Simulation in mineral processing history, present status and possibilities

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Synopsis

Mineral processing models have been discussed for many years but it was not until digital computers became available about 1960 that serious attempts at circuit simulation could be carried out. Even then the work was primarily academic until PCs could be used by engineers in plants and design offices in the mid-1980s. Since then simulation has moved quickly and it is now at the point that most processes can be simulated reasonably accurately for purposes of design and optimization. There are still some significant deficiencies, notably in dry grinding and separation, and in the chemical interactions in flotation.

Future work will involve:

- **improvements of existing models**
- **dynamic simulation for automatic control and, in particular, for training which is a weak link**
- **using advanced simulation models to predict liberation and separation from data acquired from SEM-based liberation analysers.**

Eventually mineral processes models will be part of total simulation systems which will incorporate mining and downstream processes including all environmental impacts.

Modelling up to 1960

Modelling and simulation in mineral processing technology is concerned with the design and optimization of circuits. It has become an important method of minimizing costs per tonne through increasing mineral recovery or productivity. The earliest models were by Von Rittinger[1867] and Kick[1883] who proposed equations (models) to describe breakage processes in terms of energy consumed. These conflicting models created considerable controversy when professional Institutes of Mining Engineers were formed late in the 19th and early in the 20th century and started to publish technical papers. Interest in modelling increased during the 1930s and 1940s (for example Garcia-Zuniga[1935], Sutherland[1948]) but the models which were proposed seemed to have little practical use and were regarded as interesting curiosities. It was realised years later that they were very important.

The availability of large computers late in the 1950s gave simulation an aura of respectability and created momentum in its development and use. The models of many years previously were a valuable aid in the formative years of simulation and even in 1960 it was possible to have a glimpse of what the future may hold. For years this glimpse seemed to be a mirage but for reasons discussed later it became a reality about 15 years ago and simulation is now very important. The reason is that mineral processing circuits are becoming larger, more complex, and more expensive to build and operate, and simulation offers the best and cheapest way to handle the difficult optimization and design problems which are involved.

It is not that optimization is new. It became important late in the 19th century when there was a surge of activity in the development of new processes and new equipment for the treatment of solid particles. The new processes were for the production of portland cement using kilns, for the recovery of gold by cyanidation and for the recovery of sulphide minerals by flotation and they all required fine grinding which could not be carried out efficiently in the fine crushers of the day. It was the combination of electricity—then a new form of energy—and of tube and ball mills which until the advent of electricity had been a hope rather than a reality that made these processes possible. The result was a boom in inventions of equipment of the tumbling mill type.

A. del Mar in his book on Tube Milling[1917] wrote that ‘Inventors and manufacturers are now trying every variation of shape and every means of screening to attain capacity with least expenditure of power’. There were ball

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mills divided into four horizontal segments with balls in each segment to reduce power, and many other ingenious ideas. This was an experimental approach to optimization and many of the topics he discussed, such as ball size, liner design and the location of classifiers within closed circuits, are still discussed today.

T.A. Rickard, the doyen of that small group of engineers who were metallurgists and also accomplished authors, explained the problem of circuit design and optimization with his usual clarity and wit[1897].

'There are establishments which have what they call a standard type of mill which they highly recommend for the reduction of ores running through a whole gamut of differing compositions. Like the iron bed of Procrustes, to which the wayfarer had to suit his length at the risk of summary abbreviation or painful elongation, so the manufacturer expects the ore to adapt itself to his mill or choose between being labelled unprofitable or refractory'.

The experimental approach to optimization is expensive, lengthy and often inconclusive. The alternative approach of modelling and simulation is cheap, quick and conclusive, provided that the models are accurate and model parameters can be determined. It is also important that engineers using the models appreciate the strengths and weaknesses of the models.

The mathematical base for modelling was established with the equations for flotation kinetics (Sutherland[1948] and others), size distributions (Rosin and Rammler[1933]), the energy-size reduction-grindability relationship (Bond[1952]), and the concepts of the reduced efficiency curve for cyclone separators (Yoshioka and Hotta[1955]) and selection and breakage for mills (Epstein[1948]). The first of the 'modern' models was proposed by Broadbent and Callcott[1956] who showed how total size distributions could be represented by matrices and how matrix equations involving breakage, selection and classification functions could be written to describe circuits.

While progress was being made in the formulation of models, their use for simulation would not be possible for some years because computers were required for the repetitive calculations involved and while these were then becoming available they still had to be programmed in a difficult machine language.

Modelling from 1960 to 2000

1960–1980

By 1960 the mineral industry had begun to expand rapidly. After many years of recession and wars and metallurgists were looking for new ideas, particularly on process analysis and control. The stage was set for a vigorous effort on the modelling of comminution circuits, in particular ball mill-hydrocyclone circuits which were high cost but not well understood. It was a time when there were no pressing demands because mineral prices were high and companies were very profitable. Most plants were designed with good factors of safety in terms of production rates and comminution machinery was still fairly small, at least by today's standards, and could easily be sampled.

During the 20-year period 1960–80 the concepts of modelling and simulation were firmly established, mainly by university groups who were funded by national science councils and were able at the time to undertake research without undue pressure for results. Most of these groups specialized in laboratory and computer studies but much of their work was of limited interest because plant personnel had little access to the large computers in use and were not involved in what was happening.

A few groups placed emphasis on the testing of models in operating plants and on modifying them to correct deficiencies. This was the philosophy of the group at the University of Queensland which became the Julius Kruttschnitt Mineral Research Centre (JKMRC). Its research started in 1962 with a very small project on modelling grinding circuits which was funded by the newly formed Australian Mineral Industries Research Association (AMIRA) and it demonstrated within 4 years that the Broadbent/Callcott model and simple models of classifiers could be used to improve the productivity of grinding circuits by simulation.

Industry funding of this project has continued at an increasing level since 1962 and the project has expanded to include all mineral processing operations. The lesson from the early studies in this project was not to worry too much about getting all the details of the models right before testing them in the plants but to make extensive use of plants as laboratories from the start.

1980–2000

This 20-year period was followed by another from 1980–2000 in which the mineral industry has worked under very different conditions. During this time there has been high demand but low prices for minerals, declining company profits, and declining ore grades. The combination of lower grades, rising mineral demands, and the requirement for high capacity circuits to reduce unit costs has led to very high circuit capacities and rapid growth in machine sizes and power consumption, as shown in Table I. There has been another surge in inventions, particularly of machines for grinding particles to 10 microns and less.

Table I

Increase in the maximum sizes of ball and autogenous/sag mills during 1960–2000. Data from Svedala[1997].

	Ball Mills			Autogenous/SAG Mills		
Year	Dia-ft	Length-ft	HP	Dia-ft	Length-ft	HP
1940	10	9	600			
1948				10	3.3	100
1960				22	7	1500
1963	13	18	2000			
1969				32	14	7000
1970	18.5	21	4250			
1979				34	17	12500
1987				36	17	15000
1990	20	30.5	7500			
1994				36	19	18000
1996				38	20	26000
1997	24	34.5	14000	40	22	26000
Future	26	42	21500	44	24	40200

During this time, also, personal computers became available which meant that models could be used in plant and design offices, simulation programs could be tested thoroughly, and plant and design metallurgists become involved in the model development work. All these factors have led to an emphasis by many companies on improving efficiencies by using models to assist productivity and verify circuit designs.

Present status of simulation

Simulation in mineral processing is well advanced and has contributed large economic benefits to the mineral industry, particularly in the optimization and design of circuits containing sag mills, crushers, ball mills and hydrocyclones. Two of the main reasons for these successes are:

- the availability of PC's from about 1985. These have taken simulation software into plants where model deficiencies can be observed through independent testing and corrected
- comprehensive data have been collected in plants over a long period covering a wide range of ore types and operating conditions. This has been essential in model development and verification.

Two examples which illustrate the importance of using plants as laboratories are:

- modelling autogenous and sag mills requires the correct prediction of the weight and size distribution of the mill load. It was not until many mills were emptied and the contents weighed and sized that a valid model which included the mill load could be developed
- designing comminution circuits accurately requires measurement of the breakage function of the ore using a well instrumented laboratory unit in which particles could be broken at different energies. Plant surveys augmented by breakage functions from this unit completed the data base necessary for a general purpose simulation system for comminution circuit design and optimization.

A brief review of the status of modelling follows.

Comminution

Modelling of wet grinding processes is well advanced. The Broadbent-Callcott model has proved to be widely applicable although it has been necessary to adapt the model to the characteristics of each type of mill. For example in-mill classification had to be recognized as the important feature of sag mills, rod mills and crushers whereas it was less important for fine grinding ball mills. For very large and very long mills different constraints come into play and extending models to these mills will extend our understanding of the process. Crusher models, including prediction of power usage, are widely used. Models of comminution circuits developed at JKMRC are well described by Napier-Munn *et al.*[1996].

The modelling of dry grinding processes is not well advanced but current research at Hacettepe University in Turkey, based on sampling inside mills and around circuits, has enabled 2-compartment mills to be modelled as 3–4 mills in series with the partitions acting as screens (Oner pvte comm.). Good progress can now be expected as studies proceed on the effect of variables such as ball size and load, liner type, partition design and air flow.

Comminution in mining

The last 5 years have seen substantial advances in the modelling of blasting as a comminution process. One of the obstacles to this work has been the arduous sampling requirements. At ROM sizes, samples of hundreds or even thousands of tonnes of 'muck' may be required for reasonably accurate estimates in very coarse size ranges. A number of complete blasts have been sized by JKMRC teams and the sizings were used to check and calibrate image analysis techniques for non-contact ROM sizing (Atasoy *et al.* 1998). The conclusion is that the Broadbent/Callcott and Rosin/Rammler models are useful for modelling *in-situ* rock size distributions provided that the joint structure of the deposit can be measured or estimated (Kojovic *et al.*[1998]; Kanchibotla *et al.*[1998]).

At a reasonable distance from the blast, rock is pushed apart and breaks into a distribution determined by its structure of weakness—but close to the blast, actual rock breakage takes place and in this zone models have been applied which have been adapted from ideas developed for process models. These models have far to go but are already useful for estimating interactions between blast design and milling. A major Canadian company, Highland Valley Copper, achieved a substantial reduction in milling cost for a small increase in blasting cost (Simkus and Dance[1998]).

Size separation

Vibrating screens are modelled as a probability process provided that they are not over-loaded and that the particle shapes are reasonably cubical and consistent (Whiten[1972]). But screens are notoriously susceptible to problems such as damp ore and no model will handle these successfully. The model of separators involving centrifugal forces is based on the concepts of by-pass, d_{50}(corrected), and corrected efficiency curve (Lynch and Rao[1965]) and has proved to be surprisingly successful for optimization and design of hydrocyclones, particularly since it is a mechanistic model with little theoretical basis. The development of an effective model for slurry viscosity has improved the range of wet classifier models (Shi and Napier-Munn[1996]). This viscosity prediction has been used for both hydrocyclones and dense medium cyclones. The simple efficiency curve model has not yet been well developed for air separators but the momentum is starting to build in this area.

Concentration

Models of dense medium, gravity separation, and electro-static and magnetic separation processes are well developed and reasonably widely used. Models of flotation circuits are not as advanced as comminution circuits and this is a serious defect because it is in flotation that money is made or lost in many mining operations. The models themselves are not the problem, they are simple kinetic models and are good enough. An important problem in flotation, and it applies to some extent to all concentration circuits, is concerned with composite particles which contribute much to the degradation of concentrates or to loss in recovery. Optical and scanning electron microscopes have been used for years to measure the nature of composite particles but modelling their behaviour in flotation circuits before and after breakage in regrind mills is still to be done. The Philips-JKMRC Mineral Liberation Analyser for rapid liberation measurement at high resolution is important in this context (Gu and Guerney[1999]; Gu[1998]).

The collaboration between the University of Cape Town and the JKMRC during the past few years has been valuable in modelling flotation machines and circuits. Two of the developments are:

- an instrument to measure bubble size distribution in an industrial cell which has led to the use of bubble flux which is the bubble surface area per unit area of machine cross-section as a means of scaling rate constants for different sizes and types of cells (O'Connor *et al.*[1989]; Gorain *et al.*[1997])
- an experimental procedure to determine unambiguously the proportions and rates of the floatability components. This involves floating key plant samples such as feed, rougher and scavenger concentrates and tails in a batch cell at shallow froth depth and calculating the values for the floatability components from all the data (Harris[1997]). Initial results in several plants indicate that the values are sharply defined and this has important implications for circuit design and process control strategies (Alexander and Morrison[1998]). A methodology for flotation plant simulation has been proposed by Runge *et al.*[1998].

In summary, modelling and simulation of mineral treatment processes has fulfilled the hopes of 40 years ago although rather more slowly than was expected. There are still deficiencies, in particular in dry grinding and in flotation with respect to liberation and froth recovery but the procedures to correct these are now known. As far as the future is concerned two advances which can be expected to occur are improving existing models so that they are more than 95% reliable for optimization and design, and broadening the scope of simulation so that it becomes of wider value than simply as an aid to engineers. These will be discussed.

The next 10 years—model improvement

Model improvement of every process will happen as a matter of course until the point has been reached at which further improvement will not yield economic benefits. Some areas of research will be flotation, fine grinding and dry grinding. The economic factor will also be introduced.

Flotation

Modelling based on floatability components can be expected to consolidate and become standard industry practice. While current work indicates that recoveries can be predicted with reasonable confidence prediction of concentrate grades requires a detailed understanding of froth recovery and drainage, entrainment and mineral liberation. Good progress has been made in all these areas but the current approach requires enormous and costly data collection surveys.

A collaborative project (AMIRA P9) is tackling these issues with UCT and JKMRC as major research providers and a transportable pilot plant provided by Baker Process. A better understanding of the interactions in flotation may result in less severe data collection requirements. The modelling of chemical interactions remains the ultimate goal but is unlikely to be reached within the next 10 years. But even this goal may be reached if the idea of real collaboration between research groups in different organizations takes hold.

Dry grinding

Dry grinding is a high-cost process used mainly for cement clinker and steaming coal but also for many other minerals. The program at Hacettepe University in Ankara is indicating how multi-compartment tube mills can be modelled and this work should be well advanced in 3 years. It needs to be extended to tower roller mills, Horomills, and various types of air separators. Some of the questions which arise in dry grinding are:

- what is the effect of ball size, particularly in the second compartment of the mill?
- what are the effects of change in air flow through the mill and separator, and of change in separator speed?
- what is the optimum circuit for each application of dry grinding, recognising the possibilities which now exist with new types of fine grinding units and air separators?

The requirement for modelling dry grinding circuits is the same as for any other type of circuit, i.e. a large program of plant work must be carried out covering a wide range of operations for different types of units.

Fine grinding

Ultra fine grinding is coming into common use for regrinding concentrates and to improve recovery by leaching from refractory gold minerals. At the JKMRC models have been developed for tower and stirred mills together with a laboratory technique for ore characterization. These models were developed on laboratory and pilot mills and need to be validated for larger mills.

The economic factor

The purpose of modelling is to use simulation to improve economic performance and, while increase in productivity or metal recovery implies this, it is not common for economic factors to be included explicitly as apart of models. It is true that this would involve considerations of the cost of items such as equipment, power, labour and supplies, of the contract conditions for sale of products, and of other factors which may vary widely between localities.

Hence, capital cost modelling in a simulator is of limited benefit as the parameters tend to be notional. Once a plant is operational however, the smelter contracts and operating cost factors become much better defined. For multi product concentrators a simple model which predicts how the distribution of products interacts with the smelter contract can be very valuable. In a broader context a 'mine to mill' simulator absolutely requires a quantitative understanding of operating cost structures as well as technical interactions.

The next 10 years—the wider view

In 1960 simulation of mineral processing circuits was a hope with little substance, today it is a reality. What are the hopes for tomorrow, knowing that computer power and software are no longer inherent limitations?

A few possibilities are:

- Extend the simulator to cover the entire production chain. Within 10 years an interactive simulation from mine to flotation concentrate is achievable with extensions to other physical separation systems including coal. Further extensions to hydro and pyro metallurgical processes other than by cost is an attractive area for collaborative research because no one group can cover the entire process range
- Convert the present steady-state simulator into a dynamic simulator for various uses such as in process control and training.
  - In the case of process control modelling circuit dynamics as the engineering design is developed, can be used to check the process control system and tune the controllers. The KenWalt group pioneered this approach in South Africa. On-line use of dynamic models will also bring benefits; for example integrating the JKMRC dynamic SAG mill model with on-line feed size analysis will lead to a comprehensive control system and on-line use of flotation models will improve results
  - In the case of training simulators that can be developed for operators and engineers. Education is a weak link in mineral processing and training which makes maximum use of computers and modern communication technology is now necessary. There would be value in developing several levels of training simulators to support formal courses.
- Measure the ore texture from core samples and predict liberation and separation from more sophisticated models. The Philips-JKMRC Mineral Liberation Analyser is well suited to collecting data to calibrate the JKMRC ore texture model and this has the potential to predict liberation at any size so that preconcentration and grinding strategies can be evaluated from ore samples alone
- Use of advanced computational methods. Cost has limited the use of DEM and CFD but it no longer does. Three-dimensional simulations can now be carried out and their use will become standard practice over the next 10 years.

Final comments

How should the simulation work be carried out to ensure that the benefits are available as soon as possible? Probably by postgraduate university groups in close collaboration with industry because jointly they have access to the wide range of skills which are necessary and they have an excellent track record in innovative simulation work. After all, the simulation of mineral processing operations gained its momentum with their work which started in the 1960s.

Because of the success of simulation it is also necessary to have a reservoir of professional skills and for models to be available within well-supported commercial products. There are now a number of organizations world-wide whose principal business is to use simulation as well as to carry out training, software development and technology transfer. One of these is JKTech—the commercial division of the JKMRC. JKSimMet and JKTech owe their success in no small part to those original student researchers who laboured with primitive computers to develop the first generation of simulation models.

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