IDENTIFICATION OF BOTTLENECKS IN LOGISTICS SUPPLY CHAIN INPUTS IN MINING INDUSTRY BY USING SIMULATION

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ABSTRACT

The objective of this study is to develop a methodology to identify bottlenecks in the supply chain of inputs for the mining industry, more specifically to the process of pelletizing or agglomeration of fine iron ore pellets. This methodology is based on computer modeling and simulation of supply chain and the definition of appropriate indicators to assess their logistics performance. A model of discrete event simulation was developed to represent the current configuration of the supply chain, focusing on highlighting the main processes that comprise it. Taking as a base, variations of the model were built in the form of experiments, to evaluate and verify the effectiveness of alternative configurations in different possible scenarios for the whole system. The importance of the proposed theme is the lack of academic research focusing on the Brazilian mining sector and, more specifically, the input supply chain of production processes involving suppliers and customer. The current academic collection is more focused on the process of distribution of finished products, involving producers, wholesalers, retailers and end customers. The results obtained in the experiments proved prescient when confronted with reality, the proposed methodology is developed and proved effective as a tool to support analysis and decision making in such studies.

Keywords: supply chain management, modeling, simulation, discrete event, and logistics.

1. INTRODUTION

In the last decade (2001-10), the trend towards the globalization of the world economy has driven rapid growth in emerging countries such as Brazil, Russia, India, China and South Africa, also jointly known as BRICS.

The capability to produce effectively and efficiently, and to meet established goals and challenges, is intimately linked to better results for companies in terms of profitability. The management of the supply chain, from suppliers to customers, allows a holistic view of the entire process, assuring the identification of the obstacles which could prevent compliance with committed deadlines, volumes and quality, optimizing the production process.

According to Ballou (2006), the balanced management of this chain requires, first of all, a planning at strategic level capable of balancing the costs inherent to the variables: <u>inventory</u>, <u>transportation</u> and <u>location</u>. Not only the costs, but also the risks of interruption in the flow of products and information at each phase of the process, should be shared so as to prevent an imbalance among the links of the chain. This planning must be carried out in conjunction with the parties which are part of the system, namely the suppliers, carriers, outsourced parties, end customers, etc.

Inserted in this environment are mining companies where the gains from increase in production scale, derived from investments in expansions and/or organic growth (through productivity gains) are decisive in diluting their fixed costs, increasing their economic/financial profitability and assuring their consolidation in the seaborne iron ore pellet market.

Therefore, the main objective of this paper is to identify the bottlenecks in the input supply chain for a specific industrial activity, through an analysis of the main components, resources and variables which best represent this system.

The identification of these bottlenecks along the chain will allow the evaluation of the adequate service level, between suppliers and customers, to meet the agreed requirements for delivery time and volume, as a function of the demands and the logistic efficiency along the input supply chain itself.

The adequate service level should provide a balance between the inventories and resources necessary, both for the suppliers and carriers, and also for the customers, avoiding waste, idle time or saturation which would certainly cause additional increases in the costs for the parties involved or, in the worst case, for one of the parties, relieving the other.

The assessment of the logistic efficiency of the supply chain will demand a critical analysis of the planning of the volumes required by the client, as a function of production pace and campaigns, the capacity of the suppliers to produce and allocate stocks within the specifications required by the client, the transportation mode and packing of the cargo, and, finally, the client's capacity to receive, check, unload, store and provide inputs to be consumed in the production process.

These steps, which correspond to the sequential links of the chain, are functionally interconnected, present characteristics which involve a high level of uncertainty and assings complexity to the system, which characterizes the stochastic nature of the process. This balance among the links which form the chain must also allow an increase in the capability of transporting cargo, from the suppliers to the consuming company.

The critical analysis of the logistic interactions along the chain must support the management decision making with the objective of aligning the current system capacity with the future profile of demand for goods and/or services.

A long list of products and services is purchased by this company. However, this paper is focused on the inputs to its production process.

2. DATA/METHODOLOGY

The company chosen as the object of this study was SAMARCO MINERAÇÃO S.A., a company that mines, beneficiates, pelletizes and exports iron ore pellets. It has two industrial units (Germano in Mariana, Minas Gerais and Ponta Ubu in Anchieta, Espírito Santo), which are linked by two parallel pipelines of 396 km each.

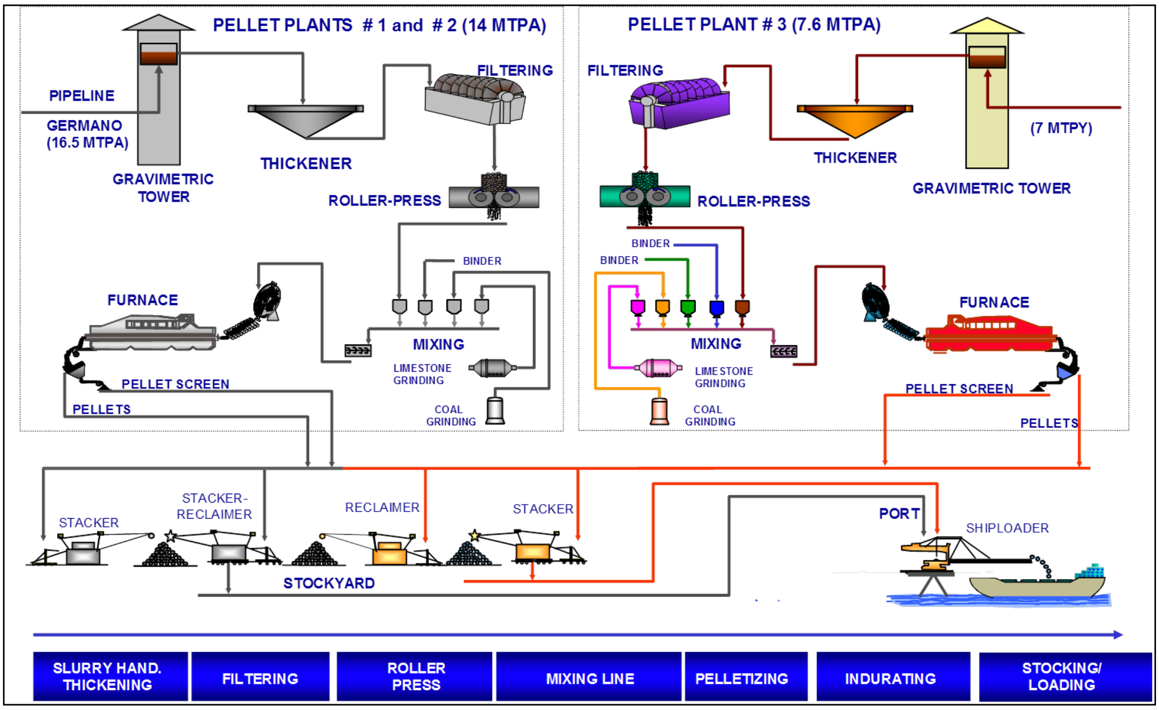

Figure 01 - Samarco operational flow diagram – Ponta Ubu Overview. *Source: Samarco (2010)*

According to Botter (2001), the definition of “System” is the phase which involves the determination of the boundaries and restraints to be used during the investigation of the operation of the system or a part thereof (subsystem).

Thus, considering this industrial profile, it would be complex and time-consuming to represent the supply chain in full, with regard to the main consumables which feed the entire system – both for the data collection phase required, and for the validation and verification of the entire model.

In view of the need to simplify this representation, yet still assuring the characterization of the system in question, the choice was made to detail the phase of iron ore pelletizing, which concentrates the inputs which are most relevant in terms of cost and operational risks.

According to Ballou (2006), the definition of supply chain involves all the functional activities which are repeated countless times along the path on which the raw materials, inputs and materials are gradually converted into finished products, adding value to the customer.

In this specific case, the focal point of this study refers to the phases which include the activities of: forecast of demand and purchase of inputs required for the Company's production planning, hereinafter referred to as “client”; production, storage and transportation of these inputs by their main suppliers, and, finally, the receipt, handling, preparation and consumption by the client company. Figure 02 represents the various phases which form the supply chain in question.

This study will not address the phases related to production, storage and distribution of finished products by the client company.

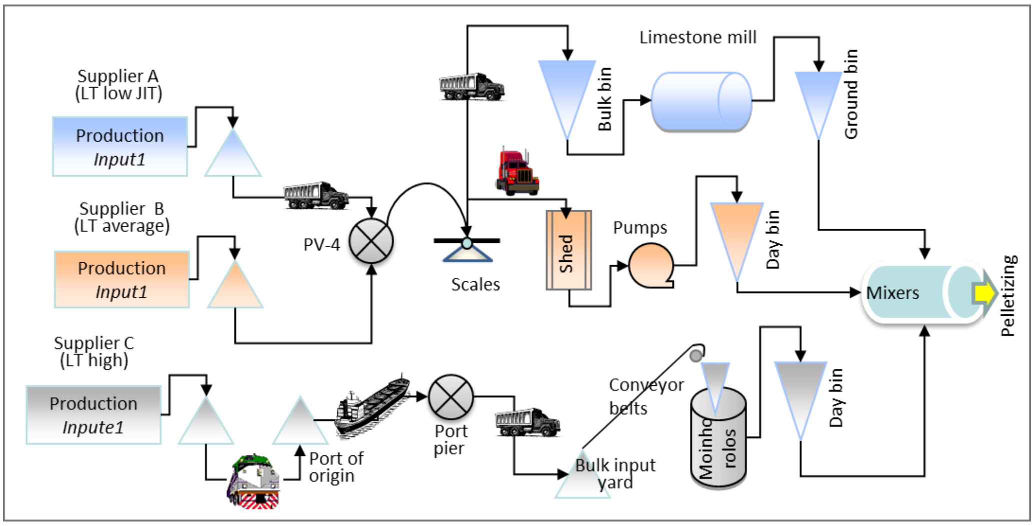

Figure 02 - Supply chain of pelletizing inputs.

Among various inputs purchased by the client company, the choice of the ones which are best suited to a critical analysis of the behavior of the variables along the chain was based on a 3D matrix (figure 03) represented by the axes: (1) annual disbursement with inputs in millions of Reais, (2) complexity of the supplier market, which may be divided between high or low, (3) impact of the input directly on the production process, where one evaluates the risks of interruption of supply, operational and environmental safety.

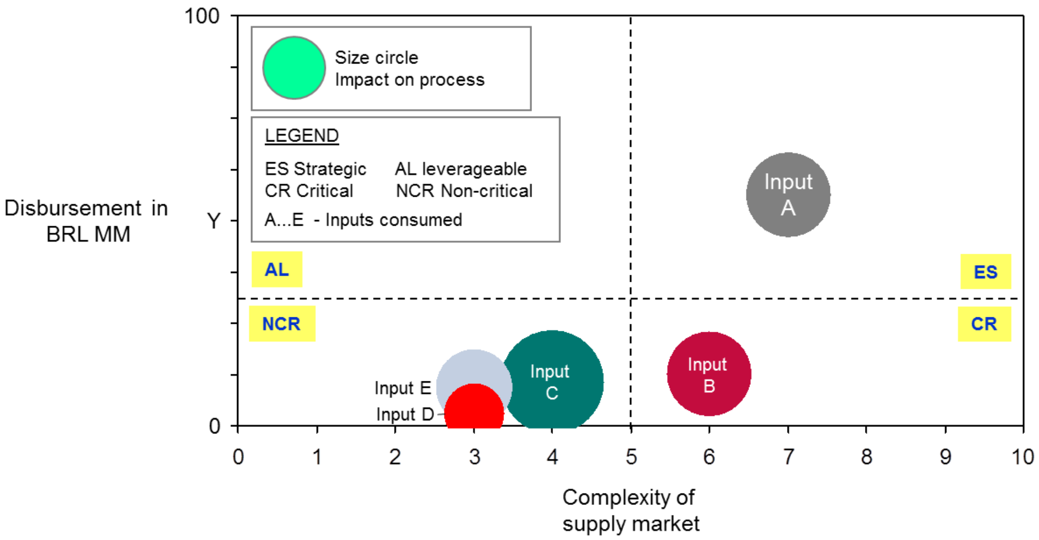

Figure 03 – Company's procurement strategy matrix based on "*The Klaljic Portfolio Purchasing Model*".

In addition to the matrix, another important parameter taken into account was the delivery lead time, due to its relevance in the sizing and application of the logistic resources in each link of the chain, and, mainly, between the links.

Having evaluated the input group, with the objective of grouping them according to their physical characteristics, packing modes, delivery lead times, transportation modes and handling forms, storage and preparation for consumption, three consumables were singled out, represented and named here according to their characteristics, namely:

(1) *Input_1 – average annual disbursement, high operational risk, shorter lead times among all inputs, allowing a characterization as a logistics system with Just in Time (JIT) tendencies. Uses truck hauling with distances of up to 300 km for the complete cycle (round trip), and particularities with regard to the processes of storage, weighing, unloading and handling for consumption*

(2) *Input_2 – average annual disbursement, median operational risk, lead time of around 20-30 days. Uses truck hauling with distances of up to 1.5 to 2.0 thousand km, and particularities with regard to packing the cargo, unloading and handling for consumption;*

(3) *Input_3 – high annual disbursement, high operational risk and long lead time due to being imported. Sea freight, combined with truck hauling.*

Methodology to be used in modeling and simulation

The methodology is based on the use of computer modeling and simulation, as well as on the definition of a set of indicators suited to evaluate the performance of the chain. This will help in the analysis of the logistic interactions which occur among these companies at the level of product and data flow.

Banks et al. (2000) shows the steps to be taken to guide the developer of the model in a simulation study.

This methodology follows twelve steps, as shown in Figure 04.

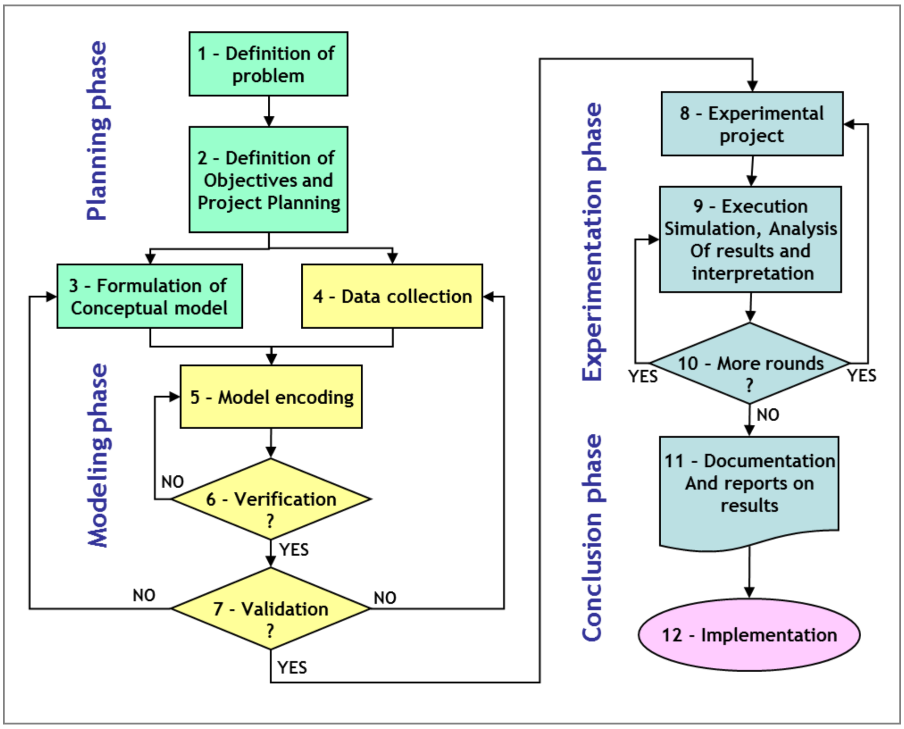

Figure 04 – Methodology of modeling and simulation adapted from Banks et al. (2000, apud FREITAS, 2001, p.15).

Thus a simulation model was developed for a base scenario, i.e., the current configuration of the chain, seeking to represent its main processes and functional activities. Based on this model, it was possible to carry out experiments with new scenarios and new configurations of the chain, being planned by the company, as well as sensitivity studies of certain variables inherent to the chain itself.

The configurations or parameterization of the input supply chains under analysis were a result of the experiments proposed for this study, namely:

(1) As Is Model: as shown in Figure 02 and relative to the three specified inputs (*Input1*; *Input2* and *Input3*);

(2) Expansion of the installed production capacity of the client (Samarco). With this, the demand for consumables will increase accordingly, and the input supply chain must support this new scenario.

To this end, some conditions were tested, namely: (a) increase of storage capacity (client and supplier), resources for grinding, pumping, weighing (client); nominal transportation capacity (carriers), and/or production capacity (suppliers); (b) change in the transportation mode, using rail instead of trucking – shown in Figure 05. This condition was applied to the supply chain of input1 as a function of the current favorable operating conditions.

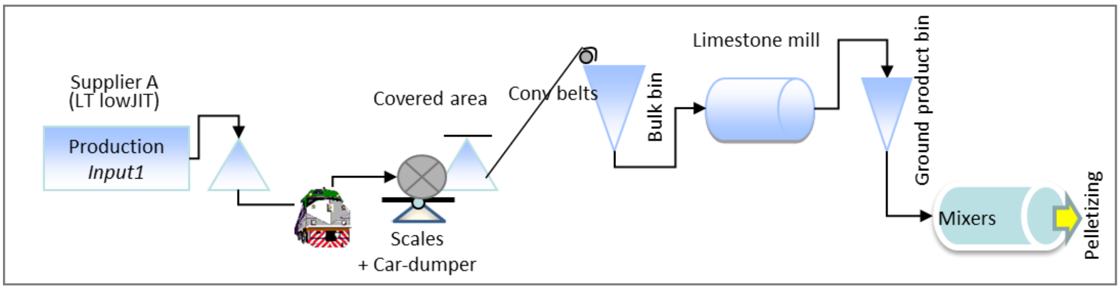

Figure 05 - Experiment B: change in transportation mode, from truck to rail.

Therefore, the changes proposed in the infrastructure along the chain, seeking to support the probable scenario of increased input demand were simulated and evaluated through the new models which portray these propositions.

Each process flow of the supply chain was detailed, in modules (supplier, carrier and client) and submodules, showing each activity and its interconnections, as seen in Figures 06 and 07.

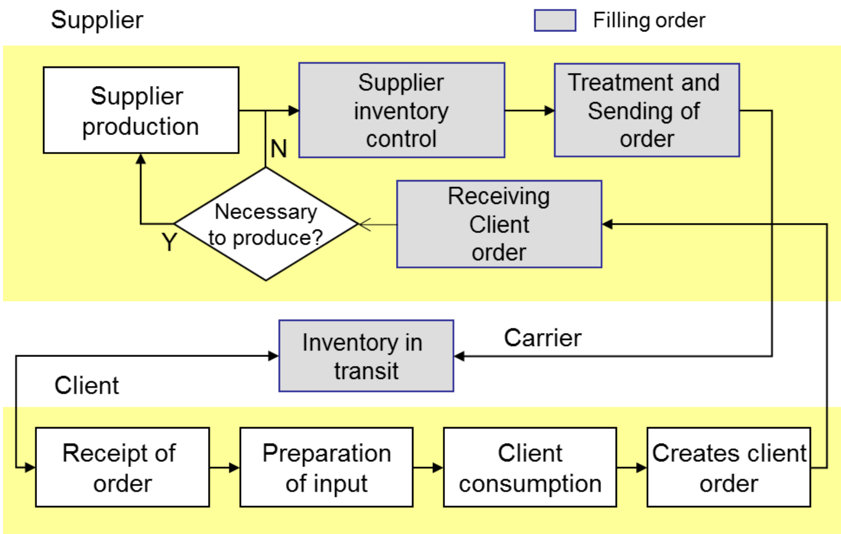

Figure 06 – Flow diagram of the supply chain of *Input_1*.

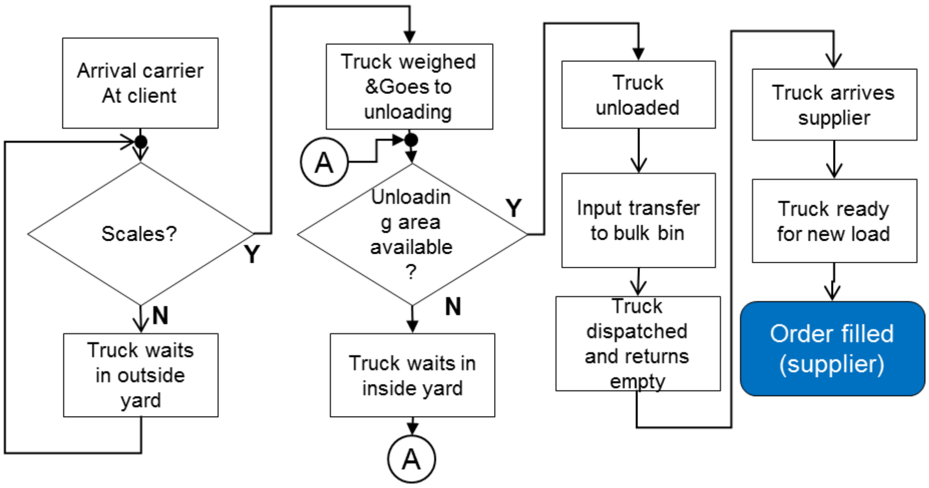

Figure 07 – Flow diagram of the receiving client order.

Data collection and treatment

The information was obtained directly from the input suppliers and the client's technical areas.

It is important to point out that the data were often consolidated not only as a function of the assumptions made for the model, but also to maintain the confidentiality and security of the data.

The data are associated with the modules, submodules and processes which represent the supply chain and were summed up in Table 01.

Main variables identified along the SC	Supply Chain's Modules		
	Suppliers	Carrier	Client
Input production rate	X		
Storage capacity	X		X
Transportation mode capacity	X	X	
Transit time	X	X	X
Resource capacity			X
Time and Consumption in production campaigns			X

Table 01 – Data collection for simulation model.

All the main variables identified along the SC were collected, measured and inserted in the simulation model, represented by the best "distribution curve" that reflects the model, as shown in Figure 08.

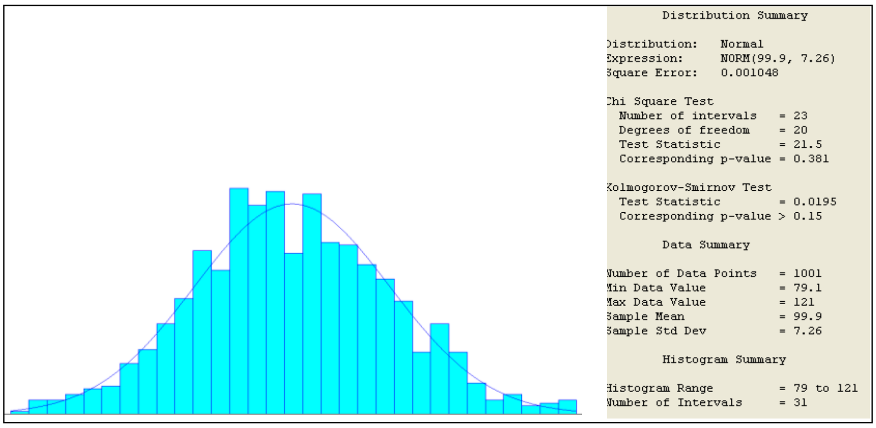

Figure 08 – Production profile of *Input1*.

Computer Simulation Model

After having described the conceptual model of the input supply chain, portraying it so as to represent the real system, while respecting the assumptions adopted, a simulation model was developed to allow the analysis of the chain within the basic scenario (as-is) with its main processes and functional interactions.

Based on the development and validation of this simulator, it was possible to change the input configurations and variables, parameterized in the model, to allow the evaluation of new scenarios and sensitivity analyses.

The development of the simulation model which best matched the methodology presented by Banks et al. (2000) was carried out with the direct help of Arena software, professional module, version 8.

The following criteria were considered in the choice of this application: (1) suitability for the modeled system, (2) user friendliness, and (3) access to complete versions of the software.

Arena is, at the same time, a simulation language and a work and experimentation environment, which were used to test the model and present its results through advanced animation resources.

The representation of the Arena simulation model used programming resources provided through the "project bar", mainly (a) basic processes, (b) advanced processes, and (c) advanced movement.

The time horizon for simulation defined for the model was of 365 days, starting on January 01, 2010, and ending on 31 December 2010, considered sufficient to assure that all the modules and submodules of the model could be activated and tested several times, and to allow the understanding of the behavior of the real system through the model developed.

The warm-up time was set at 60 days, period in which the data generated were discarded, minimizing the influence of the initial parameters adopted in the model.

As to the number of replications in the same simulation round, the criteria adopted in this study was to check the variance in the output of the model related to some of the indicated variables and determine if the resulting confidence intervals are within acceptable limits.

This is an interactive process, where the procedures should be repeated until the desired limits for the confidence interval are obtained (FREITAS, 2001). Studies carried out indicate that the objective is to seek confidence intervals for which the value of h (semi-confidence interval) is equal to or lower than 10% of the sample mean.

The model was run with 1, 2, 8, 16, 32, 64 and 80 replications, with results compatible with 80 replications, as shown in Figure 09.

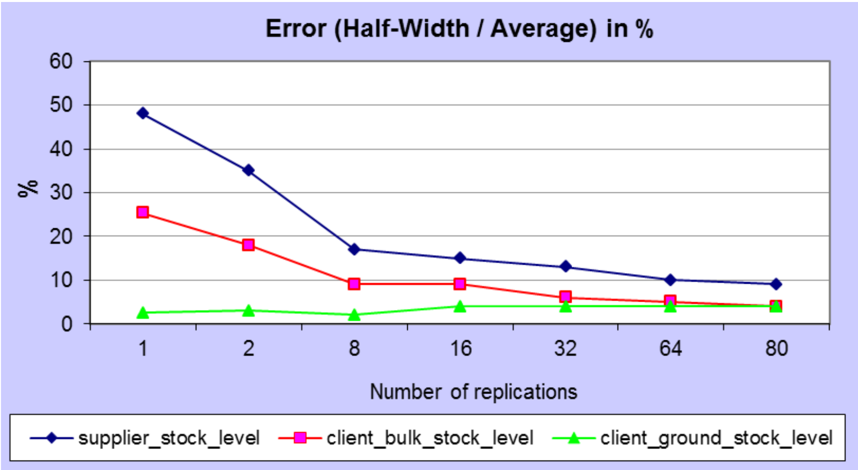

Figure 09 – Error due to number of replications.

Verification and validation of the model

The verification of the adopted simulation models, phase in which one assures that the model executes what is intended, was carried out in parallel with the phase of translation of the conceptual model to a computer one.

Among the techniques suggested by Freitas Filho (2001), the chosen one was the use of tracking devices, such as the “break on module” present in the window “run – run control” of Arena.

For validation, the phases in which one confirms that the model behaves like the real system sufficiently to substitute it in experiments, an analysis was made of the main outputs compared to the real results of the production process of the client company relative to the period in question. The evaluated variables are found in Table 02.

As a series of premises and simplifications was adopted in regard to the real system during modeling, the differences in the results obtained should validate the simulation model. This difference, although it does not indicate the exact percentage of the amounts calculated in 2010, shows a strong correlation with them.

Variables	Unit	Comparative results - real system and scenarios					
		Real 2010	C.e1 *As Is*	Real 2010	C.e2 *As Is*	Real 2010	C.e3 *As Is*
Interruption of production *[1]	hours	0	0	0	0	0	0
Average inventory level in day bins	%	78	80	68	75	72	78
Occupation rate mills or pumping	%	65	63	78	74	65	60
Average inventory level in bulk bin	%	38	35	60	57	52	55
Average inventory level at suppliers	%	48	44	72	67	-	43
Number of orders	unit	345	319	128	137	8	9

Table 02 – Comparative results between real system and simulation.

However, in spite of the validation of the model, any decision making based on its results must be closely followed by specialists and preceded by an evaluation of the quality and adequacy of the results achieved.

3. RESULTS/FINDINGS

Initially the simulation model was validated and verified for the current situation, known also as the “as-is” situation. To this end, the variables were parameterized considering the capabilities of production, storage, transportation, receipt and consumption at the time, both for the suppliers/carriers and the client.

The expansion of the production capacity of the client company allowed the evaluation of the various scenarios in regard to the input supply chain, as shown in Table 03. These scenarios 0, A and B were applied as a form of seeking the rebalancing of the supply chain.

Expansion "e"	Condition (A, B or C)		Input (j) *Input 1*	*Input 2*	*Input 3*
Expansion from 22 to 32 dry metric tons	Increase in nominal capacity and quantity of resources available along supply chain	A	C.e1.A	C.e2.A	C.e3.A
	Creation of area for temporary and intermediate storage close to client facilities	B	C.e1.B	-	-
	Change in transportation mode, using rail instead of trucks	C	C.e1.C	-	-

Table 03 – Conditions to be tested in the expansion scenarios, per input.

The increase in the production capacity was perceived in the model through the variable which determines the consumption of each input in the client's production process.

The main objective sought during the simulation was the lack of occurrence of interruptions in production, as a result of the balancing of the chain, under analysis, in view of the new scenarios.

In this condition, the analysis of the behavior of the system as a function of the proposed conditions was executed, preferentially, in the direction of the link from the client to the suppliers.

In general, for the three inputs, the initial propositions were similar and are represented in Table 04.

Simulations	Proposal	Metrics
I	Maintenance of original metrics in new scenario	-
II	Increased storage capacity in client bin for ground input	*client_ground_stock_level*
III	Installation of one more mill (*resource: mill; pumping*)	*client_input_transf_quant*
IV	Increased storage capacity in bulk input bin at client	*client_bulk_stock_level*
V	Increased number of resource for receiving - scales, car dumper, unloading slots.	*resource: road scale* *truck_unloading*
VI	Increased average capacity of transportation mode (truck, ship, train).	*truck_load_cap* *ship_load_cap*
VII	Increased storage capacity at supplier	*supplier_stock_level*
VIII	Increased nominal production capacity of suppliers	*production_hour*
IX	Reduction in availability of mills and pumping systems	*client_input_transf_quant*
X	Increase or reduction in transit time from suppliers to client.	*supplier_client_route*
XI	Increase in time between inventory management	*inventory_mgt_meantime*

Table 04 – Proposed simulations for each Input.

It is important to point out that these propositions were mixed, step by step, to allow alternative simulations and a greater number of results, expanding the data base

The simulation rounds were named R1 to Rn and were based on the propositions and combinations presented in Table 04 (column of "Simulations", I to XI).

The scenarios were analyzed observing the behavior of the 16 variables with the respective metric units, pursuant to Table 05. Example: Scenario C.e1.A. The first and most important was the number of hours of interruption in production. This guided all of the simulations and the goal was to minimize it as much as possible, until the entire system regained its balance.

Scenario C.e1.A	Unit	Results of simulation rounds												
Variables		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13
Interruption of production	hours	125	157	77	0	18	100	101	86	170	440	277	185	0
Average inventory in day bins	ton	2601	2669	3518	3238	3104	2607	2581	2729	2534	1916	2304	2476	3409
Level of average inventory in day bins	%	70	66	72	88	84	70	70	74	68	52	62	67	84
Average performance of mills	ton/h	110	112	111	140	131	110	110	109	110	100	109	110	131
Occupation rate of mills	%	88	90	88	73	76	87	88	87	88	94	88	88	78
Average inventory of bulk bins	ton	670	661	664	565	621	715	736	745	728	802	459	999	603
Level of average inventory of bulk bins	%	34	33	33	28	31	36	37	37	36	40	23	50	30
Occupation rate of unloading area	%	56	58	57	59	56	57	43	43	43	53	56	56	59
Scales occupation rate	%	28	29	28	29	28	28	21	22	22	26	28	28	29
Average inventory at suppliers	ton	3017	2977	2969	3407	3291	3025	2977	3980	4193	3136	2976	3040	3240
Average invent. at suppliers	%	67	66	66	76	73	67	66	88	93	70	66	68	72
Lead-time for delivery to client	hours	0,95	0,94	0,94	0,92	0,92	0,50	0,47	0,48	0,47	0,91	0,55	1,05	1,04
Total lead time of order in hours	hours	4,21	4,20	4,21	4,58	4,41	3,76	3,62	3,61	3,61	4,08	6,81	4,48	4,54
Number of orders	unit	227	224	227	202	215	226	301	291	290	263	241	228	218
Average number of vehicles per order	unit	49	50	49	55	52	49	37	38	38	42	46	52	51
Vehicle capacity	ton	30	30	30	30	30	30	40	T(35, 40, 45)	T(35, 40, 45)	30	30	30	30
Proposed simulations		I	II	II	III	III	V	V and VI	VI and VII	V, VI e VII	I and IX	I and X	I and IV	II and III

Table 05 - Scenario C.e1.A – Simulation result.

The results achieved were, finally, consolidated (Table 06 – example: scenario C.e2.A) and evaluated to fulfill the objectives of this study.

Results achieved (C.e2.A)	R13	R15	R1	Observations
Non occurence of production interruptions	0	0	404h	-
Increase in average inventory level in day bins	99%	96%	59%	Expected results should be above 80%
Reduction in occupation rate of mills, allowing the planning of preventive maintenance	45%	56%	76%	Expected results should be below 60%
Increased average inventory level in shed	88%	83%	51%	Inputs with average lead time should maintain higher inventory levels
Increased overall lead time of order	106h	95h	88h	Function of number of orders and number of vehicles per order
lead times for delivery	0.99h	0.99h	0.97h	Equivalent
Reduction of number of orders by 30-40%	112	136	196	Increased inventory in shed allowed smaller number of orders associated with higher number of vehicles per order
Increase in average number of vehicles per order, by 40-70%.	26	21	15	
Maintenance of average inventory level at suppliers	3603	3594	3555	Equivalent

Table 06 - Scenario C. e2.A – Results achieved.

Initially, for all the scenarios, the increase in specific consumption of the input led to interruptions in production, representing a loss of revenue of millions of Reais due to lost profit.

The alternatives which would allow the mitigation of the negative effects on the Company's revenue would certainly increase operating costs, reducing the margins in the financial statements.

Some attention points during the simulations: storage capacity and occupation rate of the available resources (ground input bins or day bins, mills, pump system, bulk input bins or bulk bin, unloading areas, highway truck scales, storage areas and transportation modes) for the client and the suppliers, and the delivery lead time, total and during receipt at the client.

The stock levels of the day and bulk bins were several times considered insufficient to maintain the availability of the input in high consumption campaigns. In Figure 10, we can see the saturation pints (upper limit) and the product unavailability points (lower limit) in the client's production day bins.

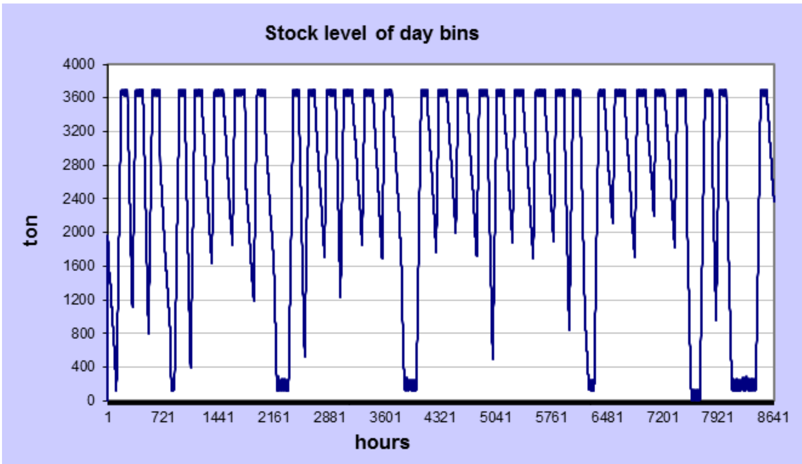

Figure 10 – Stock level of day bins – *Input_1.*

As a result of simulation rounds, as noted in the table 05, it was possible to observe that the grinding process or the pump system for pneumatic transport are bottlenecks in the supply chain, being incapable of grinding or pumping the input and transferring it to the day bins, in view of low performance. The acquisition of new mills and pumps is crucial to the balancing of the chain in the expansion scenario, for all inputs.

During the production campaigns involving lower consumption, or even where there is no input consumption under analysis, the level of the day bin should reach the upper limit, then going back down during the higher consumption campaigns. At this time, the replacement of the input in the day bins for mills and pumps is essential to maintain the demand imposed by the system, as seen in Figure 11.

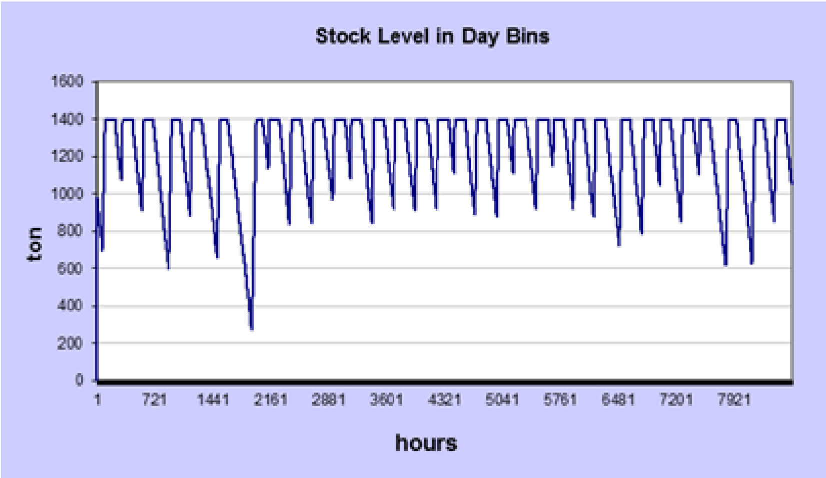

Figure 11 – Stock level in day bins – Input_2.

One of the assumptions made is that the occupation rate of the mills and the pump system should be maintained below 80% and 60%, respectively, so as to allow the necessary preventive maintenance.

However, in view of the high investment required for the purchase of new mills and pumps at the required rated capacity, an association was made, during the simulation rounds, of smaller mills and pumps, with ½ of the rated capacity, with day and bulk bins with higher storage capacity (10-30%), placed upstream and downstream of the grinding process.

Another alternative was to expand the useful area of the storage shed for bulk inputs, expanding the safety inventory and associating them with the additional grinding or pumping system.

The strategy to raise the inventory level in the input shed allowed a greater consolidation of the number of orders by the client, and, as a result, a greater number of vehicles by request of the suppliers.

The critical analysis of the number of requests in the period, associated with the number of vehicles per period, was essential in the evaluation of the input lead time and its influence on the overall supply chain.

In general, the unloading area for the bulk consumables, as it is dedicated to the process, or, in other words, is exclusive for receiving a given input, presented occupational rates compatible with the required demands. However, the weighing area, represented by the truck scales, showed that it dedicated up to 1/3 of its time to a single input. As it is not dedicated to the input, the weighing process was a point of attention during the simulations.

The increase in resources during the phase of receiving the input – weighing and unloading – only proved to be a benefit to the chain when associated with the change in the nominal capacity of the trucks (from 30 to 40 tons) with the use of a B-train (twin-trailer truck). For some inputs, such as Input_2, the increase in the capacity of the vehicles used for transportation was not simulated due to the high usage of B-trains and triple trailer trucks.

When the change in the type of vehicle for transportation was linked to the increase in production and storage capacity of the suppliers, the result observed was not, in and of itself, sufficient to justify the change

Thus the elevation in the average inventory level of the suppliers should represent an increase in fixed assets, without necessarily representing a gain in the performance of the supply chain.

The results point to the direction that the suppliers are suitable sized, in terms of production capacity and storage area, to meet the new consumption demand of the client.

For the consumables which are transported by trucks, such as Input_1 and Input_2, the increase in transit time between suppliers and the client, caused by the increase in number of vehicles driving along federal highways and the time spent waiting in line to be weighed and unloaded at the client, generated the second worst result among the simulations.

For the consumables shipped from overseas, such as Input_3, the safety inventory level in the stockpile yard must be sufficient to assure the quantity required by the grinding system (day bins, mills and bulk bins), between the receiving of the cargo via sea vessels, as shown in Figure 12.

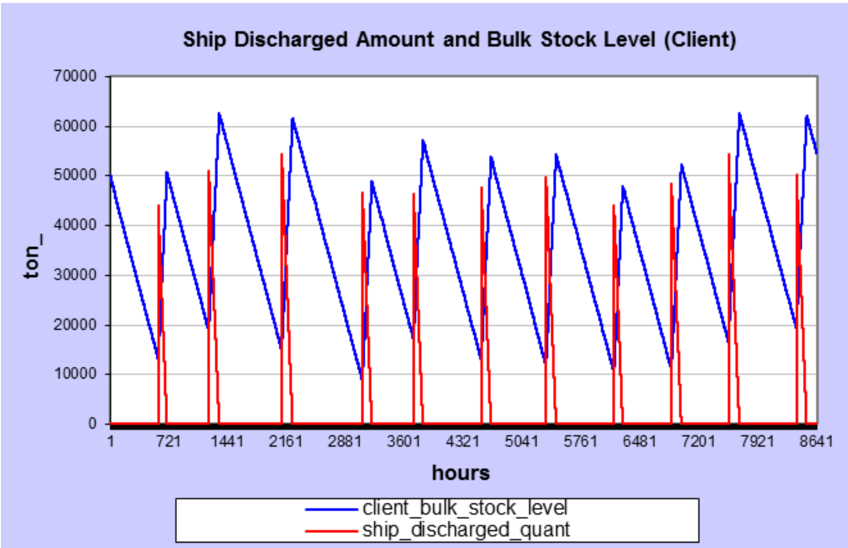

Figure 12 – Results achieved by client – Input_3.

The change in vessel size, replacing Handymax with Panamax vessels, and increasing the transit time between the shipping port of the suppliers and the receiving port of the client, in view of the purchase of products from areas farther away, led to unfavorable results for the supply chain.

Using larger vessels should reduce the total cost of transporting the input via sea freight, in view of the dilution of the fixed costs of the shipper. However, the increase in total lead time will impact the first links of the chain with a required increase of the current inventory levels, in order to assure bulk input volumes sufficient to meet the new demands of the grinding process.

It is important to point out that, in general, the supply chain bottlenecks evaluated are found in the client's production process. The links related to the suppliers and shipper are better prepared to handle the new scenarios.

The results obtained with the change in the transportation mode from truck to rail (scenario C.e1.B) show that the change should come together with increases in the supplier stockpiling capacity and the bulk input at the client, to allow a more regular flow of products between origin and destination. Figure 13 shows the average inventory levels at the day and bulk bins.

Increasing the inventory management time from 12 to 24 hours, together with a higher demand for bulk input, will allow a lower number of orders to the suppliers, a higher volume of input per order, and a larger number of railcars per train, generating an optimized use of this means of transportation. An increase in the receiving resources (car dumpers) should be evaluated to inhibit the increase in overall lead time for the orders.

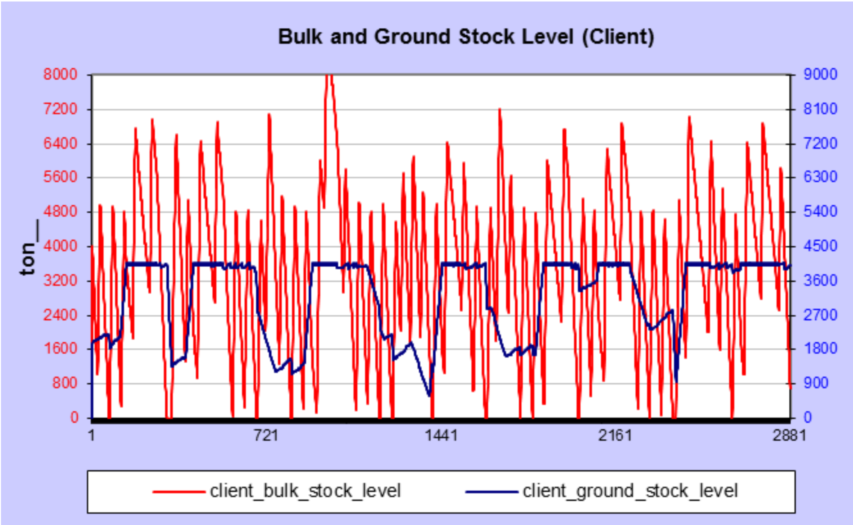

Figure 13 – Results achieved by client with rail mode.

Several other analyses such as these may be carried out based on the results obtained in the experiments. These analyses supply input for the company to decide on the prioritization of supply chain investments, in order to allow meeting the short, medium and long range objectives defined for the product.

Therefore, the analysis methodology proposed in this paper may be a important tool in decision making, when associated with expert opinions.

Performance indicators

The process of choosing the most suitable performance indicators for the supply chain, according to Beamon (1999), should consider three types of indicators: (1) proper use of resources – inventory levels, use of equipment, (2) desired output – hours of production interruption, production, specific consumption, lead time, and (3) flexibility, i.e., how well the system reacts to uncertainties – number of order as a function of consumption demands, inventory levels and transportation mode capacity.

The supply chain performance indicators defined were:

- Storage or inventory – average stock in day bins, bulk bins, shipping port, suppliers, in transit;
- Production – time of production interruption, specific consumption in client production campaigns (Figure 14), grinding capacity of the mills or capacity of the pumping systems, and supplier production capacity (Figure 15).

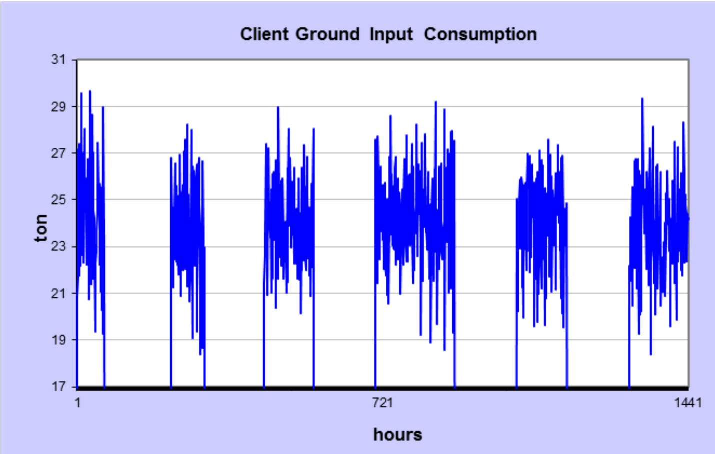

Figure 14 – Production indicators "client consumption".

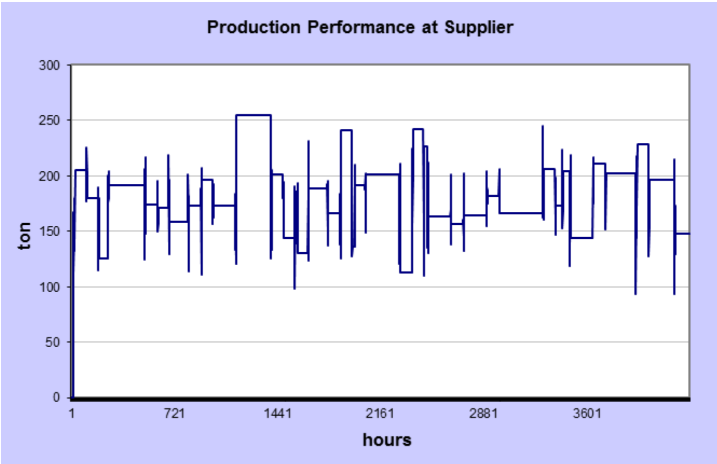

Figure 15 – Production indicators "Supplier production".

- Transportation – number of vehicles per order, lead time for client receipt;
- Procurement – total lead time per order.

4. IMPLICATIONS FOR RESEARCH/POLICY

The critical analysis of logistics interactions using the simulation model proposed will allow managerial decision-making by mining industry with the objective of matching actual system capacity to future demands for service and products. Also, the proposed theme can improve academic research focusing on the Brazilian mining sector and, more specifically, the input supply chain of production processes involving suppliers and customer.

With the objective of detailing the results obtained, some points can be listed, such as:

- Development of a single simulation model to represent the supply chain of the "n" inputs under observation.

  Although this brings greater complexity to the model, and, as a result, requires additional time for the development of the computer simulation, the benefits would be focused on the possibility of a better evaluation of the effects on the resources shared along the system, when subjected to a higher rate of occupation.

- The reevaluation of the input parameters of the model, accompanied by the execution of ore experiments.

  Although many parameters were submitted to a statistical analysis of the set of data collected, the great majority was adjusted to curves of normal or triangular distribution, as a way to simplify the depuration of these input parameters.

- The simulation of other probable scenarios, using the same models developed or adapting them.

  This will allow a broader critical analysis of the probable operational restraints when submitted to new vicissitudes.

Thus the SMD tools adopted would allow a more appropriate measuring of the performance of the supply chain between suppliers and clients, and could also show the gaps between the achieved and expected results.

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