The Non-Linear adaptation of a Multi-Variable Predictive Controller as applied to the Mill 3 Circuit at Alcoa's Wagerup Refinery

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ABSTRACT:

The operation of grinding circuits are vital to the success of most mineral processing operations in the provision of effective size reduction whilst maximising throughput. However these same circuits, and especially semi-autogenous grinding (SAG) mills, are highly interactive with product re-circulations that produce non-linearities. This makes the optimal control of these difficult by conventional controllers, such as PID.

In order to account for the non-linearities and the abnormal situations that continually beset these circuits, it is necessary to adapt linear control techniques to cater for these situations. The Honeywell Hi-Spec Solutions SmartGrind^{TM} controller is a marriage of multivariable predictive control (MPC) with techniques that provide non-linear adaptation of the control to optimise the circuit. Optimal control is achieved by incorporating pattern recognition techniques to detect and act on discrete events (eg ore type changes) and adaptation of the MPC to account for known process and equipment non-linearities.

Alcoa's Wagerup Refinery is the first site world-wide to have this technology applied to the SAG milling circuits and this has resulted in throughput increases and significant improvements in circuit operations. This paper describes the adaptation of multivariable control to the refinery's Mill 3 bauxite grinding circuit and the capacity/operational improvements achieved thereof.

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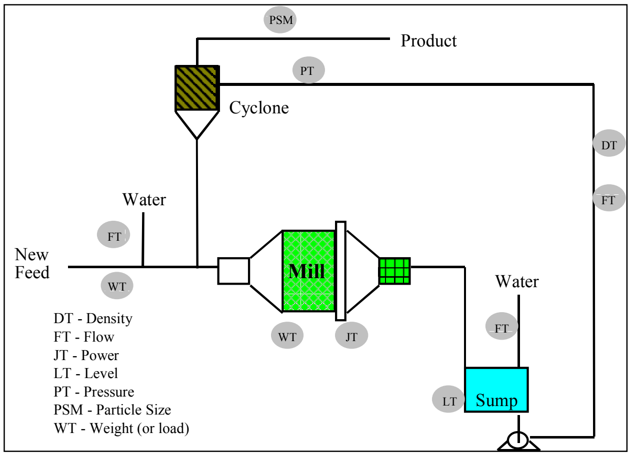
INTRODUCTION

Multi-variable predictive control (MPC) has been popularised and exploited by the oil & gas industry for the last 15 years. This technology has been used to maximise the profits of processing plants, by applying a control solution that can stabilise and push the plant close to many constraints simultaneously. MPC has been applied in this industry because if implemented well, it can realise significant improvements in throughput in the region of 2 to 5%. The payback on a typical MPC project is normally less than one year.

The mining industry has recently been looking at MPC technologies because economic pressures dictate that maximum value be extracted from their process equipment. The application of MPC to milling circuits poses a number of technical challenges. These challenges arise from the discrete events, non-linearities and time dependent process changes that occur within typical milling circuits.

Milling Processes

A typical grinding circuit is shown in below.



The grinding mill illustrated uses many measurements for controlling the stability and throughput of the operation. There are three physical inputs to the circuit (New feed, and two water additions) and one output (properly sized ore from the cyclone). In addition, the circuit draws power, and measures flow, density, level, weight, and other signals such as particle size.

The main objective of the grinding circuit is to deliver to the downstream processing material of the correct size for recovery of the valuable minerals. Generally milling circuits are the bottleneck for the process. Considerable additional revenue can be attained by pushing additional material through the milling circuit.

Control Problems

There are three main difficulties experienced with the control of milling circuits:

1. Delay Times
   Because of the large capacity of milling equipment and the re-circulation of material there can be considerable lags between making a set point change and seeing the completed change on the process variable. Some steady state settling times may approach 2 hours or more. Thus in order to correctly account for disturbances a mill operator must be constantly considering the process situation up to two hours ahead of the current time, this can cause instability especially with inexperienced operators.

2. Variable Interactions
   Variables also interact with the other variables to different degrees. For example, product size could be controlled by the cyclone feed density which, in turn, could be controlled by the sump water addition. However alteration of the sump water addition will also affect the circulating load which, in turn, will affect the mill load, power and ultimately the product size. Thus in order to adequately control this process, all variables should be controlled simultaneously.

3. Power Load Relationship
   There is an inverse parabolic relationship between mill power and load which is dependent upon ore type, size, operating density and ball loading. Maximum grinding efficiency, and therefore maximum production rate, occurs at the point of maximum power on the power / load relationship**.** On this basis there should be a theoretical optimum load set point that maximises production. In practice it is desirable to operate somewhat below the optimum, to ensure consistency of process gains. The optimum operation therefore implies selecting a load setpoint slightly below the inflection point on the power/load curve, with the intention to maximise production, while maintaining controllability of the mill.

Multi-variable Predictive Control

The majority of mill controls make extensive use of PID (Proportional, Integral and Derivative) controls. However in order to cope with the variety of problems, the control schemes are de-tuned and run conservatively to avoid process upsets. Generally changes are only made on an infrequent basis which provides for a more stable operation but may fall short of optimising the circuit (and sacrifice profits). This means that the circuit is operated below the possible constraints, providing the potential for throughput improvements.

In order to control this process, control schemes must be able to account for multiple interactions between variables. This is the domain of multi-variable predictive control (MPC). MPC formulations enable robust control that can handle input and output constraints, dead-time, high order dynamics, co-linear control problems (from a dynamic and steady state perspective) and optimisation.

MPC ADAPTATION FOR MILLING

The key to successful acceptance of MPC in this industry is the ability of the controller to handle unusual process upsets and to recognise operation realities such as:

- Discrete events such as changes in ore size and type can lead to process upsets such as mill overloads and/or power excursions in SAG mills. These events, sometimes can be measured and some can be inferred from patterns in process signals.
- Process equipment dynamics is non-linear within the band of normal operation. Examples of these are:
- Events leading to mill overload can show changes in model type (1st order to integrating) and gain inversion.
- The performance of the mill product sizing device (e.g. DSM screen)
- Availability & reliability of process instrumentation.

Controlling a SAG mill is a non-linear problem near capacity constraints. Designing a controller that addresses the above issues can be split into 2 groups.

- Factors that can be influenced (controllable) by the handles available (feed/liquor), and
- Factors that are not directly measurable, but can be detected by subtle changes in plant measurements.

Controllable Factors

During normal operation the following process models are key to controlling the milling circuit.

- Feed rate (increasing feed increases the mill load)
- Liquor flows (increasing liquor flows decreases the mill load)

Feed and liquor flows exhibit linear behaviour significantly below the capacity limit of the mill but as the mill is loaded, non-linear behaviour can be observed.

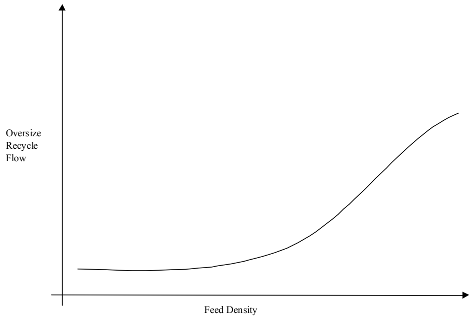
The physical capacity limit of the mill can be defined as the point where the discharge mechanism cannot remove all of the material that is being fed into the mill. This causes a problem with a linear controller because the dynamic models change from a positive stable model for bauxite feed (or negative stable model for liquor additions) to positive integrating (unstable) models for both. These changes arise when the material entering the mill cannot be removed. Thus mill contents integrate above “maximum” capacity and have stable dynamic models below maximum capacity. These model changes can be attributed to changes in the mill operating curve, physical limitations of the mill or interactions between the two. They can be temporary (a dynamic transient) or permanent in nature (pulp lifters or grates are limiting).

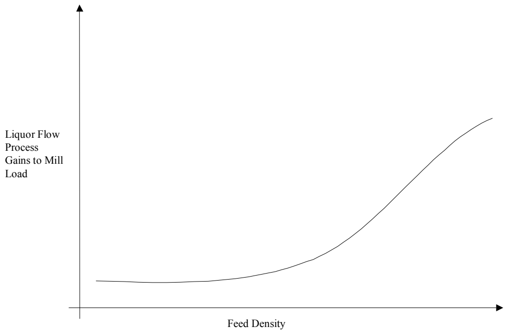
Mill feed is made up from fresh bauxite feed, liquor addition and recycle from the sizing device. Recycle is not measurable or controllable but can be influenced by manipulation of the density at the sizing device.

Recycle is influenced by a number of factors.

- Oversize recycle increases as sizing device feed density increases
- Oversize recycle increases as sizing device feed flow increases
- Oversize recycle increases with long term plugging of the sieve

The influence of density on the recycle has been found to be the most effective method to linearise the influence of the sizing device performance on mill load. This can be done by adjusting the process models of the on-line multi-variable controller. The following graph illustrates this concept.





Uncontrollable Factors

Whilst operating high feed rates, the following factors must be accounted for by the control application.

- Ore type and size changes
- Changes in slurry consistency (which can be partially dependent on feed type/size and recycle)

These disturbances can shift the mill operation to a position below or above the maximum circuit capacity. The latter implies potential mill spillage.

These uncontrollable process changes are not directly measurable, but an inference of them can be made by on-line statistical analysis of the load, power and mill discharge flow signals and combinations thereof. The installed application uses mill load/power and mill load/ discharge flow analyses to improve control of the mill at high capacities.

Mill Load/Power

As discussed previously, SAG & AG mills have an inverse parabolic relationship with respect to load and power. The shape and position of these curves is dependent on ore size, ore type, operating density, feed rate, recycle, ball loading and mill physical characteristics. This means the shape of the curve can change within normal operating parameters. Operation on the RHS greatly increases the tendency for mill spillage.

Detection of this "state" is done by a statistical error analysis using a moving window of operating data. RHS detection is interfaced with the multi-variable controller Mill load CV high limit to guide the mill to a more desirable operating point.

Mill Load/Discharge rate

Changes in the mill “state” such as those described above can cause a coincidental rise in mill load and reduction in mill discharge flow. This is not necessarily a “bad” mill dynamic, but mill feed rate should not be increased in such a situation. In a similar method to above, the mill load high limit is temporarily constrained as the disturbance should be allowed to move through the mill.

Rapid changes in Power or Load

Some disturbances require rapid reductions in feed rate. If these disturbances are not addressed mills can over fill or trip on motor power protection. The application installed on the SAG mill at Alcoa Wagerup reduces feed rate upon detection of a rapid change in mill load or power.

ALCOA WAGERUP MILL 3

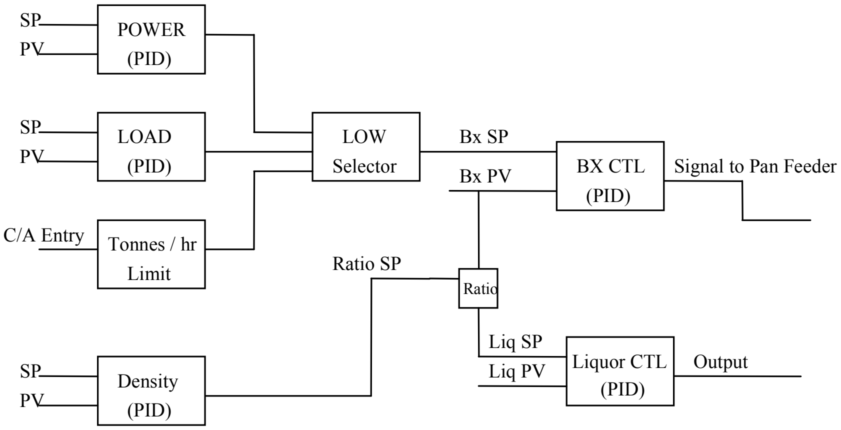
Process Description

The Wagerup Semi-Autogenous Grinding (SAG) Mill is a closed circuit milling device, in which feed bauxite is slurried and ground in the presence of steel balls. The mill discharge passes through Dutch State Mines (DSM) sieving screens and oversize material is returned to the mill feed chute, while product or undersize material is pumped to slurry storage facilities. The circuit was well instrumented although deficiencies were found with some of this equipment during the course of controller implementation.

The control objectives are:

1. Maximise mill production rate.
2. Maintain DSM feed density.
3. Maintain product grind
4. Minimise process disturbances (eg mill overloads etc.)

The mills were previously equipped with a PID-based control strategy This control scheme uses a low selector determines whether power, load or tonnage (a high limit imposed by the operators) is used for control of the bauxite feedrate. The pulp density is regulated by a PID controller, which adjusts the ratio of liquor to bauxite. This is illustrated below:

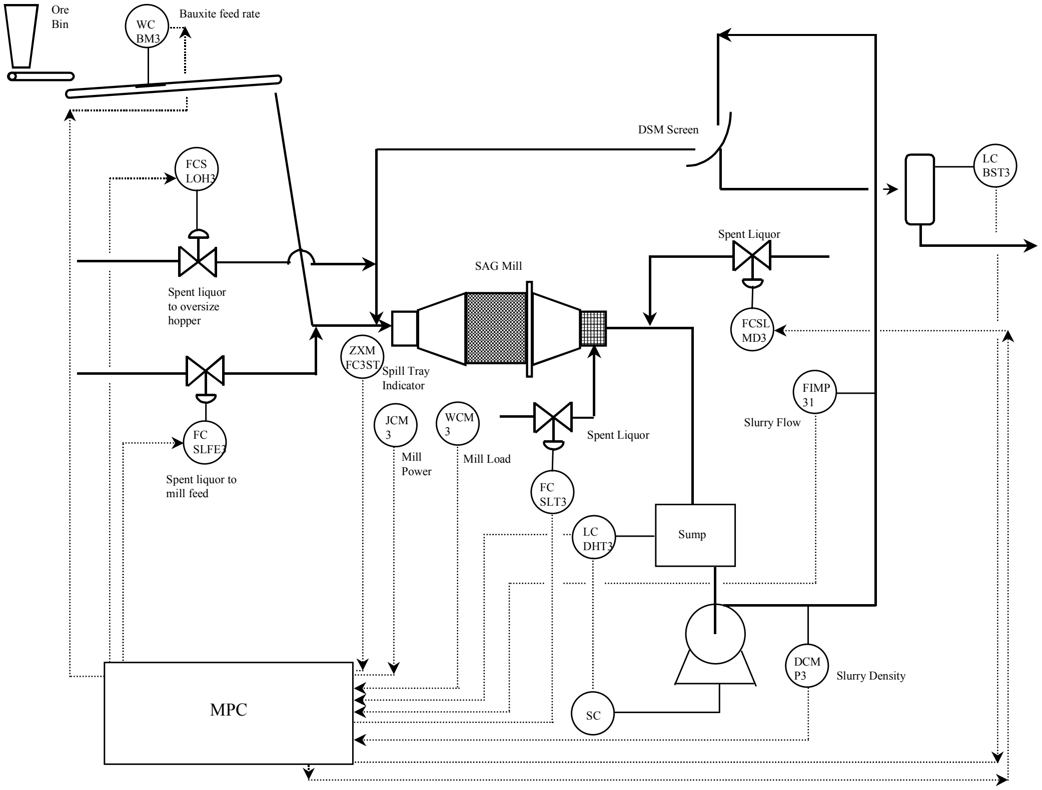


This scheme was found to work satisfactorily, though for optimum use it was heavily reliant upon the operator for the correct selection of the set points. If this was not done, saw-toothing could occur in switching from one selected item to another. In addition, it was found that for the majority of the time the control of the feedrate was just selecting the feedrate limit put in by the operator because they had entered a lower than optimum setpoint to obtain stable operation.

The major problem experienced was overloading of the mill, which resulted in material spillage. Under this circumstance the feedrate was cut resulting in production losses. This was estimated to result in over 1% loss in production.

MILL 3 SMARTGRIND^{TM} IMPLEMENTATION

The SmartGrind^{TM} implementation on Mill 3 is illustrated below.



The application provides set points to the bauxite and liquor additions, the manipulated variables (MV's). It does this to keep the variables that need to be controlled, controlled variables (CV's) within constraints. The existing control scheme (ratio control to spent liquor and the low select to the bauxite feed SP), was not utilised.

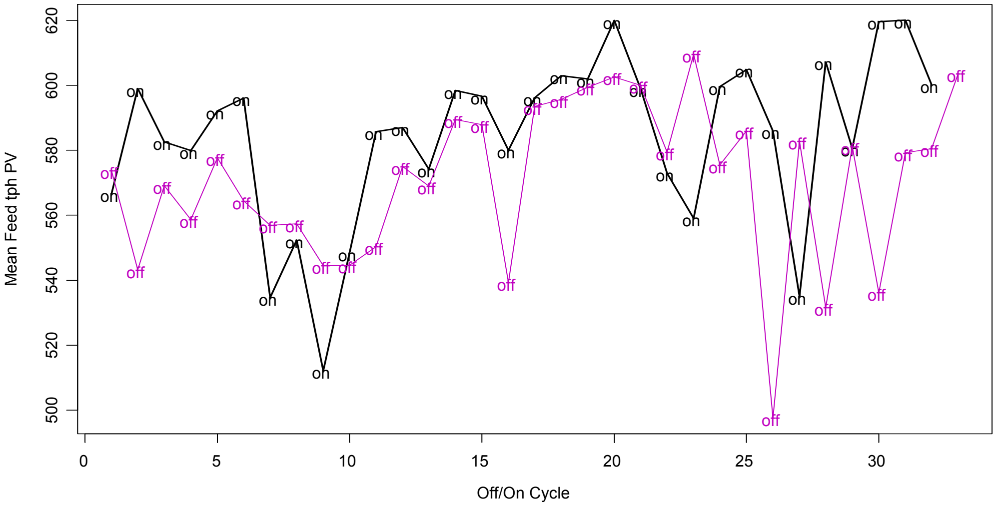
The MPC application, as a first priority, tries to keep the CV's and MV's within limits. Its next priority is to optimise the mill operations by pushing the MV's to maximise the throughput such that all its and CV's are within specified limits. The non-linear adaptation serves to provide the controller with the robustness to cope with the varied conditions experienced.

BENEFITS

Performance Tests

A rigorous series of on/off trials, for the MPC, were conducted over a two month period to determine the controller benefits under real operating conditions. This performance test was designed to mitigate the possible effects of external factors on the control operation, these being factors such as feed ore changes, bin level changes, ball charge, screen operation, day versus night and shift crews. Nominally 12 hour periods of on and off running were assigned and data was collected as 6 minute averages. This data was then reviewed and periods classified as either controller ON or OFF and periods of data to be ignored for various reasons.

The data was analysed by considering each trial period when the controller was ON and OFF as a trial block. The average throughput of the ON versus the OFF period was compared and a difference calculated. This was then repeated for successive blocks and is summarised graphically below:



In order to account for the different sample sizes all the data points in the ON and all in the OFF were averaged and the means and standard deviations compared. This allows each average to be evenly weighted and for a statistical confidence to be established. The results are summarised below:

	SmartGrind ON	**SmartGrind OFF**
Average Throughput (wtph)	588.0	579.3
Sample Number	5007	6853

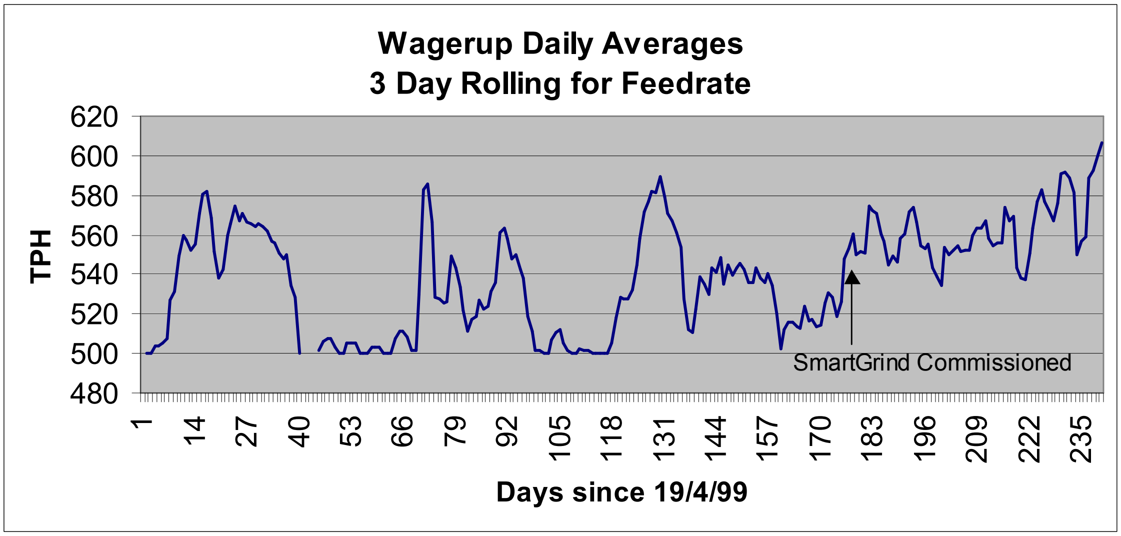
Mean Difference	8.7 wtph (1.5%)
95% Confidence	+/- 11.6 wtph (+/- 2.0%)

It should be noted that the low throughput is also a result of the operators actions to mimic the operation of SmartGrind^{TM} when the conventional controller was in use. This was observed to occur after several runs of SmartGrind^{TM} ON. This could not be designed out of the performance test given the time constraints at the time.

Long Term Trends

The performance trials have increased the operator awareness of the control issues around the milling circuit. The result of this is that to a certain degree the operators mimic the action of the controller and hence have operated the circuit better since the controller was commissioned even if it is not being run. This is felt to have resulted in a smaller improvement that might otherwise have resulted.

A long term trend of the mill throughput shows a gradual increase since the controller was commissioned, even though the controller was not on for all of this period. This is shown below:



Since the MPC controller was commissioned there has been an increase in throughput and a number of record productions have been achieved. Whilst there have been other factors that have influenced this increase in throughput the SmartGrind™ controller has helped to sustain this improvement.

Non Quantifiable Benefits

In addition to the quantifiable benefits a number of other benefits have been identified:

- A reduction in the frequency of mill spillages. This was predominantly due to the inclusion of control modules to detect mill over loading.
- A decrease in the workload associated with cleaning up mill spills and a decrease in the use of illegal dilution (hose-water) and portable (hire) sumps.
- A positive acceptance from control attendants and the request to apply the scheme to other mills
- Consistently high mill throughput from a day to day basis enabling record mill throughputs to be achieved on mill 3 for same feed conditions
- The ability to increase mill throughput as favourable ore was presented to the mill circuit, resulting in record tonnages achieved through the mill.
- Standardisation of mill operations.

CONCLUSION

There are clearly significant benefits to be gained from the use of advanced control techniques for the control of grinding circuits. Multivariable predictive control (MPC) is a well proven advanced control technique that has been successfully applied for many years within the refining industry. In order for it to be successfully applied to grinding circuits it is necessary to account for the non-linearities within the circuit that could cause problems for MPC by itself. If this is done then this technology is applicable for grinding circuit control.

The application of a suitably adapted MPC controller to the Alcoa Wagerup grinding circuit resulted in an agreed throughput increase of 1.5%. In addition to this there were significant gains from stabilisation of the circuit and the subsequent reduction in variability assisted in all aspects of the circuit operation. This was clearly demonstrated by the operator acceptance of the controller and the high utilisation. The result being that together with the throughput increase there will be significant additional benefits resulting from the improvement in circuit operations.