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15th Triennial World Congress, Barcelona, Spain

EVALUATION OF THE ECONOMIC BENEFITS OF MILLING CIRCUIT CONTROL

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Abstract: An analysis is given of experimental methods and pitfalls for the determination of the economic benefits of milling control strategies. Four particularly important aspects that influence results are external effects, reference conditions, measurements and sampling, and the influence of people. The benefits to be obtained are those associated with dynamics and those associated with operation at optimum operating points. *Copyright © 2002 IFAC*

Keywords: Economic evaluation, process control, milling circuits

1. INTRODUCTION

Milling is often the most costly surface operation in the mining industry. Its capital costs are high, so improved throughputs at the same product size can lead to substantial savings on plant expansions that might otherwise be required. Running costs of milling are also high, particularly those of electrical power and consumed steel (linings, lifters and grinding media).

Apart from having high capital and running costs, milling usually has a very large impact on the efficiency of downstream extraction processes. Inadequate milling usually leads to direct losses through lower recoveries downstream and can sometimes lead to further financial losses associated with an inferior downstream product.

The effectiveness of a milling circuit is generally measured in terms of its throughput, its product size, and its consumption of power and steel. However, meaningful measurements or estimations of the economic effects downstream of milling – particularly those due to product size – are difficult to obtain. These estimations need either a model for the effects of size on the downstream process or experimentation to expose the downstream effects of milling.

The Measurement and Control Division of Mintek has implemented many control systems on industrial milling circuits. Despite encouragement to provide for adequate conditions to evaluate the economic value of good control, circumstances in industry are normally not conducive to yielding results without the application of care and special techniques.

Koudstaal et al. (1981) give results for multivariable control of milling on a gold mine, in which gold losses were reduced by 28% and solids throughput was increased by 8%. Pauw et al. (1984) reported an improvement of 1% to 3% in throughput, at the same grind, by better control of pebble additions. Gossman et al. (1984) obtained an increase in throughput from 71 to 79 t/hr and an improvement in power usage from 31 to 27 kWh/t<75μm. Hulbert et al. (1990) reported reductions in product size standard deviations (of 10-minute averages) from 5 to 3%<75μm, for run-of-mine (ROM) milling. ROM milling has fewer degrees of freedom than normal for control, because the coarse feed (which acts as grinding medium) and the fine feed cannot be adjusted independently. Craig et al. (1992) reported throughput increases of 11%, at the same grind, for ROM milling. In conventional milling circuits, size can be controlled tightly, as in the results of Schubert et al. (1998) where standard deviations were less than 1%<75μm from set point. Babarovich (2001) obtained size control to within 1%<75μm of set point, a throughput increase of 9%, and a payback for the control system of 40 days.

The study and application of methods to evaluate benefits of control are discussed by Craig and Koch (2001).

2. THEORETICAL EVALUATION

The benefits of a control system can be estimated theoretically by the use of mechanistic models in simulators. Unfortunately, even if the results are valid, they usually convince only the theorists and the converted.

Models that reflect steady-state conditions only are not particularly useful for the task. They can only indicate differences in performance due to different choices of set points for operating conditions. The optimisation of steady-state conditions is only one component of a control system. Milling circuits are seldom operated at smooth steady states and their transient conditions have a large impact on product size and therefore downstream performance.

Unfortunately, a milling circuit whose control is to be investigated is often not tied just to a single downstream process. For example, the product of several milling circuits might go to a common thickener before further processing. Unless all the milling circuits can be subjected to the same test procedures, any effects of the tests on downstream process efficiencies can usually not be measured. In this case, theoretical models or separately measured effects on the downstream process need to be used. Many flotation plants without good control are sensitive to fluctuations in flow, which can then cause losses of the order of 1% in recovery. Apart from this, non-linear variations in size are also likely to cause losses in flotation of around 1% or more. A third effect is operation of a milling circuit at the wrong average grind, which is likely to incur loses in flotation of more than 1%. In leaching processes, the losses can be somewhat less, depending on the normal levels of extraction.

When milling control is improved, the improved trade-off between throughput and product size can be used according to operational needs. Typically, the improvement from a mediocre to a good milling control system will increase throughput by about 10%, at the same grind. In the absence of better models or measured results, this trade-off can assumed to be governed by the well-used approximation that the rate of production of fine material (e.g. material passing 75μm) is constant.

3. EXPERIMENTAL DESIGN

The following four tasks are critical in test work for the measurement of the benefits of a process control system. One task is dealing adequately with external effects that might tend to influence experimental results. Another task is establishing reference conditions against which the process control system is to be compared. Another is obtaining accuracy and repeatability of measurements and representative sampling. The forth task is proper accounting for the actions of people.

In the discussion below, it is assumed that a "new" process control system is to be evaluated and compared to operation under some reference conditions or a reference control system.

3.1 *Design to eliminate external effects*

The most popular test work to evaluate a new control system entails measurements of plant operation during periods "before" and "after" its installation. This might seem to be exactly what is needed, but the results of such tests usually tend to be very misleading. The main problem encountered with "before" and "after" tests is the influence of external factors. Almost invariably, there is at least one external factor that is different on average during the "before" and "after" periods, and that has a large indeterminate influence on the results. A common occurrence is for a fault to be fixed or a process modification to be implemented, after which management is understandably unwilling to allow continued operation of the plant under the original conditions.

External effects cause variations in the operation of a milling circuit that are not wanted as part of the results of the experiment. Such factors can be physical changes to the process, changes in calibrations, changes in operating procedures unrelated to the control, and (most often) changes in the characteristics of feed material.

The characteristics of external factors need to be accounted for as a function of time. Some specific examples are as follows.

- **A change is made in the calibration of the product-size measurement (manually or perhaps by a sudden undetected fault).** This introduces a step change from one level to another in a key measurement. If such a change occurs near to the transition between "before" and "after" test periods, the results will clearly be biased.
- **During the period in which operational data is obtained, mill linings wear down from new to old.** This introduces a continuing one-directional change with time. Such a change will definitely cause bias between successive "before" and "after" test periods.
- **Processes upstream of milling have daily, weekly and monthly cycles that impact on results.** Bias is introduced unless similar numbers of equivalent cycles occur in comparative tests.
- **The size, hardness and grade of the ore entering the milling circuit change**

erratically, including very slow to very fast variations in time. The very fast components of change tend to have their effects on results reduced by averaging during individual test periods, if adequate averaging of measurements is done and samples are composited over time in an unbiased way. The slow components of change can introduce bias in relation to how they influence individual periods of comparative testing

The best solution for the elimination of external effects is to interleave many relatively short test periods over an adequately long time span. This technique tends to spread the slower-acting components of the external effects more evenly between the conditions being compared. In addition, individual test periods in a good experimental design should normally span one or more full cycles of any periodic external effects.

Let ∝ and β represent continuous test periods for running a milling circuit under reference conditions and under the new control system, respectively. A very good strategy for experimental evaluation is to run a series of periods ∝β∝β∝β∝β…, where ∝ and β are of the same duration – typically a day or a number of days each. There should typically be at least four pairs of periods and ideally many more. There should be enough pairs of periods to reduce the averages of external effects sufficiently to give significant conclusions for the tests.

The length of the periods ∝ and β should not be too short compared with the response characteristics of the plant. The average residence time in a milling circuit of fine-ore feed is typically of the order of an hour. The average residence time of rocks is typically of the order of half a day. The average residence time of steel balls is typically of the order of several days.

If sampling and measurements are to be carried out around the milling circuit only, the ideal length of the periods ∝ and β would probably be one day for ball and rod milling and two or three days for autogenous milling. The rate of consumption of steel and changes in the steel load are in this case regarded as external effects that are not of importance in the evaluation of the process control system.

If the performance of a process downstream of the milling circuit were to be included in the test work, the time allowed for responses would need to be longer by typically some hours to a day or two. In this case, the ideal length of the periods ∝ and β would probably be 1 week.

The influences of external effects in ∝β∝β∝β∝β… tests can be modelled and eliminated as follow. A long-term deterministic trend is obtained from the averages of results for successive ∝β pairs. The ∝β pairs of results are normalised to remove this trend and produce the same value for the averages of all ∝β pairs. The differences in normalised results for each ∝β pair is then treated as a real difference between operation under the reference conditions and the new process control system, plus additive noise due to the external effects. The average of differences between the ∝β pairs gives the estimate of the effect of the new process control system relative to reference conditions. Statistical t-tests can be done on the sets of differences to determine confidence limits of these estimates. Note that if a statistical *difference* between the modes of operation is to be proven, the two-sided t-test should be used, and both positive and negative differences could then be significant. However, if a statistical improvement is to be proven, the one-sided t-test should be used in conjunction with the condition that the average difference must reflect a positive improvement.

3.2 *Reference conditions*

The most sensible reference condition might seem to be the “normal” conditions of operation before the installation of the control system to be evaluated. Unfortunately, new control systems are usually installed soon after times when instruments have not been well calibrated and good statistics of operation have not been obtained. The previous “normal” conditions (including operator interactions) are often not well defined and not easily replicated in special experiments of the ∝β∝β∝β∝β… form described above. Nevertheless, reasonable reference conditions can sometimes be determined by careful observation of the associated control strategies and operating procedures, and replicated with good supervision.

Another reference condition that might be considered is operation with the old control system as it could operate, when configured, tuned and run properly. The improvement of the old system might be required with or without the knowledge gained by the operation of a new control system. The effects of people in this are discussed below.

A third selection for a reference condition can be a variation on the new control strategy itself. This can sometimes be the best selection because it is well defined and can be targeted to give very specific results. For example, the reference condition can be made to have either weaker stabilizing control or different operating set points, to expose the effects of fluctuations and set-point optimisation, respectively. Special experiments of the ∝β∝β∝β∝β… type (or perhaps even a ternary experimental design ∝βγ) should be used.

Conditions of plant operation have two important aspects associated with them. One aspect is the effect of fluctuations or deviations from "normal" operation due to disturbances or system instability. The non-linear effects of fluctuations generally cause worse results, on average, for bigger fluctuations than for smaller fluctuations. The other aspect is the effect of operation at inferior operating points. Operating points can be selected manually or within an automatic control system.

Mintek has done several investigations (on flotation plants) in which control systems are compared at the same operating points. The measured differences are then solely due to fluctuations or deviations from normal operation. When Mintek compared its FloatStar stabiliser to normal PI control under these conditions, the results almost invariably showed statistically significant improvements in recovery of around one per cent.

Fluctuations in closed milling circuits have non-linear effects that are particularly important and severe in the classification stage. The stream recycled from a hydrocyclone underflow generally has solid particles that are much coarser and somewhat denser than the product material. It is common for the grade of valuable material in the recycle stream to be several times the grade in the product stream, simply because of gravity concentration. During an increase in flow to a hydrocyclone, less and finer material reports to the product stream; during a decrease in flow to a hydrocyclone, more and coarser material reports to the product stream. These two effects do not cancel each other, so the net result is that an abnormal amount of coarse material containing valuable material is ejected on average during fluctuations.

Sometimes, one of two parallel milling circuits of similar design is suggested to be a reference for comparison. Unfortunately, milling circuits tend to have many individual characteristics that can make them operate very differently. Even if the circuits happen to be identical, bias in their solids-feed compositions is still likely to occur.

3.3 *Accurate and repeatable measurements and representative sampling*

It is important that instruments should be calibrated appropriately. In comparative tests, repeatability is often more important than accuracy, provided the "slope" of the calibration curve is reasonably accurate. Calibrations should therefore not be changed partway through test work, unless special provisions are made to compensate for the changes – as possibly might be the case in experiments of the ∝β∝β∝β∝β… form described above.

Where measurements from instruments are controlled to fixed set points by a control strategy, their calibrations are important even if they are not part of the final calculation of throughput, size, downstream efficiency and economic benefits. The reason for this is that they determine the "normal" operating conditions. Changes in calibration would lead to changes in the corresponding real operating values of flows, densities, etc.

Hand sampling is generally not acceptable because it is usually biased in some way. Problems can be that the sampling is too infrequent; it is done at times decided by an operator (possibly deviating from specific instructions); it is done with a non-uniform cutting action or in a non-representative position; or the handling of the sample and its container is poor.

The best sampling of a large industrial stream generally entails two or three automatic samplers in series. Too often, an attempt is made to get an adequately small sample by having too few sampling stages, cutter gaps too small, and cuts too infrequently. The primary sampler should cut a full process stream that flows over a weir. Secondary and tertiary samplers should cut the product stream from the upstream samplers properly. The final sample should be a composite representative of a period of operation to be evaluated. All samplers should cut a fixed fraction of the feed stream they sample – there should not be any sampling at a fixed flowrate from a stream of varying flowrate.

3.4 *Accounting for the actions of people*

People can have deciding impacts on practical test work. Most control systems can be manipulated or overridden by human intervention. Ulterior motives, pressure for results and ignorance or unawareness can lead to human intervention that introduces major biases. People often play a part in the total effect of a control system if they make changes in response to their observations of the plant's or controller's operation.

When good results are wanted, people are tempted to wait until the plant operation is good before starting a test period. Similarly, the elimination of periods of "abnormal" sets of data from within test periods can be a cause of bias. Generally, the test conditions and any rules to be applied for rejection of data are best defined in advance of any test work and they should not tend to generate bias.

A common influence of people on results is the change they introduce after observing the operation of a new control system. A new control strategy that is good can expose several problems or solutions that can induce people to revise the old control system. Some possibilities are as follows.

- The old control system had not been tuned properly.
- Some old control loops had not been selected or configured properly.

- Bad operating points had been selected.
- Manual input required by the old control system (e.g. selecting set points or making changes according to some rules) had been neglected or done incorrectly.

In essence, people with influence can affect results either way. People can “help” the results of an old or new control system to be better or worse. Apart from being knowingly dishonest, someone wanting to show an old control system to be good might feel justified in upgrading it in the light of knowledge and experience gained from the new control system. Such action might or might not be appropriate for the comparison being tested.

4. PRACTICAL RESULTS

The results of tests and their validities vary from plant to plant. Some typical measurements of economic benefits that were obtained from industrial plants are discussed below. The results given for sub-optimum performance relate to seemingly acceptable, but incorrect, choices of setpoints, but not grossly bad operational problems, such as severely roping cyclones. Grossly bad operational problems can be due to bad operational procedures, bad maintenance of equipment and badly structured or designed controllers that do not handle constraints properly. They generally cause inefficiency that can be much worse than that of the sub-optimum performance discussed below.

4.1 *Trade-off between solids throughput and grind*

At good conditions of milling, the product size expressed as a percentage passing a particular size can be expected to be inversely proportional to the solids throughput. This approximation is a good one and is widely used. This means that a one per cent increase in solids throughput, at optimum milling conditions, will make the size-measurement change by the factor 100/101. This trade-off is useful in the evaluation of data from tests where both size and throughput change, but where economic benefits are wanted from improvements in just size or just throughput.

Optimum conditions for milling circuits require operation that induces the masses of grinding medium, solids and water in the mill to be at appropriate levels and the operation of classifiers to be suitable. Changes between optimum and sub-optimum operation depend on the effectiveness of control and optimisation strategies. Noting that there is a conversion between size and throughput, the evaluation of sub-optimum milling, relative to optimum milling (in respect of these variables), can be measured in terms of just one number: the percentage that throughput is lower at the same product size, which is the same as the percentage that the size coarsens at the same throughput.

The economic value of a higher throughput depends a lot on circumstances. If the mill is a real long-term bottleneck, increased throughput can deliver an extra cash flow in accordance with the value of the extra product produced. However, this is usually an inappropriate valuation. Most often, long-term throughput is determined by factors other than milling – usually the rate of mining – in which case throughputs are often fixed, while benefits are obtained by improved grinding or reduced operational costs. The value of an increase in throughput can perhaps be assessed in terms of the same percentage of the cost of installing and operating an extension to the milling plant that would double its capacity.

The economic value of a better grind depends on throughputs and recoveries. An example of a measured result from a gold-producing plant was a 0.03g/t improvement in recovery for every one per cent improvement in fineness. At 100t/hr and a gold price of \$300/oz, a one percent improvement then yields about \$20 000 per month. While milling for flotation can produce an average product size that is too fine, this seldom occurs in practice and mills are commonly run with a grind that is a little or a lot too coarse. The result is that there are commonly very good economic benefits to be derived from optimising control – generally far more than the cost of implementing a good control an optimisation system.

4.2 *Optimisation of mill loading*

The volumes of the loads of pulp and grinding medium in mills – particularly autogenous mills – have significant effects on optimisation of operation. An example of a measured result from a run-of-mine autogenous milling circuit was that the trade-off between throughput and grind at a 33% volumetric filling was 9% poorer than at the optimum (with respect to the throughput-size trade-off) of about 45% filling. However, the costs of power and steel influence the position of the real economic optimum. The power consumption was found to be 5% less, per mass of fine material produced, for 33% filling as compared with 45% filling.

4.3 *Optimisation of water additions*

In control and optimisation strategies, water additions can be used to maximise milling efficiency and also to trade-off size and throughput, as required by plant-wide optimisation or operational requirements. When there is just one degree of freedom and it is required to be used to control the trade-off of throughput versus size, no further optimisation is possible. When there are more degrees of freedom, incorrect additions of water can lead to sub-optimum operation with variations of up to about 5% in grinding or throughput relative to the optimum. The effect of water additions on the efficiency of power consumption was generally smaller than that of mill loading.

5. CONCLUSIONS

The experimental determination of benefits of good milling control requires several aspects to be taken into account in order for results to be valid. External factors tend to have large detrimental effects unless they are systematically eliminated by proper experimental design. Care needs to be taken that appropriate reference conditions are defined and used as a basis in evaluating benefits. Measurements and sampling can introduce bias if good techniques are not used. The actions and omissions of people, wilfully or otherwise, have an impact too. Special attention needs to be given to obtaining valid theoretical or experimental methods to link product size measurements to the performance of downstream processes, if the downstream process is not included as an integral process with the milling circuit in the test procedure. The benefits of good milling control can be measured with due attention to these details. They can be attributed to better average operating conditions and better handling of disturbances and fluctuations that have adverse non-linear effects on performance.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Babarovich Hansen, V.P. (2001) Plantstar expert system for optimisation of the milling circuits at CVRD’s Fazenda Brasileiro plant. ABM 5th seminar Brazil.

Craig, IK and Koch, I. (2001) Experimental design for the economic performance evaluation of industrial controllers. IFAC MMM Symposium, Kyoto.

Craig, I.K., Hulbert, D.G., Metzner, G., Moult, S.P. (1992). Optimised multivariable control of an industrial run-of-mine milling circuit. J. SAIMM, Vol. 92 No.6. pp 169-176

Gossman, G.I., Hulbert, D.G., Buncombe, A. (1984). Application of multivariable control to milling circuit at the East Driefontein Gold Mine. SAIMM Colloquium on Control and Simulation in the Minerals Industry.

Hulbert, D.G., Craig, I.K., Coetzee, M.L., Tudor, D. (1990). Multivariable Control of a Run-of-Mine Milling Circuit. J. SAIMM, Vol. 90, No.,7. pp173-181

Koudstaal, J., Hulbert, D.G., Braae, M., Gossman, G.I. (1981). The application of a multivariable controller to an industrial grinding circuit. 8th IFAC World Congress, Kyoto Japan August 1981 Reprint Vol. XXII. pp 210-215

Pauw, O.G., King, R.P., Gardner, K.C., van Aswegen, P.C. (1984). SAIMM Control of pebble mills at Buffelsfontein Gold Mine using a multivariable peak-seeking controller. Colloquium on Control and Simulation in the Minerals Industry.

Schubert, J.H., Babarovich Hansen, V.P., Smith, V.C., Singh, A., Hart, J.R. (1998) Implementation of advanced milling controllers with the interpreting expert system. Minerals Engineering '98 Edinburgh Scotland.