A perspective on modelling and simulation engineering

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The modern approach to simulation and scale-up techniques demands detailed characterization of the ore. The underlying idea is no different from what has been practiced in mineral processing since the first half of the 20th century. Gaudin's Principles of Mineral Dressing contained basic ideas of crushing and grinding laws, a liberation model, an industrial screening model, a classification model based on well-developed settling laws, gravity separation model, a magnetic separation model and a chapter on “flotation physical aspects” separated from the “flotation chemical aspects”, which is a way of modeling flotation for a given “chemical” condition.

In order to put current versus old in perspective, let us take the ball mill operating in closed circuit with a classifier. At the time of Gaudin, Kick’s grinding law had been disproved, and all that remained was Rittinger’s law. Soon later, Bond’s law became the standard method of accessing grinding efficiency. However, Bond’s law is too simplistic a concept to illustrate what Bond really accomplished at Allis-Chalmers. Bond used a basic engineering principle, which is to derive a scale-up relationship from a similarity test and an existing database of industrial grinding parameters of Allis-Chalmers ball mills. The similarity test became the standard Bond test, which is used until today for comminution characterization. The test consists of a locked cycle test with a given screen opening and the amount of grinding is bound by a circulating load of 250%. The resulting grinding demand (number of rotations required by the standard mill) produces the well-known Bond BWI, a scale-up parameter that is characteristic of the ore that is being tested. Later in the second half of the 20th century, the size-mass balance models were developed for comminution machines. These methods require more parameters to describe two fundamental processes: the rate of breakage and the appearance function. Instead of a similarity test, a fundamental test is required to determine the parameters that are needed. The test procedures are simple and flexible and no standard mill is required, however computer software is required to determine the parameters from the test results and to simulate/scale-up the grinding circuit operating under any condition that can be conceived. Furthermore, liberation models were developed that allow the liberation process that occurs during grinding to be simulated along with the particle size reduction. Going back to the beginning, Gaudin’s liberation model is the first sketch of the currently available liberation models, and it was intended to be used in the same sense, although Gaudin probably never imagined that this stage of development would be reached someday. Further along in time, DEM models appeared at the end of the 20th century, and a fundamental comminution model started to take shape. Who knows if or when this will include liberation and a particle-by-particle breakage simulation along with charge motion and all the physical phenomena that is part of the system.

With this perspective in mind, it is possible to consider that an optimum a processing route can be established for a given mineral processing plant. There are literally innumerable scenarios with every peculiarity that each case may contain. In order to illustrate “where we are” it is better to use a base case, such as the case of a typical copper porphyry processing plant. This will include crushing, grinding and flotation (and solid-liquid separation but for sake of
simplicity this is not going to be included here, although it is equally important from the sustainability point of view).

A generic processing plant could be illustrated by the flowsheet in Figure 1. The traditional design contemplates three stages of crushing followed by the grinding circuit with a ball mill. The flotation plant has a regrind ball mill also in closed circuit. The regrind circuit adjusts the liberation of the coarse particles in the rougher concentrate. If this is a processing plant in the middle of the 20th century, there would be many lines as the equipment were very small with equally small capacity. The engineer would have designed the plant with a knowledge of the Bond BWI, CWI, AI, bench flotation tests and pilot tests and mineralogical information with a “measured degree of liberation”. Column flotation did not exist and there were no alternatives for the crushing/grinding stages. In operation, mineralogical information was available sporadically, and chemical assays were carried out regularly. There was no automated control system but the plant would have many sampling points and a busy lab. On the other hand, feed grade was high and the tonnages involved were much lower than that of today’s processing plants.

Figure 1: A simple representation of a processing plant with an obsolete crushing plant and ball mill grinding circuits.

The plant in Figure 1 has a regrind circuit. The important point here is that the product of the primary grinding circuit may be coarser, with less than ideal liberation. This saves a significant amount of energy and, if the rougher/scavenger flotation cells can pick up high-grade unliberated particles, the regrind system will further liberate the phase of interest and this will be recovered in the cleaner/recleaner stages. The alternative is to grind finer in the primary ball mill circuit. For sake of illustration, assume a feed rate of 500 t/h. A ballpark estimate can be made using the grade and the known BWI of the ore. In the first scenario, the ROM is ground to a P80 of 106 microns and no regrind is necessary. If the BWI = 14 kWh/t, then the ball mill circuit would consume 12 kWh/t and installed power would be around 6 MW. With the regrind system, P80 can be adjusted to 150 microns. Now, specific energy consumption in the primary grinding circuit is 9.9 kWh/t and the installed power requirement is about 5 MW. The regrind mill consumes at most 2.2 kWh/t and installed power requirement is only 54 kW as the regrind milling circuit has to process only about 25 t/h. The bottom line is that the regrind system allows for significant savings in OPEX. On the other hand, the smaller primary
ball mill (by 1 MW) is probably offset by the additional regrind system. Nevertheless, the central idea is that liberation may be a key factor in designing an optimal plant. In order to explore this, quantitative liberation models are required for simulation.

**Understanding liberation**

Liberation is an important field of study. However, few understand liberation beyond the concept of degree of liberation, as described in Gaudin’s book. To be concise here, it is very important to organize the field of liberation in its three areas:

1- Liberation prediction. This is the area of liberation that predicts the liberation spectrum as a function of particle size, given textural information. In other words, if you have textural information (geometric information only) related to the phase of interest, it is possible to predict liberation as particle size is reduced. Usually, the required textural information (or fabric) is measured on large fragments of rock, encompassing all geometric features that form the interface between two or more phases. Barbery, King and Meloy have contributed significantly to the liberation prediction problem. Barbery’s approach is based on integral geometry and its chief advantage is that it produces 3D (volumetric) information directly. Its disadvantage is that the textural information is necessarily described by a model (tessellation of Voronoy polyhedra), and the model has to fit the real texture. King’s model is known as the Random Fracture Model, and it gets the textural information from measurement on the unbroken ore. The disadvantage is that it generates 1D (linear) information and thus requires stereological transformation. Melloy’s model is based on a number of standard textures (regular patterns) from which the liberation can be predicted. It is possible to convert a real texture into one of Melloy’s textures, but the reverse path is not available after size reduction. None of these methods can be used in simulation, and the reason is that in a processing plant it is common to observe concentration effects such as in the cyclone underflow or even grinding circuits with concentration operations in the mill discharge as for example Eveleth’s plant in the iron range and Paracatu’s gold mine in Brazil. Very little has been in this area since the turn of the century.

2- Liberation measurement. This is the most popular area of liberation and great progress has been made here. Completely automated systems based on SEMs have been developed, namely QEM*SCAN and MLA, now commercialized by FEI. Complete mineralogical information can be obtained from these systems. The problem here is that image based systems produce information from particle cross-sections, in 2D, and the information that is needed is the volume liberation spectra (3D). Mineralogists in general are not aware of this and for their purposes the image based systems are sufficient. Currently it is generally accepted that 2D data is close enough when it comes to liberation measurement. There are indeed cases where the 2D liberation spectra is sufficient: when the particles are so coarse and nothing is liberated and when the particles are fine enough so that liberation is almost complete. When the liberation size is close or around the processing size 2D information overestimates liberation significantly. A stereological transformation system has been developed that corrects for the so-called stereological bias, but research in this field stopped with the
development and commercialization of the automated systems. Apparently, it was not in the best interest of sales to be revisiting the stereological transformation procedures. As an alternative, X-Ray microtomography systems are being developed and Miller's group at the University of Utah has reported its application to direct 3D measurement of liberation in mineral particles. These systems are still quite expensive but, given time, they might become more largely utilized. Simulation of mineral processing plants requires liberation measurements in all particle sizes as data along with textural information.

3- Liberation simulation. There are two models available, King's Ljubljana model, which is a representation of the liberation process based on textural information that is derived from the interphase area per unit volume of phase and Schneider's Incomplete Beta function model based on parameters that are relatively difficult to be measured. Both models describe the internal structure of the Andrews-Mika diagram, a diagram that shows the liberation spectra at each progeny size of a single grade particle. In addition, both models are suitable for simulation and can be implemented (and are implemented) in mill models that use the size-mass balance modeling techniques. Schneider's beta function model can be calibrated against real particles but the work is extensive. Unliberated ore particles with known liberation spectra (composition distribution) has to be ground (in a batch mill, for example) and the products must be sized and liberation measured in each size class. The model allows for a number of breakage model such as preferential breakage and differential breakage. However, the model has only been calibrated for a couple of ores and the amount of work involved prevents its routine use.

**Testing for crushing, grinding and flotation**

The simulation of the circuit in Figure 1 requires detailed information about the feed stream, including liberation at all sizes and Andrews-Mika parameters, size-mass balance model parameters and flotation parameters.

Although apparently difficult, the simulation of the flowsheet in Figure 1 can be carried out, with scale-up and liberation simulation with current technology. Besides the liberation work described in the previous section, the ore needs to be characterized for its crushing properties. Traditionally the CWI is measured form coarse particles and the power requirements for the crusher stages estimated. The DWT apparatus and now the RBT apparatus from JKMRC can provide parameters such as the appearance function and the energy requirements for each particle size so that crushers can be simulated effectively.

For the grinding mills, batch grinding tests in a torque mill are required to determine the energy specific selection function required by the Herbst-Fuerstenau scale-up procedure. Alternatively, the selection function can be determined in a lab ball mill using the Austin test procedure. This is more elaborate as several closely sized samples of the ore are required. The Austin scale-up procedure is more flexible than the Herbst-Fuerstenau procedure as it allows for varying ball charge compositions. The new VertiMills can also be scaled-up using either Austin or Herbst-Fuerstenau procedures or both, and the testing can be carried out in a batch laboratory ball mill as well. For the IsaMill, a new centrifuged charge type of ball mill which uses smaller, denser grinding media, it is very much possible that testing in a small scale
IsaMill will be sufficient to determine the appropriate size-mass balance parameters. Research is currently under way at CETEM to establish a suitable procedure.

High Pressure Grinding Rolls (HPGR) or Roller Press is a new, energy efficient grinding technology that can be used to prepare feed to the ball mill circuit. HPGR testing is also available for size-mass balance models that have been implemented in modern simulators. The test consists in grinding samples (from 5 to 20 kg) in a small scale HPGR (LABWAL) under different grinding pressures. The size distributions that result from the tests are used to calibrate size-mass balance parameters. The tests also produce parameters for capacity and power scaling-up. The tests are very simple to perform and six grinding pressures can be tested in a couple of hours. Measuring the size distributions takes more time than the test itself.

For the simulation of the flotation circuit, there are several models that are currently available, with emphasis on King’s model, JKMRC’s model and UNISA’s model. King’s model is liberation ready and it requires flotation rates and the relative amount of floatable particles in each grade range, as well as the size of maximum recovery, average bubble size and the amount of water that reports to the concentrate stream as froth. The model also requires a froth transmission efficiency coefficient. All of these parameters can be measured from a laboratory batch test. The model is suitable for flotation systems where the rates of attachment/detachment control the rate of flotation. The testing for determining flotation rates in completely liberated particles is very well known and even common. When the amount of unliberated particles is significant, testing must be carried out along with liberation measurements for each particle size range and each flotation time. This is quite an elaborate task with today’s technology. Bubble size distribution measurements can be made using imaging systems such as the Anglo Platinum Bubble Seizer.

**The 21st century**

For sake of illustration, a modern flowsheet of today could be the one represented in Figure 2.

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**Figure 2: A possible modern version of the mid 20th century flowsheet in Figure 1.**

Processing plants have evolved significantly, and this is basically due to innovation, new, more efficient machinery and better knowledge of mineral processing in general. During the second half of the 20th century, expansion projects started to adopt a strategy of large unit operations,
rather than several lines of smaller units. The first significant expansion project was Kennecott’s Copperton concentrator, with large ball mills and flotation cells. The plant also adopted SAG milling. SAG mills are a better alternative than a complete crushing plant as it replaces all stages of crushing with a major reduction of CAPEX. This is true even in small, low capacity plants. The ball milling requirements are also reduced because the product of a SAG mill is finer than the corresponding product of a crushing plant. Larger mills brought in new challenges as the Bond scale-up procedure was not ready for the new, large diameter ball mills. Papua New Guinea is the example of a failed project that resulted from simply relying in a scale-up procedure that was calibrated for much smaller equipment. Also, at the end of the 20th century, column flotation technology became available and today this is the standard for fine particle flotation. Also, the larger VertiMills are probably replacing the ball mills in the primary grinding circuit, as they are more energy efficient by about 25%. The regrind mill is the IsaMill, allowing for even finer grinding as these mills are more efficient for fine grinding.

HPGR technology has also been developed at the dawn of the 20th century with potential for a 40% reduction in overall energy requirements. The plant in Figure 3 uses HPGR, but now the secondary crushing stage is back in the flowsheet. This is illustrated in Figure 3.

![Figure 3: The modern flowsheet with HPGR.](image)

**Sustainability discussion**

The current methods for designing new plants include geometallurgy and variability analysis. The testing of drill cores takes place in the first stages of conceptual design, while the feasibility of the project is being evaluated. The plant is designed to attend 80% of the ore body (Vale specification). The conceptual design is usually made with OPEX in mind; energy efficiency and recovery are the chief objectives. If the project is given the go ahead, engineering starts and at this stage, CAPEX is favored instead of OPEX. Is this the best way of organizing new mining projects?

As new, more energy efficient equipment are developed, their CAPEX is also elevated by the manufacturers, offsetting the OPEX gains. This is market economy, and there is nothing wrong
here. However, from a sustainability point of view, this may not be what we want. Should something be done to incentive the use of the more energy efficient equipment?

The development of new equipment is faster than the model development for their best use, simulation and scale-up. Are we going to be lagging behind forever?

The mining industry’s conservative. This is because of the risky nature of the business, very susceptible to market oscillations. Nevertheless, technology has been developed incrementally, and since Gaudin’s visionary book, we have made very significant progress, especially in the late years of the 20th century. The “third wave” probably has much to do with this progress. Ore bodies are being exhausted, and what is left are tougher, lower grade, difficult to liberate ores. It is essential that research and development continue to offset the energy intensive, lower recovery mining projects of the future, otherwise the price of commodities will increase accordingly.

**Infinite list of things to do**

We have made great progress, but in the short run we still need to:

1. Develop and verify flotation models for simulation that are practical.
2. Develop a scale-up model for SAG milling that is as reliable as ball mill models.
3. Develop a model for the IsaMill.
4. Better power model for HPGR.
5. Better power model for VertiMill.
6. 3D X-Ray microtomography for liberation measurements in 3D.
7. And an infinite number of other items….

**Illustrations**

*Figure 4: Ultimate recovery by particle grade and size. Grades refer to hematite and quartz is the phase being floated. The information is essential for flotation modeling, and it is only possible to measure with the new automated mineralogy systems.*
Figure 5: Variability results of 150 drill core samples of a copper ore project. Geometallurgy brings certainty to new mining projects.

Figure 6: Liberation spectra measured from iron ore particles from the iron range. The high-grade particles just below the liberation size are the type of particles we want to send to the regrind circuit.
Figure 7: Liberation spectra from ball mill discharge particles. Measured in the left and simulated in the right.

Figure 8: The model for the internal structure of the Andrews-Mika diagram. Simulation of the liberation process is possible thanks to this understanding.