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MODELING OF CRUSHING ORE FLOW AND LOADING PRODUCTS FROM A MINE IN THE ARENA® SOFTWARE

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ABSTRACT

Crushing is an integral and indispensable process of mineral production, as it adds value to the product by reducing the ore granulometry for subsequent processing in the plant. Bauxite is transported by trains from the storage yards to the shipping port, which requires time and loading efficiency adjustments. Thus, in this study, simulation models of the crushing and loading wagons processes were developed in the Arena® software to validate a mining production system. The loading models presented results close to the real ones and therefore were validated. Crushing models were considered valid for providing consistent results after being tested in different scenarios.

KEYWORDS: bauxite, crushing, loading wagons, simulation models, Arena®.

MODELAGEM DO FLUXO DE MINÉRIO DA BRITAGEM E CARREGAMENTO DE PRODUTOS DE UMA MINA NO SOFTWARE ARENA®

RESUMO

A britagem é um processo integrante e indispensável da produção mineral, pois permite agregar valor ao produto, uma vez que adequa a granulometria do minério para posterior beneficiamento na usina. Neste trabalho, o transporte da bauxita, a partir dos pátios de estocagem, é realizado por trens até o porto de embarque, processo esse que demanda ajustes de tempo e de eficiência de carregamento. Dessa forma, neste estudo, foram desenvolvidos modelos de simulação dos processos de britagem e carregamento de vagões no software Arena® para validação do sistema de produção de uma mineração. Os modelos de carregamento apresentaram resultados próximos dos reais, portanto, foram validados. Os modelos de britagem foram considerados válidos por fornecerem resultados coerentes após serem testados em diferentes cenários.

PALAVRAS-CHAVE: bauxita, britagem, carregamento de vagões, modelos de simulação, Arena®.

1 INTRODUCTION

The use of mathematical tools has been widespread in recent years, as has their use in the industrial environment, contributing to improvements in the production process in order to avoid excessive resource expenditure and production waste (WAVRZYNCZAK, ULBRICHT & TEIXEIRA, 2015).

In this context, Operational Research, or OR, is a set of quantitative techniques that assists in decision-making. One of these techniques is the simulation of discrete event systems.

The use of simulation models can facilitate the decision-making analysis process, to examine and test various scenarios, so that a decision can be evaluated before being implemented in a real system (ANDRADE, 2004).

Initially, simulation systems were developed using general purpose languages, such as Forlan, Basic and Pascal. However, this required highly qualified professionals in computer programming and a greater effort in building models. In this way, programming languages began to emerge that overcame this barrier, such as the languages Gpss, Siman, Slan, etc. These languages were, in fact, libraries made up of sets of macro commands from general-purpose languages. Some of the next generation simulators were developed on the platform of these languages. As an example, there is the Arena® software, implemented in the Siman language (KELTON & SADOWSKI, 1998 *apud* SANTOS & ALVES, 2014).

The discrete event system simulation is an OR technique that studies the performance of a specific system through models implemented in software, which fully or partially replicates the properties and behaviors of the system virtually, allowing for its manipulation and detailed study (PARAGON, 2006).

The software ARENA is an integrated graphical simulation environment, which contains resources for modeling, animation, statistical analysis, and result evaluation (PARAGON, 2006).

Mineral industries are increasingly using these methods to avoid investment risks that may seem appropriate and feasible but do not meet the expectations of the team after implementation.

Mining involves extremely complex systems, with a large number of random variables. When simulating certain operations, their management is consequently improved, and process optimization is achieved. Simulation allows for the analysis of different scenarios at low cost and quickly.

In this study, simulation models were created for the ore flow in the crushing and loading operations of train wagons with products for subsequent transportation to a bauxite mining port. The intention was to try to replicate the current scenario of how these operations occur so that they can later be used for analysis and prediction of system behavior in future or alternative scenarios.

The crushing and loading processes are of great relevance to the mining enterprise, justifying the study of their behaviors through simulation models. In this work, the models were constructed using the ARENA software.

2 LITERATURE REVIEW

The practice of modeling may be developed for purposes such as expanding production, replacing equipment, or adding new products, among other applications. To properly size a system, it is necessary to analyze the main bottlenecks, which are the points where queues may form. It is also recommended to design a new system in which the optimal flow within it is planned (PRADO, 2004).

A system may be considered as a set of elements, or entities, which can act or interact with other elements to perform one or more activities that take a certain duration of time. These activities bring about a change in the system's state.

The state of a system can be defined by values assumed by a series of variables at a certain point in time, which can be referred to as the system's state variables. If one of these variables changes its value, it is said that a state change has occurred. These state changes happen when an activity starts or finishes, involving one or more entities. If none of these variables change during a time interval, no state change occurs. Therefore, state changes happen at discrete moments in time, which is why it's called discrete event simulation.

As the duration of activities is typically a random variable, along with other types of random variables that might be present in the system being simulated, it's not possible to determine in advance the exact moments when state changes will occur. This makes it impossible to handle such systems using deterministic models. This type of simulation is suitable for representing systems whose behaviors depend on one or multiple random variables.

The simulation program must then track the path of entities within the system, identifying all the moments in sequence when state changes occur and recording all the alterations resulting from these state transitions. The final behavior of the system will be the result of the sequence of state changes that the system undergoes from the initial moment to the final moment of the simulation.

The fundamental elements intrinsic to the simulation model are Entities, Attributes, Variables, Queues, Resources, Simulation Clock, and Events.

Information about the ARENA software used in this work can be found in PRADO (1999).

3 METHODOLOGY

The following phases are typically present in a simulation study: 1. Problem Definition; 2. Identification of Relevant Variables; 3. Data Collection; 4. Formulation of the Logical-Mathematical Model; 5. Construction of the Computational Model; 6. Model Verification and Validation; 7. Experimentation

The problem's characterization with relevant variables and process data is carried out through the description of the crushing and wagon loading operations. There are two types of products: raw bauxite and washed bauxite. Raw bauxite only undergoes the crushing process. On the other hand, washed bauxite, after crushing, goes through a beneficiation plant.

The crushing process involves numerous operations, and to make them easier to visualize, flowcharts and decision flows have been constructed to enhance the understanding of these operations.

Crushing Process

The bauxite extracted from the mining site or from intermediate storage piles (buffer piles) is unloaded into the hopper by trucks or front-end loaders, respectively. After this process, the ore is transported via an apron feeder to the primary crusher. The ore is transferred from the primary crusher to the secondary crusher through the force of gravity, without any intermediary equipment between the crushers. Consequently, the ore is directed to the first conveyor in the process. Figure 1 provides a visual representation of the process.

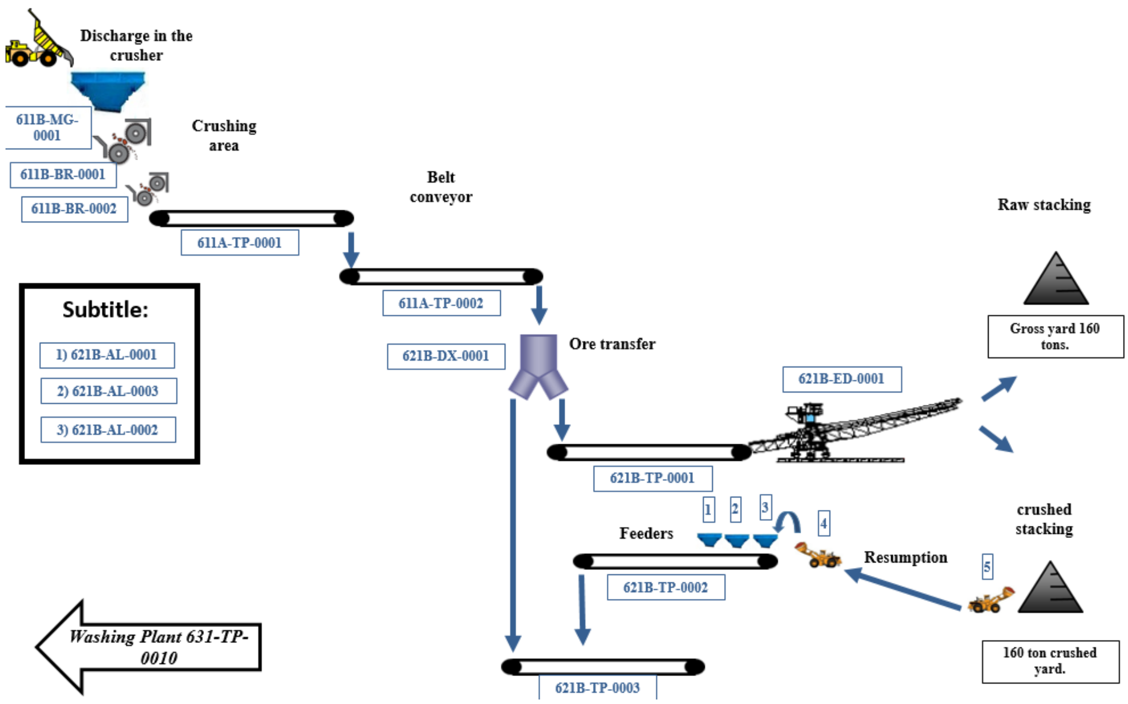

Figure 1: Crushing Flowchart.

The material continues along the second conveyor belt, which carries it to the motorized flow diverter. When the flow diverter is positioned to the right, it feeds the processing plant. When positioned to the left, the ore is directed to follow a stacking route in the storage yard.

Storage and By-Pass in the Crushed Bauxite Yard

The ore coming from the flow diverter is transported by the conveyor belt to feed the stacker, where it can be stacked in the raw bauxite (unwashed) yard or in the crushed bauxite yard. The stacker is responsible for forming homogenization piles.

The feeding of the washing plant occurs when it's in operation, with one or two lines functioning. The material from the flow diverter is unloaded onto the conveyor belt that carries the ore to the respective lines.

Reclaiming from the Crushed Bauxite Yard and Feeding the Washing Plant

The ore stored in the crushed bauxite yard is reclaimed using front-end loaders, which feed the three feeders (hoppers). These feeders discharge onto a conveyor belt that directs the material to another conveyor which feeds the processing plant.

Wagon Loading

Wagon loading takes place in the raw bauxite and washed bauxite stockyards, where the piles have been stacked. When a train arrives at the yard for loading, the wagons are positioned to optimize the movement of the loaders between the piles and the train. This optimizes the loading time of the train and facilitates determining the number of loaders involved in each loading. Each loader is responsible for filling one wagon at a time. Once loaded, the train covers a journey of around 54 km, taking about an hour to reach the bauxite loading port.

Stockyards

In the mining area, there are four stockyards: the buffer pile yard, the raw bauxite yard, the crushed bauxite yard, and the washed bauxite yard. The buffer pile yard, consisting of four piles, is responsible for maintaining the crusher's feed rate when the mining operation is running with fewer mining faces. The raw bauxite yard is where trains are loaded with this type of product. The crushed bauxite yard receives ore classified as washed but not yet processed through the plant. This area is used to store this type of ore when the plant has one or two of its lines stopped. Later, this material will feed the plant's lines. There can be up to four piles of raw bauxite and four piles of crushed bauxite. Lastly, the washed bauxite yard receives the washed bauxite product, which has undergone processing and will be loaded onto trains for transport to the loading port.

Model Development

In the constructed crushing model, there are operations involving continuous material flow, such as stacking, feeding the crushers, crushing, conveying ore through belts from the crusher to the plant, and stacker and feeder transportation from the reclaim yard to the plant. According to Ouellet (2017), building a continuous flow model of material in a process can be achieved through mass discretization, time discretization, or using the *Flow Process template* in the ARENA software.

Mass discretization is used to demonstrate the movement of a certain mass within a defined time. The smaller the discretized mass, the shorter the mass transfer time, and the system gets closer to continuous behavior. The larger the mass, the less precise the simulation becomes. Model execution time is longer with smaller discrete units, so it's important to choose a reference unit that balances precision and model performance. An advantage of mass discretization is that attributes can be associated with the discrete mass element, such as ore grades. If the process being simulated is entirely continuous, mass discretization will essentially correspond to time discretization. Mass discretization was used, adopting a discrete mass value of one ton.

Ideally, continuous flow should be simulated separately for each section where it occurs, where there is equipment through which the flow passes. This includes crushers, flow diverters, stackers, and conveyor sections. This way, the situation of each equipment can be controlled separately (whether it is in maintenance, operational, or idle). If an equipment failure occurs in a sequence of sections where continuous flow is present, the program "recognizes" this situation and halts all equipment upstream of the failed equipment.

Due to limitations in the version of Arena used for model construction, this ideal approach couldn't be fully implemented. Some simplifications were made, such as considering the repair time (MTTR) for the crusher to include the repair time for all conveyor belts up to the flow diverter and from the flow diverter to the stacker. Due to these constraints in the crushing model, maintenance was only considered for the plant's lines, stacker, and crusher.

Crushing Model for Washed Bauxite

In constructing the crushed washed bauxite model, several situations influencing the ore flow had to be considered. These include a plant line stoppage, a general plant shutdown, reduced mining fronts, and crusher stoppage. These situations can occur concurrently, such as when the crusher stops along with one or two plant lines. For each situation, one or more different flow possibilities can occur. These decisions might involve the amount of ore present in the stockpiles, whether the crushing operation is meeting the goals set by the plant based on customer demands, mine operation return time, availability of the stacker, plant lines, and crusher. The crushing models were implemented based on the decision flows used within the company, which are described below.

Plant Line Stoppage

When a plant line stops, it is checked if the stockyard still has the capacity to receive material via stacking. If the stockyard capacity is less than 150,000 tons, the plant is fed through one plant line and bauxite is stacked. If the stockyard is at its maximum capacity, only one plant line is fed, and the crusher feed rate is reduced.

General Plant Shutdown

When both plant lines stop, it is verified if the crushing operation is meeting its target. This value may vary depending on the month or production. If it's not meeting the target, bauxite is stacked in the crushed bauxite yard. If it is meeting the target, the estimated return time is evaluated, and if the stockyard can receive more material, stacking occurs. If there is no estimated return time and no space is available, the system waits until stacking is possible.

Reduction in Mining Feed Capacity

When the number of mining fronts is reduced, if the crushing operation aligns with the production plan, material is reclaimed from the crushed bauxite yard to complete the feed rate to the plant. If it does not align, the feed rate is completed with material from the buffer piles.

Crusher Stoppage

When the crusher stops, it is checked if the plant is operational. If it is not, the system waits for the crusher to resume. If the plant is operational and there is material in the crushed bauxite yard ready for reclaiming, material retrieval from the yard to the plant begins immediately. Otherwise, the system waits for the crusher to resume.

In the case of washed bauxite, to meet the production capacity of both plant lines, around 550 to 570 tons per hour, a crusher feed rate of 1200 t/h is required. To achieve this target, three mining fronts need to be operational as each contributes an average of 400 t/h. When the number of fronts is reduced, the feed rate must be supplemented with material from the buffer piles.

Data Collection

In addition to gathering parameters for operations and equipment, data on the variables involved in the processes were collected. After error elimination, the data was statistically analyzed, and probability distributions were adjusted using the Input Analyzer tool in ARENA for use in the models.

Simulation Models for Crushing and Wagon Loading

Analogously, two simulation models were constructed for the operations related to the crushing area: one for the circuit of ore classified as washed and another for raw bauxite. Similarly, two other models were built for product loading: one for loading trains with raw bauxite and another for loading washed bauxite. Further details about the models can be found in MACHADO (2019). Images containing the programming modules used in the models created for crushing and wagon loading are presented in MACHADO (2019).

Due to limitations in the software version used, it was not possible to construct models that encompassed both crushing and wagon loading operations together.

This subdivision has the advantage of creating relatively simpler models that wouldn't affect the results when evaluating only the behavior of a specific type of operation, such as loading raw bauxite.

On the other hand, this separation would not allow, for example, the use of a single model to determine the best allocation of loaders to improve the performance of various operations in which they are involved. There are seven front-end loaders that can be used in wagon loading operations with raw or washed bauxite, reclaiming material from the buffer piles to feed the crusher hopper, and reclaiming material from the crushed bauxite piles to feed the plant lines. Allocation is usually defined, aiming to achieve the desired goals in a given situation. An integrated model could test different allocation possibilities, assessing their impact on each operation, and determine the most suitable allocation of loaders to best achieve the desired objectives.

With an "unrestricted" version of the software, more animated features could be added to the crushing models. Input data could be initialized or read from an Excel spreadsheet instead of defining initial values in the variable data module. Maintenance of all equipment could be considered, along with other operations that would more accurately replicate reality without simplifications. One of these simplifications occurred in the reclaimed crushed bauxite piles, where a single pile and a single hopper for feeding the plant lines were considered, while there are three.

4 RESULTS

With the constructed models and no programming errors, the validation phase began. Model validation may be approached in two ways. If the model can be used to replicate a scenario that occurred in the system at a certain time, with records of data that can be fed into the model, information about how the system was operating, and records of control variables' results – such as accumulated production or system productivity – the model could be loaded with this information, run, and the results could be compared with the recorded data.

In some cases, this might not be feasible due to the unavailability of such information, which might be non-existent, or because the model could have been built to represent an alternative scenario of system operation that has likely never occurred before.

In such cases, the model should be fed with input data or information, and the results it produces should be compared against predictable results that it should exhibit for the input information used. For instance, if we don't consider equipment maintenance that influences the productivity of a certain operation, an increase in productivity is expected.

4.1. Validation of the Raw Bauxite Wagon Loading Model.

In order to validate this model, information regarding the process of loading raw bauxite onto train wagons recorded over a month was used. The model was fed with probability distributions obtained from data on train arrivals, number of wagons, loaded wagon mass, and loaded mass in the buckets of the loaders used during the evaluated period. Five loaders were considered for the loading process. Thus, 30 replications were conducted, each spanning a 30-day period. The number of loaded trains and the loaded mass during the period were selected. Table 1 displays the minimum, maximum, mean, and 95% confidence interval values obtained for these variables from the 30 simulations conducted.

Table 1: Values obtained from the results of the raw bauxite wagon loading model.

Variable	Mean	CI (95%)	Minimum	Maximum
Loaded Mass	49.929,73	(49.924,93 +/- 7.411,30)	21.654	101.655
Number of Loaded Trains	18,63	(18,63 +/- 2,86)	8	39

The observed number of loaded trains during the period was 18, close to the mean value, and the total mass loaded onto the trains was 45,100 tons. Table 2 displays the utilization rate of the loader resources and the number of times these resources were occupied.

Table 2: Utilization values and the number of times resources were occupied as predicted by the raw bauxite loading model.

Resources	Utilization Rate (%)	Number of Times Occupied
Loader 1	0.10	118.80
Loader 2	0.11	134.50
Loader 3	0.10	120.63
Loader 4	0.10	121.40
Loader 5	0.09	107.13
Loading Yard	0.13	18.63

It can be observed that the utilization rate for all loaders and the number of times they were used are nearly identical, as the selection criterion used in allocation was cyclical, and they are all low. The utilization rate of the loading yard resource is also low, and the number of times it was occupied corresponds to the number of loaded trains.

The reduced utilization rate reflects the fact that the demand for raw bauxite is small. As a result, the interval between train arrivals is high, meaning there is virtually no queue formation in the loading yard. This can be verified in the Arena's queue report, although it hasn't been presented in this work.

Based on the above, we can conclude that this model is validated.

4.2. Validation of the Washed Bauxite Wagon Loading Model.

The same procedure used to validate the model of loading wagons with raw bauxite was applied to washed bauxite. Thirty replications were executed, each spanning a 30-day period (one month). Among various results provided by Arena, the number of trains and the loaded mass during the period were mainly selected for attempting to validate the model. Table 3 presents the minimum, maximum, mean, and 95% confidence interval values obtained for the number of loaded trains and the loaded mass during the one-month period across the 30 simulations.

Table 3: Values obtained from the results of the raw bauxite wagon loading model.

Variable	Mean	CI (95%)	Minimum	Maximum
Loaded Mass	521.371,17	(521.371 +/- 8617)	479.059	565.425
Number of Loaded Trains	194,13	(194,13 +/- 3,3)	177	211

The observed number of loaded trains during the period was 196, close to the mean value, and the total mass loaded onto the trains was 553,546 tons. Table 4 displays the utilization rate of the loader resources and the number of times these resources were occupied.

Table 4: Utilization values and the number of times resources were occupied on washed bauxite loading model.

Resources	Utilization Rate (%)	Number of Times Occupied
Loader 1	22,64	1302,57
Loader 2	24,42	1403,70
Loader 3	22,83	1312,47
Loader 4	22,86	1315,07
Loader 5	20,11	1156,30
Loading Yard	27,84	194,47

It can be observed that the utilization rate of all loaders and the number of times they were used are nearly equal, as the selection criterion used in allocation was cyclical around 20%. This utilization rate is low, but significantly higher than the rate for raw bauxite. The utilization rate of the loading yard resource is also much higher for washed bauxite, around 25%. This value indicates that most of the time during a month, the yard remains idle due to a lack of trains to load.

The demand for washed bauxite is considerably higher, but there is still no significant queue formation due to their small sizes. The highest average waiting time is for a wagon waiting to allocate a loader, which is approximately 0.8 minutes. Similarly, there is virtually no queue formation in the loading yard. The highest value for this waiting time across the 30 simulations was 0.2 minutes.

Just like the case with raw bauxite, the washed bauxite model is considered validated based on these results.

4.3. Validation of the Raw Bauxite Crushing Model

In this situation, measured data for all input parameters of the raw bauxite crushing model were not available. The validation process in this case was carried out through the analysis of different scenarios obtained by modifying data or information in one or more models.

The different scenarios were run only once and for a simulation period of 48 hours.

Comparisons were made on variables such as the mass stacked in the raw bauxite yard (which should be equal to the mass that goes through the crusher), the mass feeding the plant from the recovery of the crushed bauxite yard, and the mass entering and leaving the buffer pile or their respective rates in tons per hour.

For scenario 1, it was initially assumed that the mass in the buffer pile was 100,000 t, the mass in the raw bauxite yard was 200,000 t, the mass in the crushed bauxite yard was 100,000 t, the crushing target was 100,000 t, the productivity of the apron feeder from the hopper feeding the crusher was 1600 t/h, the productivity of each plant line was 570 t/h, the number of mining fronts was 3, the number of loaders available for the recovery of the crushed bauxite yard was 3, and for the recovery of the buffer pile, it was 1. The maintenance of all equipment was also considered.

Figure 2 displays the tables with the values of the variables to be analyzed before and after simulating scenario 1.

Stacked dough 0.0	Lung feeding 0.0	Plant production 0.0
Plant production via crusher 100000.0	Plant production via yard 0.0	Crushed mass 0.0
Final doughlung stack 20000.0	Final doughcrushed yard 100000.0	TNOW 0.0

Stacked dough 73397.0	Lung feeding 21313.5	Plant production 50917.0
Plant production via crusher 83570.5	Plant production via yard 4884.0	Crushed mass 73398.0
Final doughlung stack 93397.0	Final doughcrushed yard 48064.7	TNOW 48.0

Figure 2: Scenario 1 simulation values chart.

It is noticeable that there was a recovery from the buffer pile, 21,313.5 t, which means the buffer pile contributes with a correspondent mass to a crusher feeding rate of 444 t/h. The mass passing through the crusher, which is equal to the stacked mass, corresponds to a rate of 1529 t/h. Consequently, the three mining fronts are responsible for feeding a mass of 73,397 t into the crusher. The ore from the mining fronts was directed to the buffer pile, likely due to stoppages of the crusher and the stacker. Calculating the mass of ore from the mining fronts that entered both the stockpile and the crusher, we get an hourly rate of approximately 1187 t/h, which is close to the 1200 t/h target, or the expected 400 t/h contribution from each mining front in the case of raw bauxite.

In this scenario, using three loaders for the recovery from the crushed bauxite yard, the mass feeding the plant corresponds to an approximate rate of 1060 t/h. At the beginning, both plant lines were operational, each with a capacity of 570 t/h.

For scenario 2, it was considered that only 2 loaders are available for the recovery from the crushed bauxite yard, and none for the buffer pile.

In scenario 3, the same parameters as in scenario 2 were maintained, except for the crusher repair time, which increased from 1.48 h to 3.48 h, and the repair time for plant line 1, which increased from 1.70 h to 3.70 h.

Figure 3 displays the results for scenario 2 (on the right) and scenario 3 (on the left).

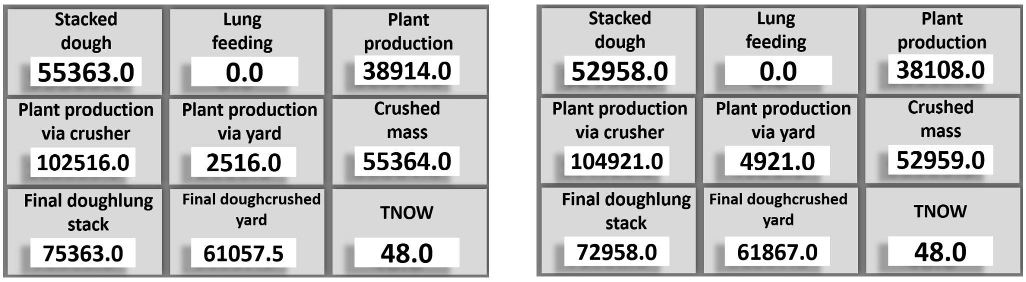

Figure 3: Scenario 2 and Scenario 3 simulation result chart.

In scenario 2, no mass was recovered from the buffer pile. The mass passing through the crusher and being stacked is smaller in this case, as it only comes from the mining fronts, which together contribute a rate of 1153 t/h, or around 384 t/h each. As there was an input of mass into the buffer pile, the total production from the 3 mining fronts amounted to 57,880 t, which corresponds to a rate of 1200 t/h or 400 t/h per front.

Since the number of loaders for the recovery from the crushed bauxite yard was reduced, the mass going to the plant also decreased, as did the hourly rate, which dropped to 810 t/h.

Due to the increased crusher repair time, the stacked mass decreased, and the mass unloaded to the buffer pile increased. Similarly, with the extended repair time for plant line 1, the mass fed to the plant decreased compared to scenario 2.

In all three scenarios, coherent results were obtained, leading to the conclusion that the model could be validated in the absence of more information about the system's behavior.

4.4. Washed Bauxite Crushing Model.

Similar to the case of the raw bauxite crushing model and for the same reasons, it won't be possible to perform validation by comparing the behavior provided by the simulation model with the behavior recorded at a previous real-time moment before the simulation was conducted.

Different scenarios with a duration of 48 hours were run and compared instead.

For scenario 1, it will be initially considered that the mass present in the buffer pile is 100,000 t, the mass in the crushed bauxite pile is 145,000 t, a crushing target of 600,000 t, the apron feeder's productivity at the hopper is 800 t/h, the productivity of each plant line is 570 t/h, the number of mining fronts is 2, the number of front-end loaders available for retrieving material from the crushed pile is 1, and there will be no retrieval from the buffer pile. Additionally, it was assumed that when the ore is simultaneously fed to the plant and stacked (when one of the lines is under maintenance), the portion to be stacked corresponds to 50% of the ore flow passing through the crusher. Maintenance of all equipment was also considered.

Figure 4 presents the charts with the values of the variables to be analyzed before and after the simulation of scenario 1.

Stacked dough	Lung feeding	Plant production
0.0	0.0	0.0
Plant production via crusher	Plant production via yard	Crushed mass
0.0	0.0	0.0
Final doughlung stack	Final doughcrushed yard	TNOW
100000.0	145000.0	0.0

Stacked dough	Lung feeding	Plant production
1433.0	0.0	54798.5
Plant production via crusher	Plant production via yard	Crushed mass
37779.5	19019.0	37212.5
Final doughlung stack	Final doughcrushed yard	TNOW
100000.0	127403.2	0.0

Figure 4: Scenario 1 simulation values chart.

It is noted that there was production from the plant through feed coming from the crusher and the crushed pile. The crushing process contributed with an average hourly rate of 745 t/h and the crushed bauxite yard with 396 t/h, resulting in a total of 1141 t/h. A portion that went through the crusher was sent for stacking. Taking this into account, the average crushing rate was approximately 775 t/h, close to 800 t/h, which is consistent with a number of fronts equal to 2.

Figure 5 presents the situation of scenario 1 up to the moment of 28.4 hours (TNOW), when line 1 enters maintenance.

Stacked dough	Lung feeding	Plant production
0.0	0.0	33958.0
Plant production via crusher	Plant production via yard	Crushed mass
22689.0	11269.0	22689.0
Final doughlung stack	Final doughcrushed yard	TNOW
100000.0	133720.0	28.4

Figure 5: Scenario 1 values at 28.4 hours moment chart.

At this moment, there was no stacking, which started to occur since only one line of the plant cannot handle more than 570 t/h. This result aligns with the decision flows related to production reduction due to a lower number of fronts than 3 and when only one line is operational.

In scenario 2, it was considered that a loader was assigned to retrieve the buffer pile, and the productivity of the apron feeder was adjusted to 1200 t/h instead of 800 t/h.

What changes in scenario 3 compared to scenario 2 is that it assumes an initial accumulated crushed mass of 560,000 t, close to the target of 600,000 t.

Figure 6 presents the results for scenario 2 (right) and scenario 3 (left).

Stacked dough	Lung feeding	Plant production
2149.5	25449.9	54258.0
Plant production via crusher	Plant production via yard	Crushed mass
53671.0	587.0	55820.5
Final doughlung stack	Final doughcrushed yard	TNOW
74550.1	146563.2	48.0

Stacked dough	Lung feeding	Plant production
1127.5	17860.6	44644.5
Plant production via crusher	Plant production via yard	Crushed mass
38873.5	5771.0	40001.0
Final doughlung stack	Final doughcrushed yard	TNOW
82139.4	140344.8	48.0

Figure 6: Scenario 2 and Scenario 3 simulation results charts.

In scenario 2, the crushed mass of 55,820.5 t is now higher due to the contribution of 25,450 t from the buffer pile with a rate of 530 t/h. The mining fronts contributed a mass of 30,370.6 t, corresponding to a rate of 632 t/h, totaling an average crushing rate of approximately 1162 t/h.

After deducting the part that was stacked, the average feeding rate of the plant via the crusher was 1118 t/h.

The total feeding rate to the plant was 1130 t/h, as there was a small contribution from reclaiming the crushed bauxite yard. Since the crushing rate in this scenario was higher due to the buffer pile contribution, there was no need to try to complete the plant's feeding rate with more material from the crushed bauxite yard, as in scenario 1. The material that went to the plant via the yard probably occurred when one of the lines was under maintenance.

In scenario 3, the crushed mass was 40,000 t, which was the amount needed to reach the target of 600,000 t. The plant feeding through the crusher was lower than in scenario 2, corresponding to approximately 810 t/h. The average feeding rate to the plant was 930 t/h, with a small contribution from the crushed bauxite yard.

The comparison between these scenarios initially suggests that the model could be validated due to the coherent results obtained.

5 CONCLUSION

Through a detailed understanding of the operations involved in the crushing process of both raw and washed bauxite ores, from the feeding of the crusher hopper with ore from mining fronts and the buffer pile, to the stacking in the crushed and raw yards, and finally to the plant feeding, as well as the wagon loading operations in the raw and washed bauxite yards, it was possible to construct discrete event simulation models representing these operations.

Important data for building and feeding the models were obtained from previous records or through direct field measurements. An essential aspect was comprehending all the limitations and flow options within the process. Numerical data obtained from random variables influencing the operations were statistically treated, and probability distribution functions representing their statistical behavior were fitted using the input analyser tool.

Four simulation models were constructed: one representing operations in the crushing area for raw bauxite, another for washed bauxite, a wagon loading model for raw bauxite, and another model for loading washed bauxite.

The wagon loading models, both for raw and washed bauxite cases, were validated by comparing simulation results with known registered values, which were statistically close to the real data.

Due to the lack of certain information records, the crushing models were considered valid based on the individual behavior of each scenario and by comparing results among them. All evaluated scenarios displayed coherent results. A future validation of this model with real data is recommended.

Once validated, the models can be used to evaluate alternative scenarios, as demonstrated in this study.

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