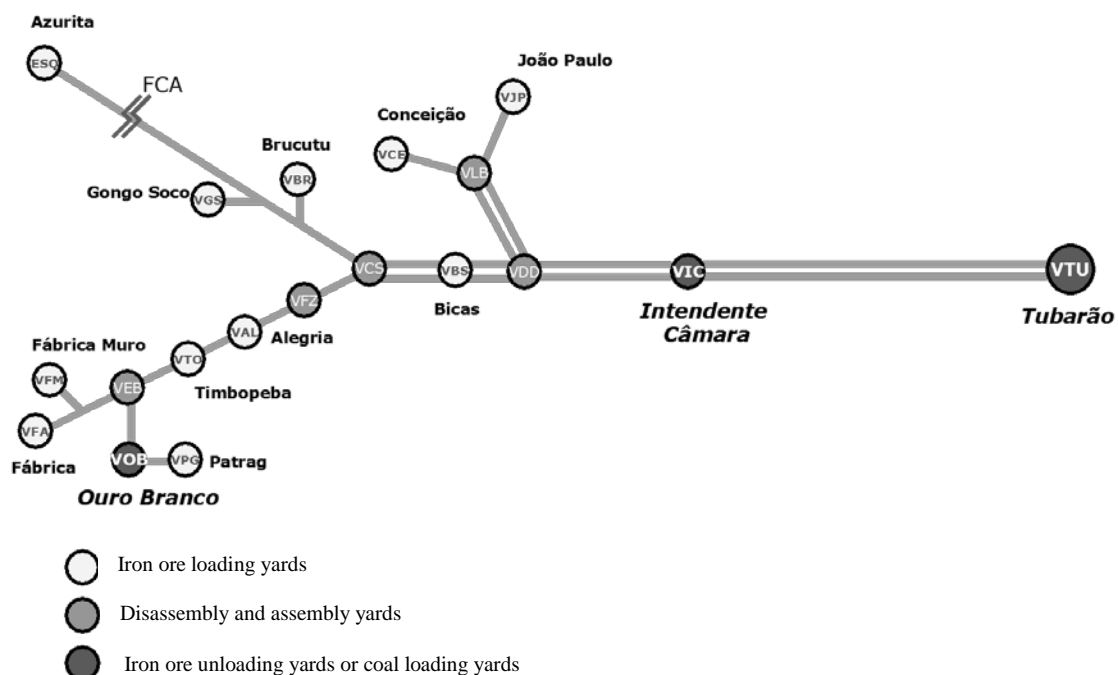


Fig. 1. VMR Railway layout

Il. 1. Layout de VMR Railway

According to the method proposed by [3] and [10], the development of a conceptual model is an important step in a simulation study. In railroads, for example, there is high degree of complexity in the movement of trains in the network because the decisions that are made to resolve problems often are not standardised. Thus, it is essential to model the actions to be performed in the primary railroad operational procedures to standardise decision-making and to simplify the procedures.

The model that was developed contains two types of trains: grid trains and cyclic trains. Grid trains obey established departure schedules, in contrast to cyclic trains, which only circulate after completing the activity in the yard where they are located. As described in [7], we consider the grid trains use an open loop framework and the cyclic trains use closed loop framework. The model assumes that locomotives and crews (machinists) are not restrictive resources and instead are permanently available for the functioning of cycling trains. Thus, this simulator focuses particularly on the railcar resources.

From this starting point, the trains follow their schedules, and traffic conflicts that may arise are resolved by the modelling, which reproduces the decisions of teams in the operational control centre (OCC).

The railway can be represented by:

- The Tubarão yard rail lines, which include the unloading of iron ore from trains headed for the port and the metallurgy company and returning trains loaded with coal. After unloading, the empty lots (VMR standard lot has 84 wagons) return to the loading points, or they may be loaded with coal. These lots display various configurations: two empty railcar lots, one railcar lot with coal and one empty railcar lot, one railcar lot with coal from and one empty railcar lot, two railcar lots with coal, or three empty railcars lots;
- Two yard lines, where the loading of coal and iron ore;
- The rail lines of the eleven iron ore loading yards;
- The rail lines of the train disassembly and assembly yards. The two-track circulation lines, which consist of eight blocks sections and two dashes. Each of these sets is approximately 7.5 kilometres long. Only one train may be allocated to each block section at a time, for a maximum of eight trains (Fig. 2);
- The single-track lines, which consist of three blocks sections and two automatic switches. Such a set is referred to as a simple section and is generally 3.0 kilometres long. Only one train may be allocated to a block section at a time, for a maximum of three trains (Fig. 3).

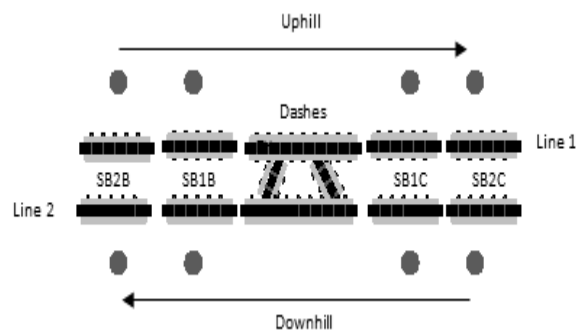


Fig. 2. Modelling of two-track section locations  
II. 2. Modelagem de locais de seção de duas vias

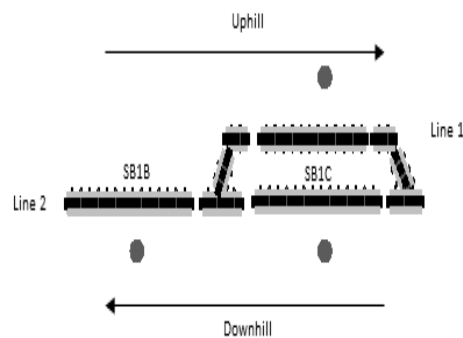


Fig. 3. Modelling of single-track lines  
II. 3. Modelagem de linhas single-track

Regarding the distribution of empty lots that leave Tubarão headed for the mines, their allocation is based on the availability and performance of the loading points. This allocation is performed at the OCC and is based on the mine schedules. To best represent these distributions, an algorithm was required. Its development may be summarised as follows:

- *Step 1:* The loading points request the loading of iron ore for external and internal markets;
- *Step 2:* A decision-making algorithm is used to analyse the distribution based on six sequential evaluations of priority.

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 to evaluate the service percentage in following the schedule and assigns priority to the internal market and whichever destination is the most delayed.

The double track is represented as a series of Houses which are sequentially connected to each other. Each house again is represented by 8 Block Sections (BSs) and one crossing. A BSs stands for a more or less straight piece of track with an approximate length of 1.65 kilometres. The crossing is a combination of switches to allow trains to switch easily from one track to the other and vice versa. In general the crossing has a length of 0,260 kilometres. The Figure represents a house with more details (Fig. 4).

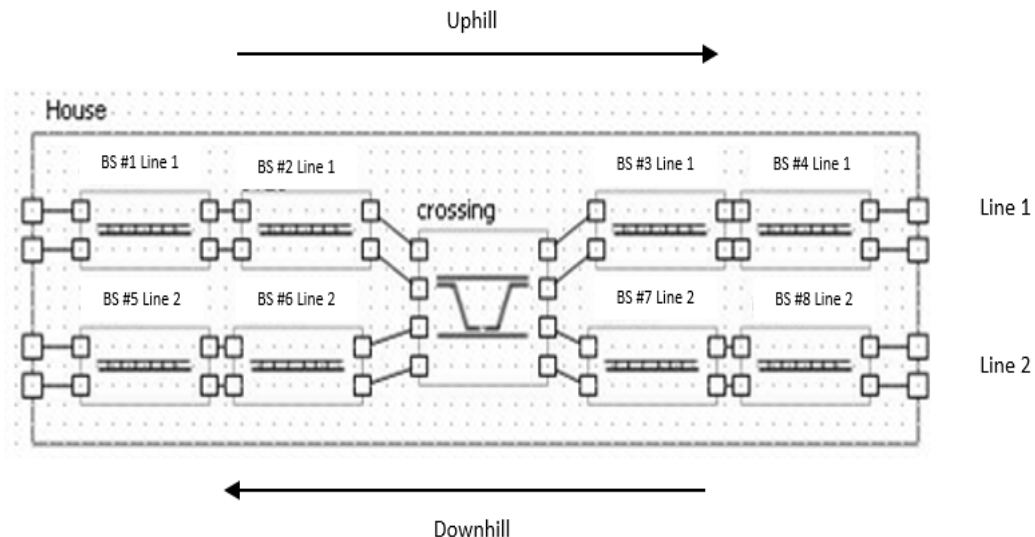


Fig. 4. Representation of a House  
 Il. 4. Representação de House

Train circulation times between the block sections (BSs) throughout the network and the probability of failure throughout the network are inputs to the system. The probability of failure may involve problems with the railcars, locomotives, tracks or signals. Each of these events is assigned a service time to standardise such occurrences. Scheduled railway maintenance necessary for the functioning and safety of the railroad is also included in the model.

The maintenance may be of the between-house type - blockage of four consecutive BSs in the same line - (Fig. 5), or house type - blockage of eight consecutive BSs in the same line - (Fig. 6).

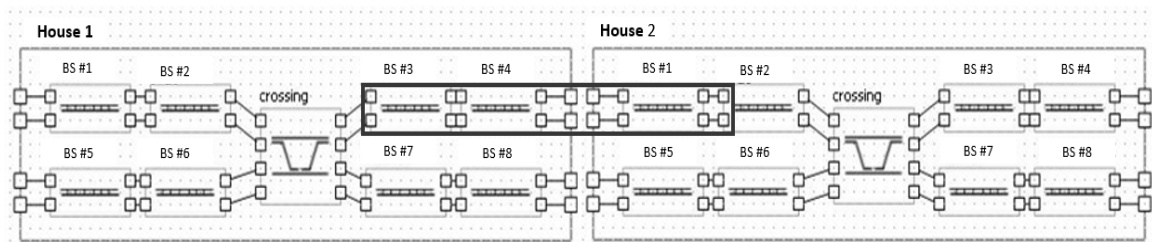


Fig. 5. Maintenance of the between-house type

II. 5. Manutenção do tipo between-house

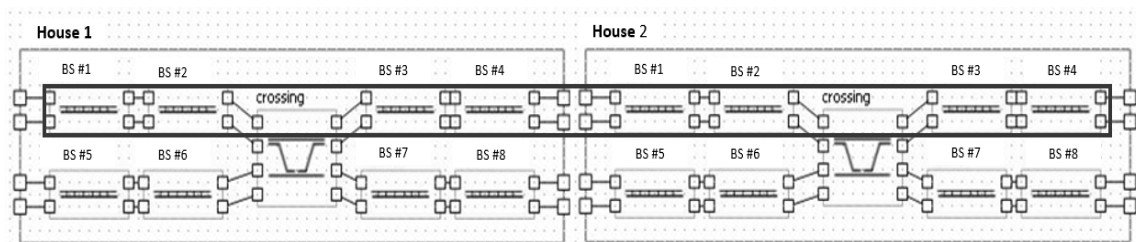


Fig. 6. Maintenance of house type

II. 6. Manutenção do tipo house

The loading and unloading equipment also undergo random corrective maintenance and scheduled preventive maintenance.

#### 4. THE SIMULATION MODEL: SOFTWARE ARCHITECTURE AND TEST-CASE

The conceptual simulation model follows four steps as described in Fig. 7.

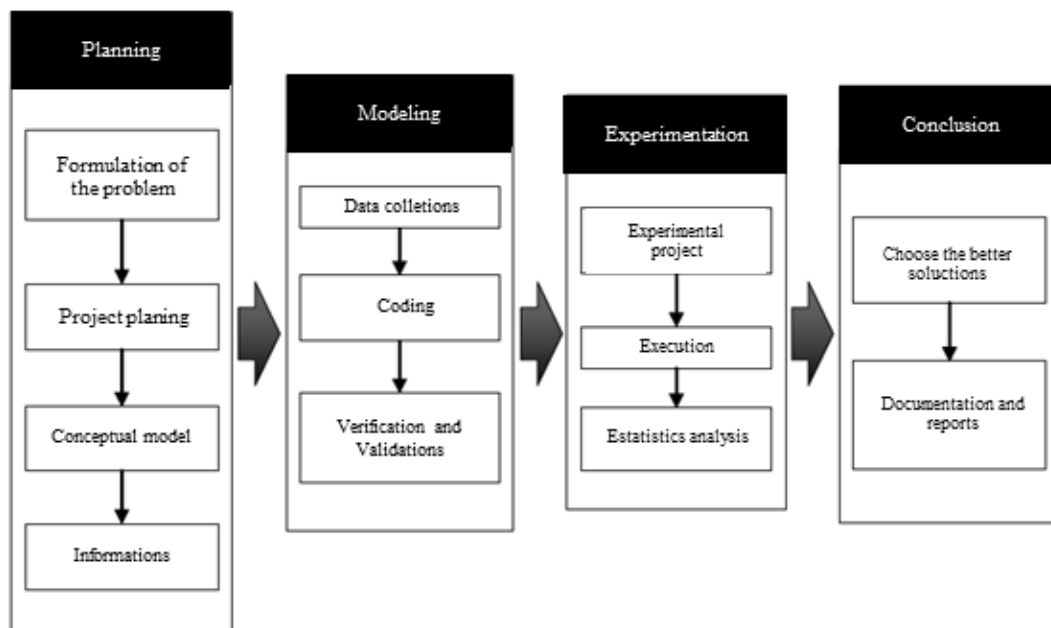


Fig. 7. Steps of modelling and simulation study

II. 7. Passos de modelagem e simulação estudo

For the development of VMR simulator, two software products were used: ARENA, for the simulation program and Microsoft Excel, as an interface between the analyst and the simulation model for the input of data and output of results. This interface is shown in Fig. 8.

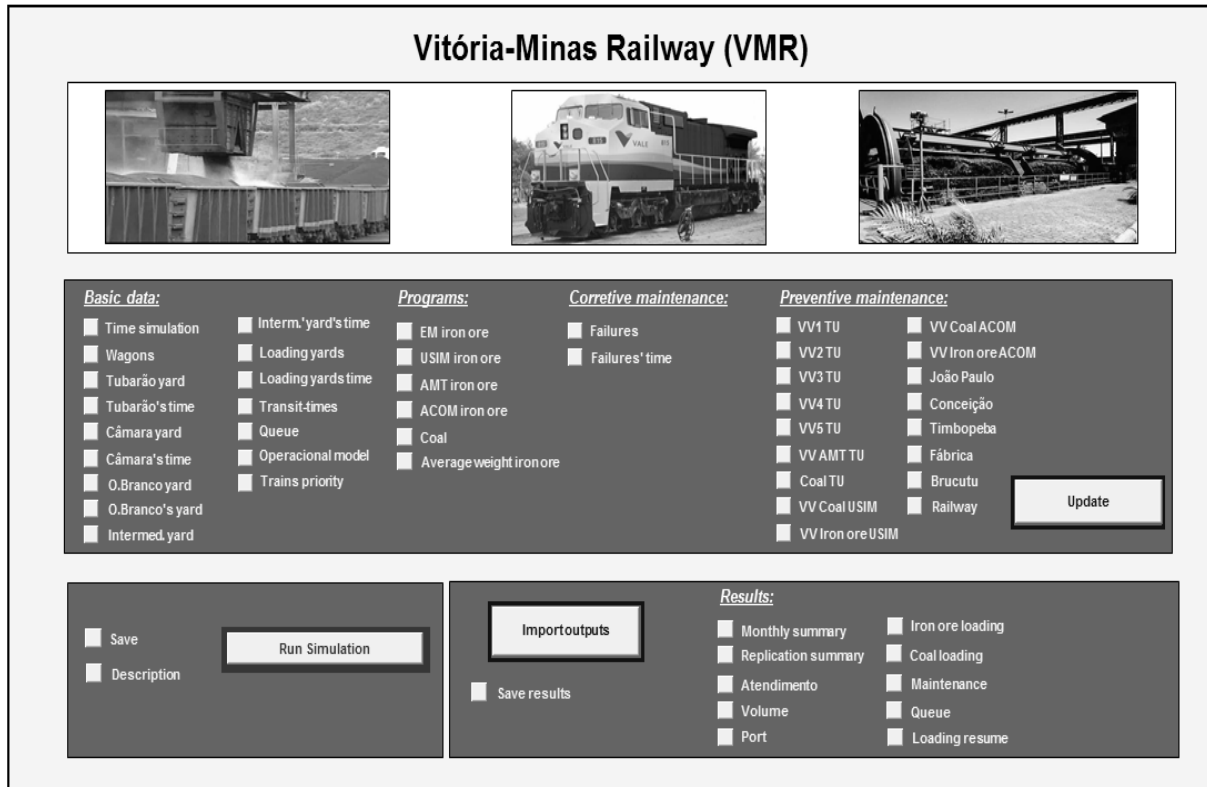


Fig. 8. User interface in Microsoft Excel  
Il. 8. Interface de usuário em Microsoft Excel

In this interface, the entire scenario that is simulated can be configured by the input of data such as the simulation time, number of replicates, warm-up period, number of lots needed to service the iron ore volume, internal and external market schedules, preventive and corrective maintenance of equipment and the rail network, operation times of loading and unloading yards, and railroad circulation transit times.

At the end of the simulation run, all the simulation results can be exported to output reports that present the monthly summary and per-transport replicate, loading servicing, ore and coal loading and unloading volumes, maintenance indications, and various cycles and queues.

In order to model a system of complex simulation [1], it must be divided into smaller and easier parts. Therefore, the model proposed in this study, few processes are represented by modular way. It allows, then, an easier and faster comprehension. As shown in section 3, this method is possible thanks to the existence and creation of templates, which are specific databases that eliminate any needing of creating many other logical processes.

#### 4.1. Simulator templates

The techniques as presented in [18] were adopted in the modelling exercise, which concerns the construction of templates. These templates are a set of blocks in ARENA software, which are grouped into a single module for ease of use.

##### 4.1.1. Main railway template



This template is used to control the trains safe circulations while on the main railroad; respecting the signal rules as well as the permanent via. It grants, this way, to each blocked section being used only by one train simultaneously. The template by using Arena represents graphically (Fig. 9). To build up the VMR railway, this template was used 85 times to represent it.

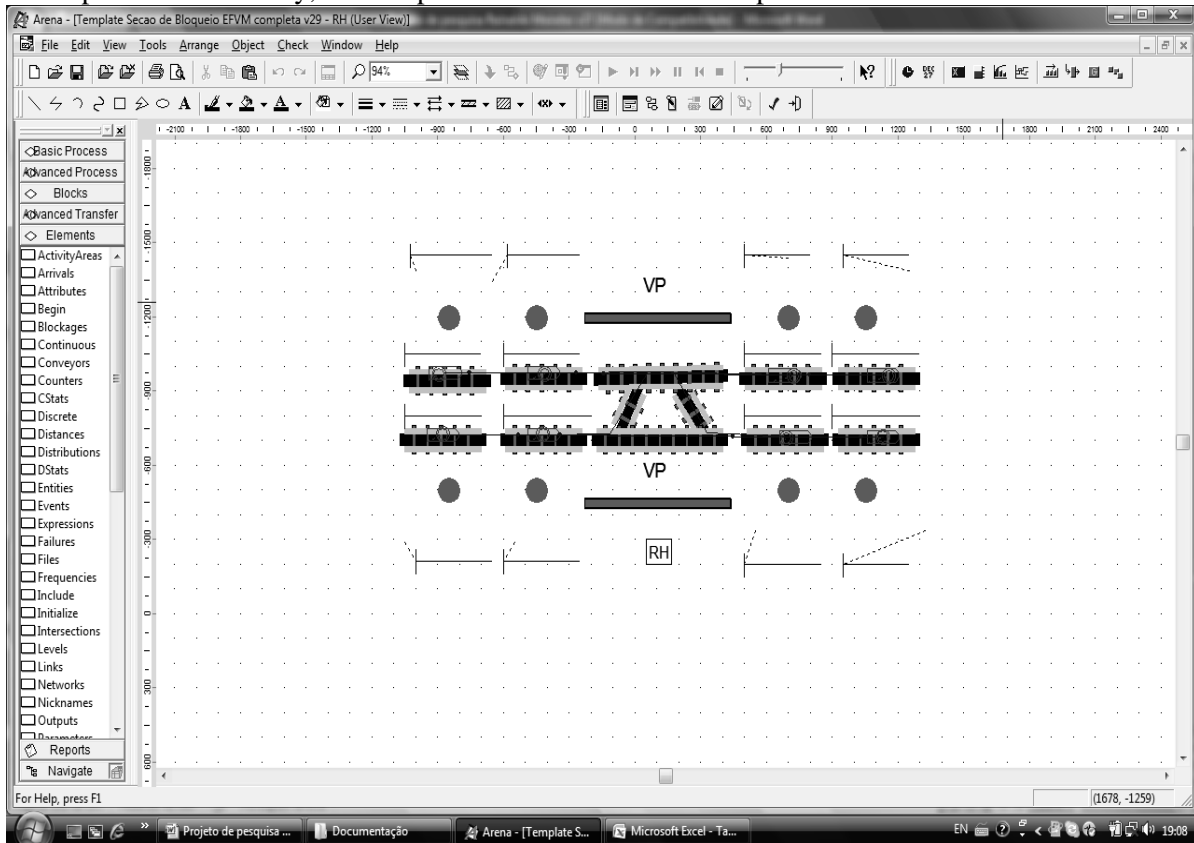


Fig. 9. Main line blocking section template  
 Il. 9. Linha principal modelo de seção de bloqueio

#### 4.1.2. Trains in/out manoeuvring area template

This template allows the entrance and exit of trains to the (un)loading area, linking to the main railway net.

#### 4.1.3. Equipment's predictive maintenance template

The database replicates the equipment's predictive maintenance programs. and captures the necessary interventions on the main railroad in order to grant the best net usage. Those interventions can even uphold not only the infrastructure (platforms, dumpers, drain, etc.) but also the superstructure (rail, clipping, ties, etc.). In order to represent this modular activity just the analyst provides few setup data, and then the maintenance software will run the odds. Some setups for instance: what equipment will be on maintenance, maintenance date, presumed timing along some extra information as predictive or permanent, and where that maintenance will take place.

#### 4.1.4. Equipment's predictive maintenance template

Fig 10 represents the relationships between the simulation analyst, the Excel interface and the simulation model developed. It's important to notice that the simulation analyst is a person who knows very well the railway operation and the simulator. This analyst knowledge is what ensures the model reliability as well as the confidence of the decision maker.

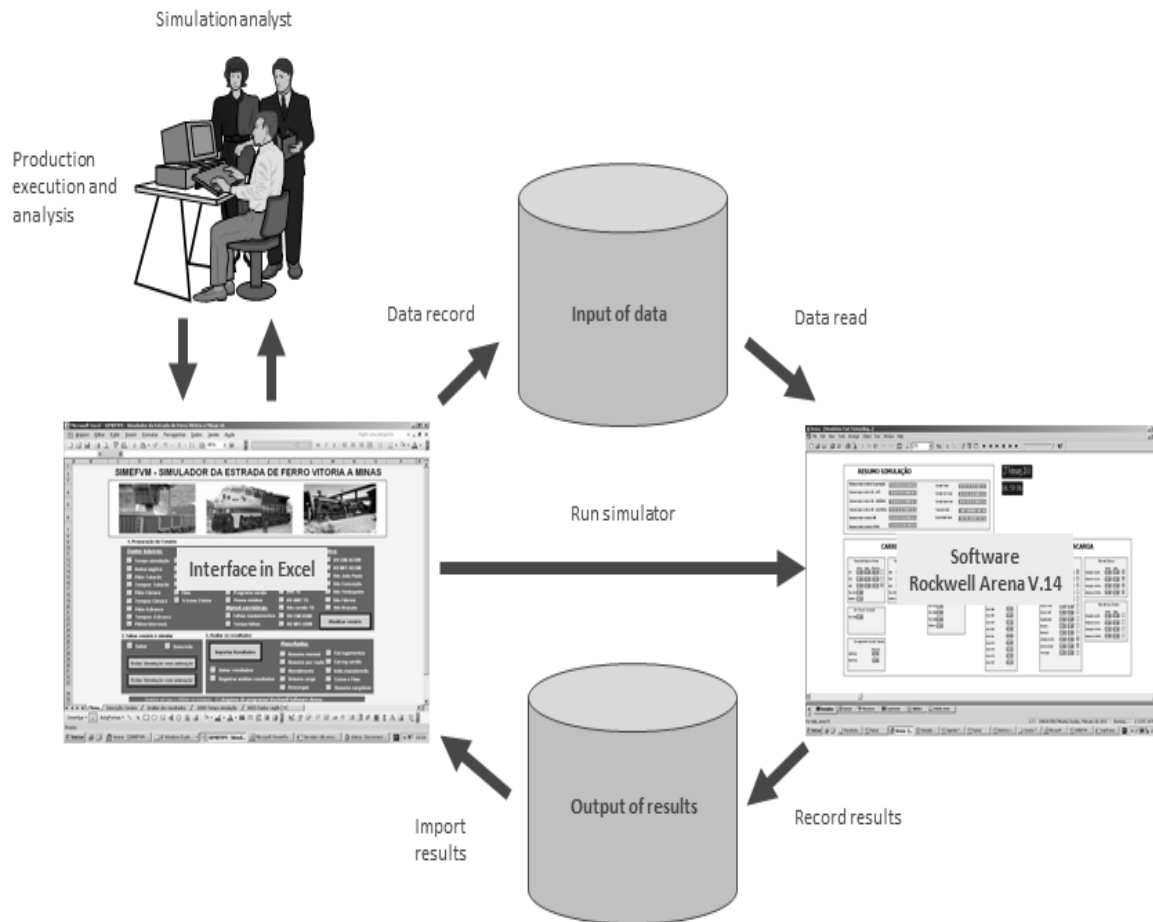


Fig. 10. Relations in the use of the VMR network simulator  
 Il. 10. Relações no uso do simulador de rede VMR

#### 4.1.5. The simulation model: test-case

One important process while developing a simulation model is the calibration and acceptance of the developed models [14]. Those can be obtained by two distinguished ways: by the comparison from real and achieved results or by using analytical techniques when not possible to get operational data. We use a total of 81 BSs simultaneously, resulting in a set of files measuring 50 megabytes.

The current volumes of the VMR Railway were used to compare the results checking if this modelling is consistently the real system. The "Scenario 1" and the "Scenario 2" used the actual data of a given year in the transportation of iron ore and coal Railroad Vitória-Minas. For target values, we used the data that were sized using analytical calculations performed by the team of the railway transport program. The Scenario 1 was based on the use of 8,566 GDE railcars, which correspond to 102 lots for the transportation of iron ore and the Scenario 2 was based on the use of 8,146 GDE railcars, which correspond to 97 lots of GDE wagons which corresponds of a 5% reduction of GDE wagons from Scenario 1. These scenarios ran 4 months with 4 replications in just 3 minutes and 14 seconds (IBM X40 Computer Clock 1.4 GHz with 1.5 GB RAM).

The simulation results consider the planning levels (Table 2) as described in [8] and represent the number of wagons lots/day at operational level for Mines branches (Table 3).

Table 2

## Simulation Results considering planning levels

<b>Planning Levels</b>	<b>Information</b>	<b>Attribute</b>	<b>Value</b>	<b>Adherence</b>
Strategic	Iron ore markets (external and internal )	Target	30.269.874	
		Scenario 1	30.095.291	100,6%
		Scenario 2	29.852.057	101,4%
	External ( tons)	Target	26.002.764	
		Scenario 1	26.032.373	99,9%
		Scenario 2	25.795.623	100,8%
	Internal ( tons)	Target	4.267.110	
		Scenario 1	4.062.918	105,0%
		Scenario 2	4.056.434	105,2%
	Coal internal 135arket ( tons)	Target	1.905.189	
		Scenario 1	1.988.746	95,8%
		Scenario 2	1.993.754	95,6%
Operational	Full cycle (hours)	Target	59,50	
		Scenario 1	57,60	103,3%
		Scenario 2	59,80	99,5%
	Ajusted railway cycle (hours)	Target	47,50	
		Scenario 1	46,40	102,4%
		Scenario 2	48,60	97,7%
Tubarão cycle (hours)	Target	12,00		
	Scenario 1	11,20	107,1%	
	Scenario 2	11,20	107,1%	
Tactical	Average weight Porto (tons/wagon)	Target	75,98	
		Scenario 1	75,97	100,0%
		Scenario 2	75,95	100,0%
	Average weight Usiminas (tons/wagon)	Target	76,29	
		Scenario 1	76,57	99,6%
		Scenario 2	76,60	99,6%
	Average weight AMT (tons/wagon)	Target	76,33	
		Scenario 1	76,27	100,1%
		Scenario 2	76,26	100,1%
	Average weight Açominas (tons/wagon)	Target	66,90	
		Scenario 1	66,79	100,2%
		Scenario 2	66,90	100,0%
			Average Scenario 1	101,2%
			Average Scenario 2	100,2%
			STD Scenario 1	2,9%
			STD Scenario 2	3,4%

The model has shown results close to the real case (Table 2), accomplishing the total volume of ore and coal as well as making the internal and external markets requests end at each loading point. The data adherence is shown in standard deviation of 2,1% for Scenario 1 and 1,9% for Scenario 2. The indicator Number of Wagons lots/day (GDE), presented in Table 2, is related to iron ore mines branches service. As can be seen in Table 3 that the reductions of the number of lots don't create a reduction of the mine services.

Table 3

Representation of Mine service			
Request	Attribute	Number of lots/day	Adherence
Total	Target	4.754	
	Scenario 1	4.704	101,1%
	Scenario 2	4.677	101,6%
External market (EM)	Target	4.073	
	Scenario 1	4.068	100,1%
	Scenario 2	4.041	100,8%
Internal market (IM)	Target	672	
	Scenario 1	637	105,5%
	Scenario 2	636	105,7%
Itabira e Bicas branch	Target	2.324	
	Scenario 1	2.315	100,4%
	Scenario 2	2.314	100,4%
Belo Horizonte branch	Target	708	
	Scenario 1	708	100,0%
	Scenario 2	697	101,6%
Fábrica branch	Target	1.713	
	Scenario 1	1.682	101,8%
	Scenario 2	1.666	102,8%
		Average Scenario 1	101,5%
		Average Scenario 2	102,2%
		STD Scenario 1	2,1%
		STD Scenario 2	1,9%

The results achieved (Table 2 & Table 3) can be used for strategic, and tactical planning levels since it considers the annual total amount transported. Based on [8] definitions, the analysis of Table 2 and Table 3 are described below.

- Strategic level:

The long term volume increasing, within 5 to 10 years, will come up with the necessity of investments to augment the system capacity. Those can be the needing of duplicate or triplicate the existing lines, a new car dumper to the Port, a new silo at the loading station, for example, or as an alternative to improve the productivity, such as increased number of wagons for trains, increasing the average weight at the loading station as well among many other possible alternatives. Besides, some indicators given by Table 2 as: the total cycle, the Port unloading cycle and the GDE's lots needing, those will be the guidelines to the long term planning sector siege the needing of multiannual rolling stock. The simulator also provides the average queue generated along the system, therefore making it easier to verify possible bottleneck points as well as critical points. Then, the investments possibilities must be proposed by the analyst based on the outputs generated and the global links at the whole logistic chain.

- Tactical level:

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

- Operational level:

The simulator is capable of responding fast and accurate to the question "what if", by all means it's possible to test the effects of the iron ore on the logistic chain when, for instance, a planned maintenance Port's or mine's machine takes place, or any railway accident happens, or the best way to dissipate any "blister effect" caused by something or by the increasing of unavailable wagons to the system.

Another scenario was based on the same assumptions except for the number of available railcars. This scenario was developed to verify whether it may be possible to follow the schedule using fewer railcars. This type of analysis allows the simulation analyst to more precisely assess the resources necessary to achieve a given transportation volume. In addition to this type of analysis, many others could be performed with this tool in a search for scenarios to fulfil the transportation demands with fewer resources.

The comparison between Scenarios 1 and 2 shows that with the use of the simulator, the analyst is able to assess more accurately the quantities of resources required to fulfil certain volume of transport. Note that the system behaves better and is able to meet the volume implementation, reduce the number of lots in the system, Scenario 2. This can be explained by the fact that the wagons can circulate faster, generating less queues on the system. Such analyses could justify reductions in rolling stock purchases, in multiannual investment. This dynamic analysis can go beyond if the analyst had in situation of having to cut transportation demand due to lack of resource, it could propose amendments: the volume distribution by loading point in the scheduled maintenance plan the route in equipment loading and unloading, etc., seeking to meet the demand. With this tool it is opened plenty of adjustments to operating assumptions, making cause-effect tests these assumptions, the search for the best scenario that meets the demands with fewer resources to transport.

## CONCLUSIONS

This paper presents a simulator developed to analyse the behaviour of a heavy haul railway considering strategic, tactical and operational planning levels. The goal of a highly efficient heavy haul railway is to maximise 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.

In particular, this paper presents the simulation models of railway networks with trains circulating in the closed loops of a railroad with double-track and single-track stretches. 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 behaviours otherwise, the simulation will not adequately represent the real system. This problem is aggravated by the fact that the cyclic trains can run in many directions, and decision-making should include the selection of the best loading point.

The model would not be validated by the users and its results would not be sufficiently reliable to support the decision-making process if all railway system complexity created doesn't appear during the modelling and system representation phases.

During coding and model testing, great difficulty was observed in computationally representing the decisions involved in the movement of trains throughout the rail network. The algorithm developed to direct the trains, was observed to be highly adequate, in that its goal is to maximise occupation at the loading points 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 adjusted by serving 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;
- Assessing 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 the current configuration of the 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 because 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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