Discrete Event Simulation of an Iron Ore Milling Process

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Abstract

One of the most common techniques for studying a system's behaviour, predicting its outputs and anticipating challenges along the way is simulation. This is a very powerful technique, especially when uncertainty and time-varying parameters are involved. Numerous simulation studies have been conducted on the material processing plants. Simulation and modelling of mineral processing systems focuses on design and optimization of circuits and machine performances. The focus of this project is on simulating the interactions between interior components of a plant using a discrete event approach. An ordinary iron ore processing plant, with several comminution and separation stages, is considered for simulation. The system here involves a continuous process, but it is supposed to be modeled as discrete events. One way is to use the batching approach and consider one hour's worth of material fed into the plant (or that of any other time period) as an entity flowing through the model. The model is developed in Arena simulation software. The goal is to get an understanding on the quality of the output and the effects of the uncertainty in input parameters and operations on it. Therefore, recoveries, processing times, capacities and etc. are selected based on the authors' experience, in an effort to mimic a real plant while avoiding complications.

1. Introduction

Mining is the process of extracting raw materials from the ground in a profitable manner. It usually consists of five major steps: prospecting and exploration, development, exploitation, mineral processing and reclamation. The oldest known mine dates back to 43,000 years ago in southern Africa, where pre-historic humans started to extract iron from a near surface mine (Newman et al., 2010). Since then people have been looking for mines and extracting material from them. A wide range of extraction procedures such as truck-shovel systems, underground mining, block caving and continuous bucket wheel excavations have been developed and implemented all over the world. The most common and best-known technique is the truck-shovel operation used in open pit mines. This technique is also used for extracting iron ore; shovels dig into the ground and dump the material onto the back of the trucks. Rocks are then delivered to plants where further processing activities such as grinding, classification, purification and concentration are done and the material becomes ready to be sold in the market. The purified product is then shipped to various destinations but mostly used for making steel.

The main goal of any mining operation is to maximize profits. The processing plant is the site where the mineral dressing or ore dressing, which is the process of separating commercially valuable minerals from the ore, is completed. Customers who wish to buy the product have a set of requirements for its properties, such as minimum metal grade, maximum deleterious material and even the tonnage of concentrate needed to be delivered on time. On the other hand, increasing the concentrate metal grade and decreasing deleterious content leads to larger amounts of tailings and lost metal, as well as to higher costs. Finding the trade-off, which enables the company to make the highest level of benefit and managing the mineral processing plant such that the desired output and costs are achieved, is a complex and challenging activity. Therefore, studying the plant is of great value. Another property of a processing plant is the variety of machines involved in concentrating the product. All of these machines impose uncertainty because of their operations characteristics as well as their failures. The uncertainty in characteristics of the rock delivered to the plant also increases the process uncertainties and makes things even more complicated.

One of the common techniques for studying a system's behaviour and predicting its outputs and challenges on the way is simulation. This is a very powerful technique, especially when uncertainty and time-varying parameters are involved. There are some fairly comprehensive software packages, such as MODSIM (Mineral Technologies International), USIM PAC (BRGM) and JKSimMet (JKTech), which nowadays are used to simulate mineral processing plants. These software packages are based on predefined models, which predict a plant's outputs for the specific input data range. The models need to be calibrated on a case-by-case basis. The outputs need verification and validation because of the complex nature of the ore and some unique characteristics of each mine.

This project aims at modeling and simulating the behaviour of an iron ore magnetic separation plant using discrete event simulation. The goal is to gain an understanding of the quality of the output and the effects of the uncertainty in input parameters on the output variables. A brief review of the previous work done on mineral processing simulation is presented in the next section. The third section defines the system of interest for modeling. The proposed approach and the modeling procedure are described in fourth and fifth sections respectively. The verification process is then presented and the output results of the model on synthetic data are presented. The conclusion and future work are discussed in the final section.

2. Literature review

Several simulation studies have been conducted on mineral processing plants. Simulation and modeling of mineral processing systems focuses on the design and optimization of circuits and machine performance (Lynch and Morrison, 1999). The first studies were intended to propose equations representing relations between various parameters of the system. The concepts of modeling and simulation for mineral processing were introduced after the 1960s. Developments in the capabilities of computers in the 1980s helped researchers conduct vast studies on the models and observe deficiencies of the models, through the use of computer programs and simulations (Lynch and Morrison, 1999). These studies can be categorized into two main groups: standalone machine simulations and plant simulations. Most of the simulation studies belong to the first group, in which researchers try to mimic the behaviour of a specific machine based on experiments and computer simulations. The idea behind the second group of studies is to analyze the plant as a single system consisting of various machines and investigate the interactions among components of the system. However, one may only be interested in studying the whole plant as a system and investigating the relationships between inputs, outputs and operating conditions of the plant instead of a machine by machine study. The focus of this project is on simulating the interactions between interior components of a plant.

Standalone machine studies have been conducted widely on grinding machines, separators, classifiers, etc. Austin et al. (2007) simulate wet ball milling of iron ore using laboratory scale tests. Another study conducted by Wang et al. (2009) investigates the grinding process within vertical roller mills. Pothina et al. (2007) propose a model to relate impact parameters to energy consumption in gyratory crushers. Dlamini et al. (2005) simulate the hydrocyclone to obtain physically realistic velocity and pressure profiles. Morrell and Man (1997) use computer simulation as well as existing plant data to design full-scale ball mill circuits. Sosa-Blanco et al. (2000) develop a simulation model for tuning a grinding circuit with the objective of optimizing a flotation plant. Another simulation of a grinding plant is conducted in Duarte et al. (2002), in which the authors use simulation to compare five control strategies in a copper grinding plant. A simulation study on the control parameters of flotation columns can be found in Bergh and Yianatos (1995). For a complete review of models for column flotation, the reader can consult the study by Bouchard et al. (2009).

One of the first simulations of the ore processing plant was done by Ford and King (1984). De Andrade, Lima and Hodouin (2006) performed another simulation study, which falls into the second category. The authors of this paper simulate cyanide distribution in a gold leaching circuit. A simulation design which treats the processing plant as a whole and suggests an approach for measuring and managing variations in a mineral processing plant is proposed in Robinson (2003). Fourie (2007) also proposes a modeling approach for studying any metal separation circuit (flotation, magnetic separation or electrostatic separation). Delgadillo et al. (2008) integrate the grinding machines along with the classifiers and magnetic separators and simulate the combination in a magnetite plant.

3. System definition

In this study, a whole processing plant simulation modeling approach is followed. The study focuses on modeling an iron ore magnetic separation processing plant in Arena discrete event simulation software (Rockwell Automation). A typical iron ore processing plant, with several comminution and separation stages, is considered for simulation. The flow sheet of the process is illustrated in Fig 1.

The plant receives run-of-mine (ROM) as trucks dump loads with specific tonnage and known metal grade into the primary crusher (in this case a Gyratory crusher); the crushed materials are carried to the stockpile through feeders and some conveyer belts. The plant's main stockpile serves as ore feed storage for all process stages.

In the next stage, ore with a known tonnage rate per hour is fed to the size reduction section. The final output of this section is two streams of ore with restricted particle size distributions (one in the range of 20 to +10 mm and the other in the range of -10 mm) and a tailing stream with particles finer than 3 mm (which is supposed to have a lower iron content and higher sulfur and phosphor grades). An Auto Genius mill and a secondary crusher are considered in this area.

Ore coming from the size reduction section is fed to the dry low magnetic separator (LMS) and dry high magnetic separator (HMS) in the order depicted in Fig 1. The final output of the dry separation section is a mixed concentrate, which is fed to the wet plant, and a tail material which is sent to the dry tailings dump.

At the beginning of the wet separation area (mixing upgraded ore with water), a closed circuit grinding mill with hydrocyclone is included to grind the material down to -2.5 mm in order to achieve higher degree of freedom of materials. The ore is divided into a higher grade material and a wet tail in wet HMS, which is disposed of in the wet tail dam. The final concentrate of the process line is obtained after meeting one more size reduction stage in a ball mill (minus 1mm) and a wet LMS machine. Both the tail and the final concentrate may need to go through the thickener, the filter, the dryer and the pumping station before settling in their final points.

The approach of this study is to simulate and trace the material characteristics through the different stages of the processing plant, from the point that material is delivered to the plant from the mine (with trucks feeding the Gyratory crusher) to the four exit points of the process defined here. The main ore feed tonnage, its rock type and its respective three grades (Fe, S and P) can be defined as inputs of the system. The main parameters of importance in output streams of materials are the recoverable tonnage in each of four system exit points and the iron, sulfur and phosphor grade in each stream.

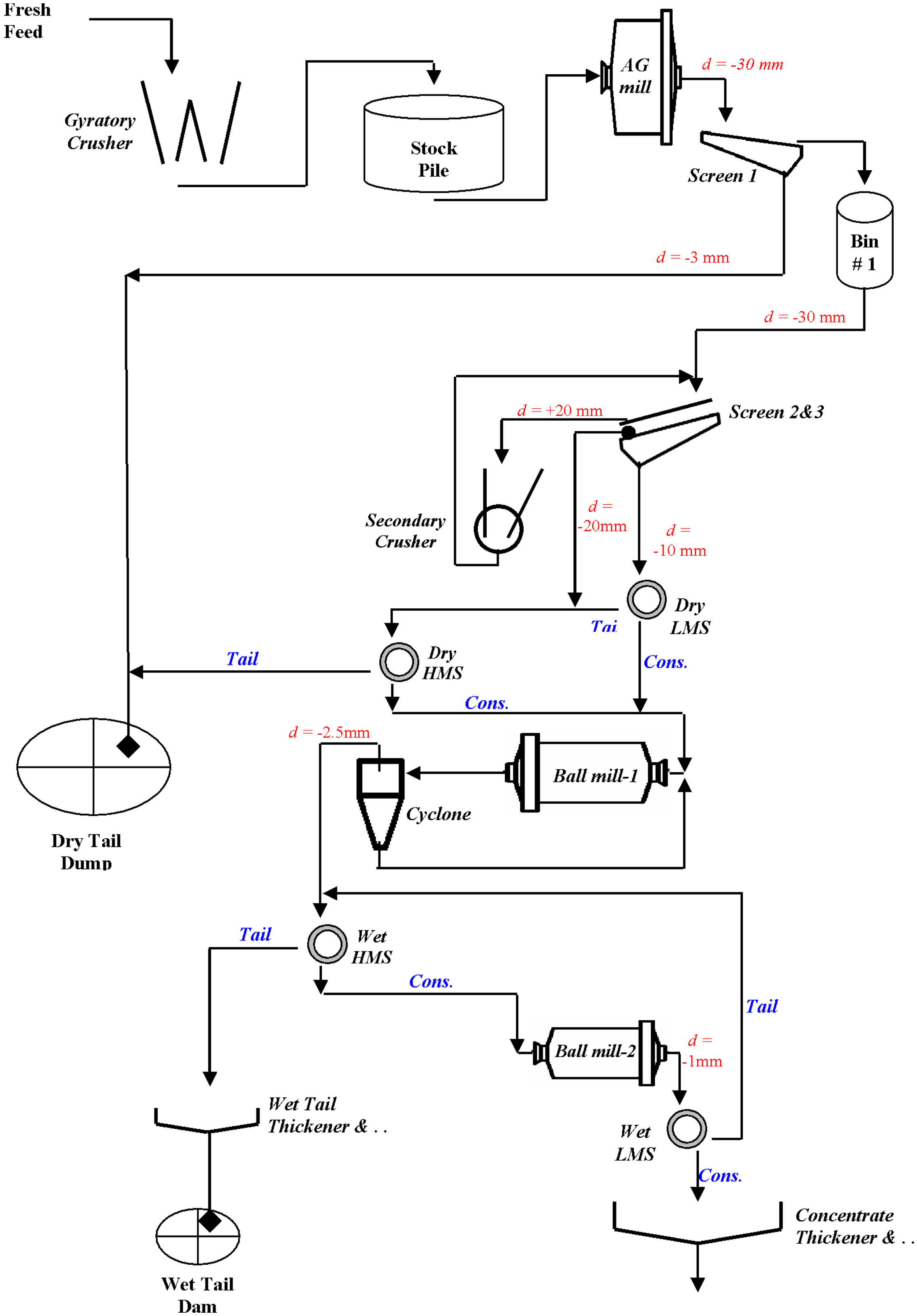

Fig 1.Hypothetical magnetic iron ore separation process flow sheet

4. Modeling approach

Among all the machines used in the processing plant, the ones which have direct effect on the recoveries and performance of the system are considered to be system modules in the simulation. The other facilities do not affect ore characteristics, but still have an effect on plant operations. So whenever it is possible, their positive or negative effects (such as failures, capacity restrictions, etc.) are added to the specifications of the corresponding main machine (e.g. conveyer belts).

The system here is a continuous process, but this project seeks to model it as discrete events. One way to do so is to use the batching approach as introduced in Lu et al. (2007), considering one hour's worth of material fed into the plant (or that of any other time period) as an entity flowing through the model. In order to make the simulation more realistic, the production of each part is stopped if any of the machines in that division fails, if the bin which feeds the plants gets empty, or if the bin at the end of the plant fills up.

Considering the process flow sheet and parameters of interest, facilities can be categorized into four main groups:

1. Storage bins and piles
2. Comminution machines
3. Classifiers
4. Separators

In the next part, the specifications of each group which are important from the simulation point of view are discussed.

4.1. Storage bins and piles

In all mineral processing plants there is a need to consider some storage areas as bins or stockpiles to keep 4-5 days of plant feed. These stockpiles/storage bins are used to store material between different stages of the processing plant in order to avoid unexpected shutdowns of the whole plant. Also, the presence of stockpiles/storage bins assure continuation of material flow in the downstream processes, when for any reason the upstream is shutdown for a short period of time. These storage bins can be considered to be shock absorbers of the processes.

Throughout this study, bins and stockpiles are modeled by tank module, to store ore material tonnage and grade and extract from it whenever process line needs feed material as representative entities. In order to keep track of the material's grades in each bin, the average weighting method is used, i.e. the material is blended in each bin and input batches are not recognizable among the outputs. The material content (level) of the tank (tonnage) is calculated based on the receiving entities tonnage (adding) and the exiting entities tonnage (subtracting). The tank grade (as a weighted average) of each species is defined by the following equation:

$$\left(AverageTankGrade\right)_i = \frac{\left(TankLevel \times TankGrade_i + EntityTonnage \times EntityGrade_i\right)}{\left(TankLevel + EntityTonnage\right)} \qquad (1)$$

where i can be Fe, S or P. It is also possible to consider limited capacities for each bin, when defining them as tank modules in Arena to avoid the accumulation of material in the plant when the next processing step is out of order because of a fault. On the other hand, if a bin runs out of material, the next part of the plant has to be stopped until a certain level (tonnage) of material accumulates in the bin.

4.2. Comminution machines

Comminution machines play an important role in mineral processing plants. In fact, it is not possible to recover any mineral or metal from ore without comminuting it down to a proper size (reaching the acceptable degree of freedom). Two types of comminution facilities are considered in this flow sheet (Fig 1). First there are some crushers which are designed to deal with coarse particles of ore. The second type of size reduction facilities considered here are mills. Mills usually deal with finer feed size in comparison with crushers, and they also grind the material to much finer particle sizes.

Regardless of all designing and operational conditions, it is important to have an idea about two main parameters of size reduction machines in order to have a correct model in the Arena simulator and to achieve a reality-mimicking model. First, one should consider when and how frequently they are out of order. This can be used as the failure schedule in the model. The second important point related to these facilities is the particle size distribution (PSD) of the discharge material. The minerals' degree of freedom, which defines the recovery of metal and grade of the concentrate, is strongly related to the PSD of feed stream to a separator.

The discharge PSD of the materials is affected by various parameters in a size reduction machine. Some of the main affecting parameters are: rock hardness, mineral size and type, dominant comminution mechanism, machine operational condition and ball content, the ratio of ore to ball and the amount of water in the mill.

Various functions, models and procedures have been developed to describe the discharge PSD for any specific type of crusher or mill; they can be categorized into two main groups. The first category contains those which are determined based on experiments and correlations of the results to a logically proper model. The second group of models is proposed based on empirical functions. Here, too, the discharge PSD of several rock types fed to a special kind of size reduction machine is examined to determine some constant coefficients. None of these methods can predict the exact PSD of the comminution machine, but they can still obtain a reasonable PSD of the discharge material in each case.

In this study, as no experiment is performed, two famous predicting functions for discharge PSD of size reduction machines are considered: the Gaudin function and the Rosin-Rammler function. The Gaudin function is used for crushers, as in Eq. (2).

$$w = 100\left(\frac{d}{n}\right)^{m} \tag{2}$$

Where w is the weight cumulative percent of the particles with diameter of d or smaller size and n and m are model constants effecting the PSD range. For each machine, different n and m are defined according to the desired coarse particle size-.

Rosin-Rammler function is used for any of the mills discharge PSD. a and b are model constants. Considering the desired coarse particle size, different n and m are defined for each machine individually.

$$100 - w = 100 \times \exp\left(-\left(\frac{d}{a}\right)^{b}\right) \tag{3}$$

4.3. Classifiers

Classifiers are used to separate particles based on physical properties such as size, density, shape. Two types of classifiers, screens and hydrocyclones, are placed in the aforementioned plant flow sheet (Fig 1). Some of them merely separate or dispose a portion of materials, while some are placed so as to create a close grinding or crushing circuit. There are some advantages to using such a circuit, including lower energy consumption per ton of fragmented ore down to a specific size and lower fine particle (over ground particles) production in comparison with the equivalent open circuit fragmentation. Design quality also affects their industrial (actual) performance to a great extent. Some of the important parameters in classifier designing procedure are: dry or wet operation, feeding rate, shape and density of particles, proportion of open area (in screens) and slurry feed pressure (hydrocyclones).

From the simulation point of view, one needs to trace particle size range in feed, over flow, and under flow. Tonnage and grades of over flow and under flow streams should be traced as well. The mean time between failures (MTBF) and mean time between repairs (MTBR) for the classifiers must be taken into account in the simulation modeling based on the historical data. The MTBF and MTBR should be considered for the classifier itself, and for supplementary instruments such as belt conveyors, pumps, feeders and slurry tanks.

In the simulation model, output tonnages are determined based on feed tonnage and particle size distribution. Also, the PSD of the outputs of classifiers are determined based on the input feed PSD and linear interpolations. It is assumed that the grade of the ore in over flow and under flow of the classifier is not the same as the input feed. Therefore, using the R_g concept (to be discussed later) and considering each classifier as a separator of the metal, the metal content of each stream is determined.

4.4. Separators

Separators in mineral processing plants play a significant role in the mineral processing flow sheet design. For any kind of separator, the machine recovery and concentrate stream grade are two of the most important parameters that managers in plants are interested in knowing and controlling. In the assumed iron ore separation flow sheet (Fig 1), two types of magnetic separators in both operational conditions (wet and dry) are considered. High intensity magnetic separators (HMS) and low magnetic separators (LMS) are classified under the category of physical separators. As the category name suggests, in such separators we deal with inherent physical properties of minerals (magnetic property of iron minerals) much more than their chemical properties.

There are many parameters affecting magnetic separators recovery. The metal recovery of a magnetic separator (either low or high intensity) can be affected by various parameters such as particle size of material fed to the machine; mineral's degree of freedom; metal carrying (ore) type; magnetic intensity of the machine; physical and operational characteristics of the machine; bed thickness of material fed to machine in dry magnetic separators and solid content of slurry fed to machine in wet separators.

For modeling purposes it is necessary to define a function for metal recovery, and a function for determining what weight percentage of the materials should go to concentrate stream or tail stream. Logically, these functions should be defined based on grade, mineral type and particle size distribution of the feed. But since there are no experimental data available, an acceptable constant metal recovery (R_g) and concentration ratio (CR) for each separation machine is defined. At this step of simulation, it is possible to calculate all mass balance related parameters for each machine output stream.

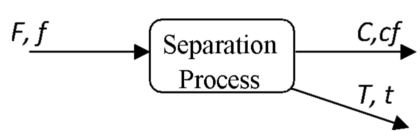

Fig 2.A schematic separator

Considering Fig 2, if F, C and T are defined as feed concentrate and tail tonnage, and f, c and t as feed concentrate and tail metal grades respectively, R_g and CR can be defined as in Eq. (4) and Eq. (5).

$$R_{g(i)} = \frac{Cc}{Ff} \tag{4}$$

$$CR = \frac{F}{C} \tag{5}$$

i stands for iron, sulfur or phosphor. Having $R_{g(i)}$ and CR, concentrate and tail parameters for all separators can be calculated using Eq. (6) to Eq. (9).

Concentrate tonnage: $C = \frac{F}{CR}$ (6)

Tail tonnage: $T = F - C$ (7)

Concentrate grade of species: $c_i = R_{g(i)} \times CR \times f_i$ (8)

Tail grade of species: $t_i = \frac{F \times \left(1 - R_{g(i)}\right) \times f_i}{T}$ (9)

5. Modeling

The model is developed in Arena simulation software (Rockwell Automation), version 13.00. The plant is separated into 4 divisions which are shown schematically in Fig 3 to Fig 6. Recoveries, processing times, capacities etc. are selected based on the authors' experience and are presented in Tables 1 to 4. All of the machines on the processing line are assumed to have the same capacity, which means that the processing time for each batch on each machine is calculated as the tonnage of the batch divided by the hourly production capacity of the line.

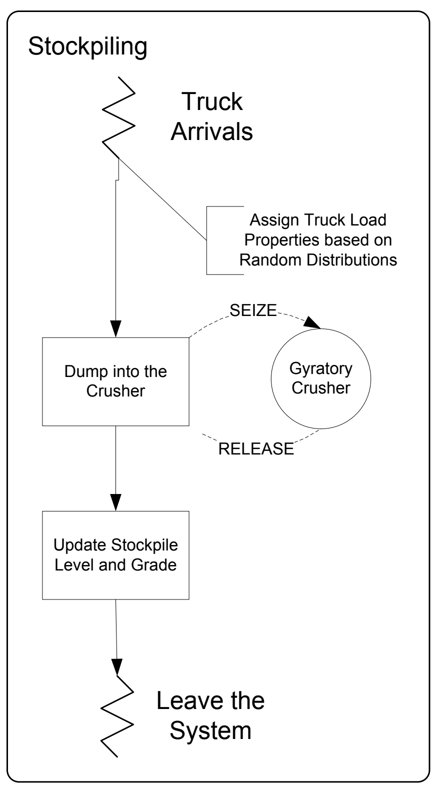

Fig 3.Truck Arrival Section

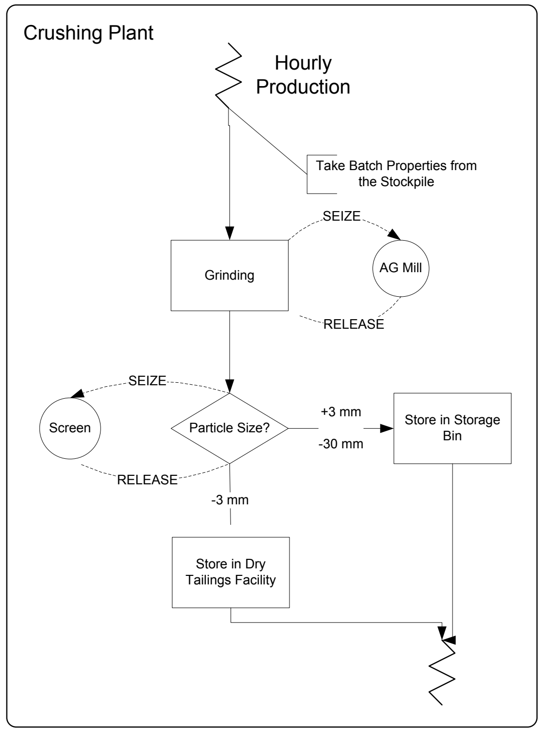

Fig 4.Crushing Plant

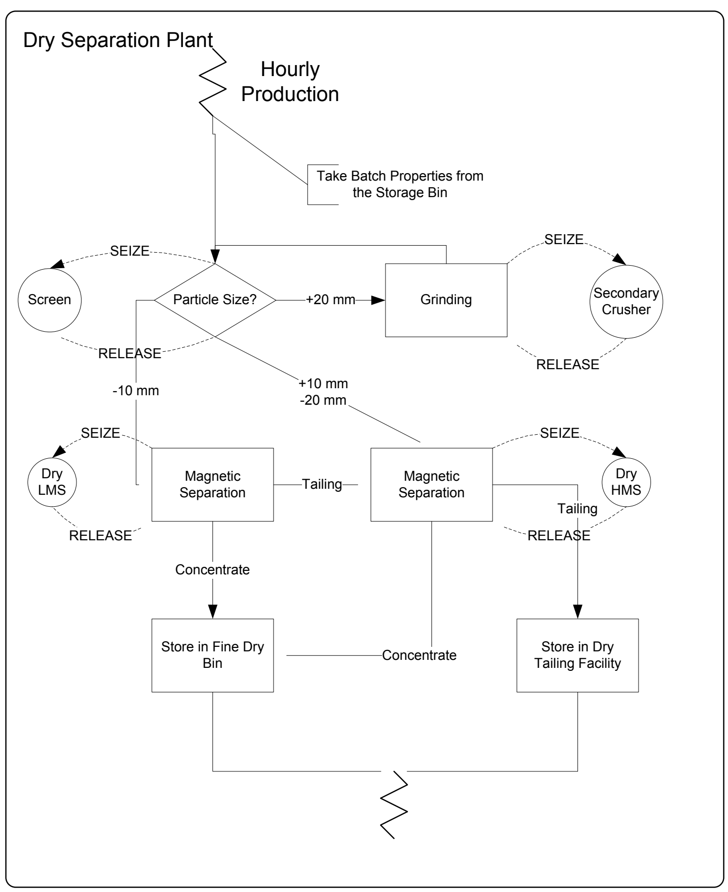

Fig 5.Dry Separation Plant Part 1

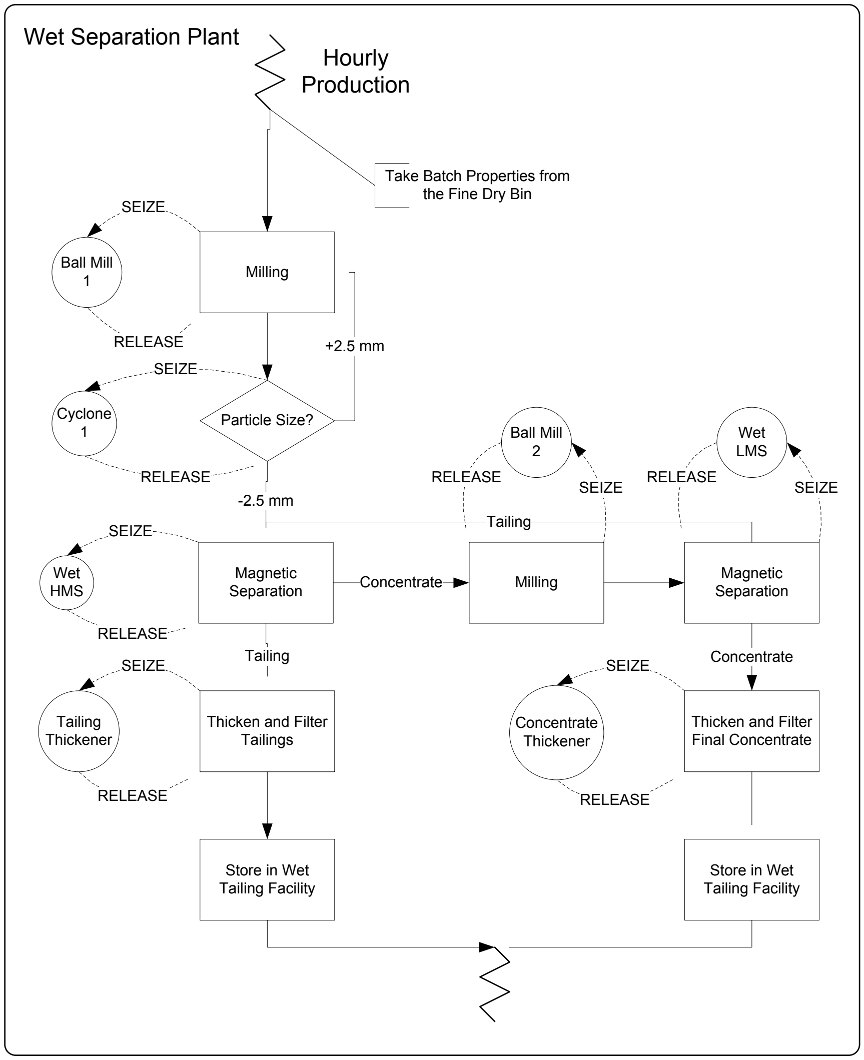

Fig 6.Wet Separation Plant Part 2

Table 1.Production Rates

Trucks Inter Arrival Time	Truck Load	Crushing Plant Production Rate	Dry Plant Production Rate	Wet Plant Production Rate
9 mins	NORM(200,10) tonnes	TRIA(950,1000,1050) tonnes	TRIA(830,860,900) tonnes	TRIA(670,710,750) tonnes

Table 2.Machine Failures

Failure	Resource	Uptime (days)	Downtime (days)
fOverhaul	All	355	10
fGyratoryCrusher	rGyratoryCrusher	59	1
fSAGMill	rSAGMill	9.6	0.3
fSAGMill2	rSAGMill2	175	7
fScreen1	rScreen1	59.6	0.3
fScreen2	rScreen2	9.6	0.3

fCrusher	rCrusher	89	1
fLMS	rLMS	29.8	0.2
fHMS	rHMS	19.8	0.2
fBallMill1	rBallMill1	89.6	0.3
fCyclone1	rCyclone1	29.6	0.3
fBallMill2	rBallMill2	179.6	0.3

Table 3.Recoveries

Machine	CR	Rg Fe	Rg P	Rg S
Screen1	-	TRIA(0.97,0.98,0.99)	TRIA(0.50,0.60,0.70)	TRIA(0.60,0.70,0.80)
Screen2	-	TRIA(0.35,0.40,0.45)	TRIA(0.60,0.70,0.80)	TRIA(0.50,0.60,0.70)
Dry LMS	TRIA(1.60,1.70,1.80)	TRIA(0.90,0.92,0.94)	TRIA(0.25,0.30,0.35)	TRIA(0.30,0.35,0.40)
Dry HMS	TRIA(1.30,1.35,1.40)	TRIA(0.92,0.94,0.96)	TRIA(0.25,0.30,0.35)	TRIA(0.30,0.35,0.40)
Wet HMS	TRIA(1.30,1.35,1.40)	TRIA(0.90,0.92,0.94)	TRIA(0.18,0.20,0.22)	TRIA(0.10,0.15,0.20)
Wet LMS	TRIA(1.30,1.40,1.50)	TRIA(0.80,0.82,0.84)	TRIA(0.09,0.10,0.11)	TRIA(0.09,0.10,0.11)

Table 4.Bin Capacities

	Stockpile	Storage Bin 1	Fine Dry Bin	Concentrate Bin
Capacity	5 days of plant operation feed (120,000 tonnes)	1 days of downstream operation feed (24,000 tonnes)	Unlimited (10,000,000 tonnes)	Unlimited (100,000,000 tonnes)

6. Model verification

The developed model is run for a pilot evaluation and verified using synthetic data. Since the objective of the study is to track the grades and tonnages of material, a limited amount of rock with constant grades is fed into the plant and the changes in its grades and tonnages are studied. In order to verify the model and make sure that all of the tonnage and metal content of the feed is retrieved at either of the system outputs, a 24-hour run is considered. In this case, the trucks are scheduled to arrive in constant 2 hour periods with 200 tonnes of rock. In order to make sure that no material is inside the system when the simulation terminates, the number of created trucks is limited to 10, which leaves 2 hours free of input, during which time the system can process existing entities. All material carried by the trucks are assumed to have a constant metal grade of 40 percent and 0.2 and 1.5 percent for phosphor and sulfur respectively. The verification results are summarized in Table 5.

Table 5.Model verification results

	Feed	Screen1 Tailing	Storage Bin	D-HMS Tailing	Fine Dry Bin	W-HMS Tailing	Final Concentrate
Rock (tonnes)	2000	242	1758	293	1465	473	966
Metal Grade (%)	40	7		7		15	71.92
Metal Content (tonnes)	800	16		21		72	682
Phosphor Grade (%)	0.1	0.331		0.262		0.086	0.001
Phosphor Content	2	0.80		0.77		0.41	0.01
Sulfur Grade (%)	1.5	3.719		2.877		1.539	0.014
Sulfur Content	30	9.00		8.43		7.28	0.13

There is no change in grades or tonnages in the first part of the model (stockpile). Before the material is sent to the grinder from the stockpile, a screen separates very fine particles and sends them to the dry tailing dump. 242 tonnes of material are sent to the dump with the properties presented in Table 5 . Two other tailings can be identified at dry and wet HMS machines, which hold 293 and 473 tonnes of material respectively. The total amount of tailings and final concentrate is almost equal to the tonnage of feed to the plant. However, 26 tonnes of material are lost in the system. The explanation lies in the cycling load of the system. In order to avoid having an unlimited number of entities in the system, batches smaller than 0.2 tonnes are removed from cycles without having recorded anywhere. These two holes are responsible for the losses in the metal, as well as in the phosphor and sulfur contents.

7. Results

After verification, the model is run for 365 days with the failures and maintenance plans applied to it. The first day of the run is considered as warm-up and is not used in calculating statistics. In addition, uncertainty is added to grade, recovery and production tonnages. In order to have a more balanced production line, different batch sizes are selected for different parts of the model. The crushing plant is run with average production of 1000 tonnes/hr where the dry and wet lines are set to run with average rates of 880 and 735 tonnes/hr based on the tail and concentrate produced in each part. Approximately 8.1 million tonnes of rock are fed into the processing plant and 1.6 million tonnes of concentrate are recovered. This concentrate has an average metal grade of 70.15 percent. This means the overall recovery of the plant is approximately 86.6 percent. The results obtained are presented in Table 6 and Table 7.

Table 6.Tonnages and grades

Plant Divisions	Stockpile	Crushing Plant	Dry Plant	Wet Plant
Total Ore (million tonnes)	7.99	6.92	5.75	3.72
Average Metal Grade (%)	39.68	44.21	52.28	70.44
Average Phosphor Grade (%)	0.1183	0.0807	0.0361	0.0013
Average Sulfur Grade (%)	1.4670	1.1650	0.4852	0.0132
Average Working Time (%)	68.35	89.74	91.12	92.44
Average Residence Time (mins)	-	0.9	0.9	2.76
Total Waste (million tonnes)	-	0.95	1.15	1.82
Metal Lost (1000 tonnes)	-	62	82	277

Table 7.Bin Levels

	Stockpile	Storage Bin	Fine Dry Bin	Concentrate Bin
Capacity (tonnes)	120,000	24,000	2,000	10,000,000
Average (tonnes)	2183	765	194	0
Maximum (tonnes)	4338	949	548	90

8. Conclusions and future work

The study shows that we can simulate a mineral processing plant, which is a continuous process, as a combination of continuous and discrete events by assuming batches of feed as entities through the system. The batching strategy seems to be the best method of dealing with continuous systems, but it is important to be careful about batch size definitions. During this step, using some simple assumptions for separation mechanisms, we could trace all materials along the process line; and in the end, we came to the same sum of material introduced into the plant at four exit points. The experience shows that it is difficult to use many equations in Arena models (Assign modules). In such cases we can integrate Arena with some other powerful mathematical software.

The most important step for future work is to develop the model based on real processing plant data and to use mine plans for scheduling the material delivered to the plant. The next step is to study a real plant and come up with better failure and uptime distributions. Additionally, it is possible to balance the processing line and calculate appropriate processing times based on machine capacities.

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