Applications of Discrete-Event Simulation for Mining Process Plants in Chile.

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ABSTRACT

The article describes the development and application of a new discrete time-event simulation modeling methodology used in the copper mining industry in Chile. The proposed methodology creates a simulation model that represents a mine-mill operation, and it is used to evaluate different improvement options to maximize the system performance. Two applications of this methodology to existing copper plants in Chile are presented in this work.

Keywords: Simulation model, mining operations, mine-mill process, copper industry, transport model.

1. INTRODUCTION

The copper mining in Chile is the largest in the world. The economic importance of this activity has originated important developments and research, resulting in a better knowledge of the operation of the metallurgical process units. However, when an industrial facility is complex, or has too many types of equipment, originated by a number of expansions, or the case when surge bins between stages are of limited capacity, then the interrelationship between the different process units is not well known, thus inefficiencies may occur, producing a remarkable lack of process capacity. To overcome this issue, simulation has gained increased attention as a technique for planning and analyzing new mining operations, or modifying and improving existing ones, around the world. The simulation of a system corresponds to the numerical evaluation of a model by using a computer. This process enables the observation and measurement of the performance of a system under existing or proposed configurations of interest, over long periods of time. Thus it makes possible to carry out experiments without altering the real-life system, measuring the outcome to help the decision-making process with valuable information. Furthermore, for a complex system simulation is often the only feasible method to investigate the problem and evaluate alternative operational conditions, hence becoming a tool for justifying investment costs. On the other hand, simulation models can also study the behavior of a system before it is implemented, improving the design stage of the project.

In [5] Sturgul and Li (1997), the authors emphasize that the advantages of simulation in the mining industry are not only to provide management with a detailed look into the future but also to allow the company to make critical decisions and understand a variety of issues about the current system. Several experiences for simulation models in mining operations in Canada ([7] Vagenas, 1999), Europe ([4] Panagiotou, 1999), South Africa ([6] Turner, 1999) and Australia ([1] Basu & Baafi, 1999) have been reported in the technical literature. Most of these applications have been made in the research of surface and underground mining, with special interest in truck/ship transport. However, there are no reported experiences in the use of this tool in the analysis and development of the mining copper industry in Chile or South America, in spite of it increasing importance.

Lynch and Morrison in [3] mention that economic factors have become more important in recent simulation modeling, since consideration of the cost of items such as equipment, power, labor, suppliers, and of the contract conditions for sales of products are commonly considered in simulation models to improve economic performance. This increasing importance and economic advantages of simulation motivated this research work, which focuses on the development of a methodology based on the use of a dynamic stochastic discrete event model, namely models evolving with time. These models include random input components and for which the states variables change instantaneously in response to certain events taking place at separate points in time (discrete events models). This simulation model will allow a decision maker to define the dynamics of the transportation/crushing/comminution operation of a mining facility, to make better operational decisions, resulting in an increase of mineral processing flow, increasing also the operation revenues.

The proposed methodology is used to improve the mineral throughput in two existing Chilean mining facilities, a large concentration plant and the dry-area of a large hydrometallurgical plant. In this article, simulations of the
current operation conditions were developed, and several improved scenarios were run (with marginal investment requirements) in order to increase the mineral flow in both cases.

The simulation models were built and run by using ProModel™, discrete event software widely used in the manufacturing industry.

2. BASIS OF THE SIMULATION

The information required to build a simulation model based on discrete event software is listed as follows. An ideal case model is needed to ensure that the mass balance of the studied system is correct.

Data Gathering
In order to build a robust simulation model, a thorough understanding of the system is needed, and therefore detailed information must be collected. The required information to build this model are the flow diagram, a detailed description of the plant’s operation, the equipment characteristics (capacity, length, velocity, residence time, etc.). Also the operational statistics play a crucial role to obtain a realistic model, with information related to the maintenance and failure duration of different events, and the daily/hourly flow measurements. Benchmarking information of several mining facilities shows that it is required operational information of at least a thousand shifts to obtain a reliable data to build a simulation model.

Modeling the Ideal Case
In order to create an affordable simulation model, it is required to simplify the system by creating discrete blocks representing sets of mining/transport/process units. The constraints imposed by the simulation software set the precision, units, and time of simulation. Once this criterion is fixed, the design data (equipment characteristics, ore feed rate, etc.) requires to be escalated in order to create a realistic simulation model. The fundamental components of the simulation are:

- **Entities**: the elements which travel through the system (tons of ore).
- **Locations**: the objects that build the transport system (storing places, processing units, conveyor belts, etc).
- **Arrivals**: entry points of entities to the system.
- **Process**: definition of how the entities interact with each location, and their routing rules.
- **Data Gathering**

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### Statistical Analysis of the Operational Data

The second step of the proposed method considers the construction of a more realistic model, where locations present delay periods due to maintenance or failure events. These periods are created as random functions in the model, based on the operational information available.

The operational information must be analyzed and refined, dismissing “outliers” and defining stable periods to assure a 95% confidence interval for the data. Maintenance and failure events of each location are classified, defining only the events that are directly related to the defined location. The interferences caused by other locations in the system are dismissed.

After processing the operational information, frequency tables of the “Time Between Failures” (TBF) and “Time To Repair” (TTR) of each location are created. By using statistical software, empirical functions are fitted to define TBF and TTR functions for the model. For both cases studied in this paper, the results show that most TTR functions follow the Pearson distribution, whereas TBF functions fit better the Log-Logistic distribution, as it is shown in Figure 1.

3. CONSTRUCTION OF THE CURRENT SITUATION CASE

In order to create a realistic simulation model, it is required to use a stochastic methodology that represents accurately the current situation of the studied facility.

### Monte Carlo Method

The operational statistics, previously analyzed and processed, is incorporated to the Ideal Case in the form of TBF’s and TTR’s functions, creating a Stochastic Model. The probabilistic nature of the simulation hence results in a variability range for downtime events (namely events that stop a location, make it unavailable for the transport of entities).

According to the Monte Carlo Theory (see [2] for example), the average of an estimated quantity obtained by a stochastic simulation should get closer to the real average of this quantity as the number of experiments increase. On the other hand, the Law of Large Numbers and the Central Limit Theorem state that the distance between the real and the simulated quantity (error) should decay to zero proportionally to \(1/\sqrt{n}\) where \(n\) is the number of replications. This theoretical bound is not very realistic, and in practice the error decay rate is much faster if a “good” random numbers generator is provided, which turns out to be the case of ProModel™ (by using the prime modulus multiplicative linear congruential random number generator \([8]\)).

In order to ensure that the difference between the average simulated quantity and the real average quantity is small, a stability approach is considered in the proposed methodology.

With this approach, the minimum number \(n\) of replications of the experiment to ensure a robust approximation can be determined. Basically, a fairly large number of replications are run to observe the evolution of the averaged quantities simulated of interest as \(n\) increases. After reaching a difference between the real and estimated quantity is smaller that 2% it is considered that the simulation is stable, and the minimum number of replications for the case studied is set.

### Calibration of the Current Situation Case

To validate the results obtained by the simulation model, a comparison between simulated and real control variables is performed. If the difference between these two values is bigger than 2% then the model needs to be calibrated. Since the input information of the model usually involves truncation of some
quantities, there is a certain degree of freedom to adjust the model parameters. These parameters are chosen to achieve an error of the approximation below 2% in every control variable. When the desired range of precision is reached, then the model is considered calibrated.

Sensitivity Analysis
After the calibration process is finished, a sensitivity analysis is carried out to measure the relative importance of the down time effect of each location on the global system. To determine the relative importance of some location, simulations are run considering all the downtimes of the system turned off but the one associated to the location of interest. The system throughput for each run is compared to the ideal case throughput. This methodology allows identifying bottle-neck situations in a specific location and detecting maintenance engineering improvement opportunities. The results of this analysis are summarized and displayed usually as a Tornado Chart.

4. CASE SCENARIO EVALUATION

Using the calibrated simulation model as starting point, improvement options can be simulated and evaluated, in order to maximize the plant throughput. Some potential scenarios to evaluate are listed as follows:
1) Improvement of availability and use of critical equipment, implemented through variations of the TBFs and/or TTRs.
2) Adding new accumulation and/or process units.
3) Variation of other model parameters such as mine production rate or maximum treatment capacity of certain equipment.

The study of improvement alternatives is the most interesting and valuable part of the whole process, since the throughput increase produced by proposed alternative is quantified, with no modification of the real system. Given the complexity of the plant, the outcome of these simulations is not easy to predict because of the non-linear stochastic nature of the system, making this methodology remarkably useful for management decisions. Furthermore the investment/profit of each scenario is estimated by using available benchmarking information. The most cost-effective improvement option is therefore determined.

In order to evaluate the proposed methodology, two case studies are presented, where the main concern is to increase the current ore throughput of the system with the minimum investment.

5. CASE STUDY Nº1: AN EXISTING COPPER CONCENTRATION PLANT.

The first case study is applied to an existing large copper concentrator plant in Chile. The industrial complex receives ore from an underground mine and produces copper concentrate. Figure 2 shows a diagram of the principal process units considered for this case studied. The material flow starts from the mine, where ore is crushed and transported by a series of conveyors belts and bins to the mill site. There are several kilometers of distance between the crushing and milling sites, therefore the importance of the conveyor system is emphasized. The processed mineral has two possible grinding paths. The preferential path considers a grinding system associated to a semi-autogenic (SAG) mill. If this line capacity is full, a secondary path is utilized (secondary/tertiary crushing circuit). The secondary crushing circuit consists of a secondary crusher, in which the fine ore is ground to a finer size. If it does not meet the size requirements, it is sent to a tertiary crushing system and is screened again. A single large ball mill helps to decrease the particle size of this circuit. The ore produced from both grinding paths feed the semi autogenic mill where water is included to form slurry, to later proceed to the flotation process. The flotation process separates minerals by taking advantage of differences in their hydrophobicity prior to refinery process.

The model was built following the design information for each unit process. The statistical operational information was provided by the plant’s management, which accounts for about 500 labor shifts. The failure and maintenance data was analyzed and filtered. The duration and frequency of each equipment’s down time was analyzed according to the different types of failures. The statistical analysis was carried out consistently to the process blocks considered for this study, and condensed into TBF and TTR functions for each process unit. The daily flow through Bin A was chosen as a control variable, as well as the ore feed to both mills. Other quantities of interest were also computed, such as the average total days a month for which the system’s total production is over a certain threshold fixed value, and the utilization factor of critical equipment. These last variables allow a better understanding of the system and serve as a comparison tool between alternatives, rather than validation or calibration purposes.

After the stability analysis and calibration process, the current situation model was run. Several improvement alternatives to the current situation model were evaluated:

Case 1: Using the current situation model, a slight increase in Bin A capacity was considered.
Case 2: Built up from Case 1, adding an improvement of programmed maintenance of critical equipment.
Case 3: Built up from Case 2, adding a major improvement of the availability of the largest conveyor in the system.
Case 4: Built up from Case 2, adding a slight improvement of availability of the largest conveyor in the system and new Bin parallel to Bin A.
Case 5: Built up from Case 4, adding a major improvement of capacity to the SAG Mill’s Bin.

The results of these simulations are summarized in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Flow through Bin A</th>
<th>Comparison against Current Situation Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>104%</td>
<td>3%</td>
</tr>
<tr>
<td>Case 2</td>
<td>109%</td>
<td>8%</td>
</tr>
<tr>
<td>Case 3</td>
<td>112%</td>
<td>12%</td>
</tr>
<tr>
<td>Case 4</td>
<td>113%</td>
<td>13%</td>
</tr>
<tr>
<td>Case 5</td>
<td>116%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 1. Case Study Nº1 Results.

After an economic evaluation, Case 4 was selected due to its large increment of ore throughput (13%) and its reduced cost estimation (in comparison with Case 5, which presents a larger flow increment).

6. CASE STUDY Nº2: AN EXISTING HYDROMETALLURGICAL PLANT’S DRY CRUSHING AREA.

The proposed methodology was also applied to study an existing hydrometallurgical plant’s dry crushing area, which is depicted in Figure 3. In this case the ore is fed directly into the feeders at the primary crusher, which are located at the entry points of the plant. The ore processed by the primary crusher is carried by conveyor to the secondary crushing process where it is previously screened. Particles fine enough to bypass the...
secondary crushing process go directly onto the grinding process, while large pieces of ore are crushed by the secondary crusher. If the ore is still oversize, it is sent to one of two tertiary crushers and continues in this cycle until the particles are fine enough to pass through the screen and enter the agglomeration process. Once the ore is sufficiently fine, it is conveyed to the fine ore bins and is stored. Later on it is sent to the agglomeration tank, where water and sulfuric acid are added to be piled up in lixiviation heap. The produced solution goes later to a solvent extraction-electro winning system to obtain copper cathodes.

The information used in the operational statistical analysis accounts for one year of operation. The definition of the process’ block arrangement is motivated by the format of the statistical information of maintenance and failure. The plant’s throughput is usually measured in one of the conveyors, hence a control variable was created to measure the flow through this block, and it was also used as the calibration parameter.

The stability analysis and calibration process were followed by the sensitivity analysis, where the importance of the relative influence of each block of equipment down time effect on the system was measured. The associated tornado chart is shown in Figure 4.

After defining the current situation model, it was run and its results defined the actual ore throughput of the system. Several alternatives were proposed to increase the system’s throughput:

**Case 1**: This case considers: increase of power/velocity of several conveyor belts, increase of ore feed to the system and construction of a second agglomeration tank.

**Case 2**: Built up from Case 1, adding a new conveyor identical and parallel to the existing one, for receiving the undersize of the secondary sieve.

**Case 3**: Built up from Case 2, adding the use of more explosives in the mine, the so-called “Mine-to-Leach”.

**Case 4**: Built up from Case 3, adding a new sixth tertiary screen.

**Case 5**: Built up from Case 1, adding a large stock pile right after the primary crusher.

**Case 6**: Built up from Case 1, adding a new complete third line of secondary crushing.

**Case 7**: Built up from Case 1, adding a second fine ore silo parallel and similar to the existing one.

**Case 8**: Defined as a combination of Cases 4 and 5.

**Case 9**: This case summarizes all the proposed improvements options with the exception of the large stock pile.

**Case 10**: It contains all the modifications described in all the cases.

The results of the simulations of all the cases are summarized in Table 2.

<table>
<thead>
<tr>
<th>Operational Value</th>
<th>System’s Throughput</th>
<th>Comparison against Current Situation Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Situation</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Model</td>
<td>98%</td>
<td>-</td>
</tr>
<tr>
<td>Case 1</td>
<td>105%</td>
<td>7%</td>
</tr>
<tr>
<td>Case 2</td>
<td>106%</td>
<td>8%</td>
</tr>
<tr>
<td>Case 3</td>
<td>106%</td>
<td>8%</td>
</tr>
<tr>
<td>Case 4</td>
<td>113%</td>
<td>15%</td>
</tr>
<tr>
<td>Case 5</td>
<td>110%</td>
<td>12%</td>
</tr>
<tr>
<td>Case 6</td>
<td>108%</td>
<td>10%</td>
</tr>
<tr>
<td>Case 7</td>
<td>108%</td>
<td>10%</td>
</tr>
<tr>
<td>Case 8</td>
<td>118%</td>
<td>20%</td>
</tr>
<tr>
<td>Case 9</td>
<td>116%</td>
<td>18%</td>
</tr>
<tr>
<td>Case 10</td>
<td>119%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Table 2. Case Study N°2 Results.

7. CONCLUSIONS AND FINAL REMARKS.

The described methodology can be used not only by the Chilean mining companies but also for others. The mining processing plant optimization model can be used as a general production planning tool for any mine-mill operation. Optimization of the existing system can be evaluated, and investment/operational decisions can be supported. The model is flexible enough to have different arrival rates from mine production, and inventory capacity limits. It also can model different kinds of processing/transporting units.

The proposed improvement options evaluated for the two studied cases represents an increase up to 20% of the production throughput, which implies close to 20% of production increase (cathodes or copper concentrate), but normally more than 25% of revenues. To the best of the authors’ knowledge, the application of this methodology is unprecedented in the copper mining industry in Chile and South America and represents a powerful tool for designers and decision makers in the mining industry.

REFERENCES


Figure 1: TTR or Down-time duration (a) and TBF or Frequency (b) Example.

Figure 2: First Case Study. Mine-Mill Process. Copper Concentration Plant.
Figure 3: Second Case Study. Dry Grind Area. Hydrometallurgical Copper Plant.

Figure 4: Sensitivity Analysis for Different Equipment Down-Time.