DESIGN, DEVELOPMENT AND IMPLEMENTATION OF A GRINDING EXPERT CONTROL IN ELEVEN GRINDING CIRCUITS AT SOUTHERN PERU COPPER CUAJONE

Nelver Benavides and René Llerena

Southern Peru Copper Corporation – Concentradora Cuajone
Campamento Minero Southern Peru Cuajone
Peru

Fernando Cornejo and Andrea Festa

SGS Minerals Canada - Advanced Systems Group
1140 Sheppard Avenue W. Unit #6
Toronto, Ontario, Canada M3K 2A2

Alan Gomez

SGS Minerals Chile - Advanced Systems Group
Puerto Madero 9600
Parque Industrial Puerto Santiago
Pudahuel, Santiago, Chile

ABSTRACT

The Advanced Systems Group at SGS in collaboration with Grupo Mexico's Cuajone Mine designed, developed and implemented a global expert control system for eleven primary ball mill circuits. Each circuit operates in a closed loop with a single cyclone classification stage with the overflow product reporting to flotation. The primary objective of the expert system is to stabilize and optimize the performance of each grinding circuit, delivering increased throughput while keeping the cyclone overflow product quality in range. The control strategy contains three different multi-input modes to maintain control with varying levels of instrumentation availability and to ensure sustainability of the application over time. This innovative approach considers a combination of available instrumentation, soft sensors and fundamental control developed on process engineering principles. The resulting application delivers the ability to switch between control modes in response to the plant's instrumentation availability. The expert system was proven to increase by 4.8% the average throughput of the eleven ball mill circuits in parallel with a reduction of almost 10% in power consumption and 2.4% in fresh water usage. The system maintained a utilization rate close to 95%.

INTRODUCTION

The key elements in the implementation of any advanced control system are continous availability and reliability of plant instumentation. These elements allow for accurate and timely decision-making of any advanced tool and promote better control. However, experience has shown that the average processing plants have often instrumentation deficiencies which can negatively affect the utilization and functionality of advanced control techniques.

In Grupo Mexico's Cuajone Mine, SGS proposed an alternative approach for addressing this common siuation in today's plants. This approach utilized compensating techniques including soft sensors as well as relative process indicators; both designed to substitute for the lack of specific instrumentation readings such as Particle Size Indicator (PSI). This innovative approach resulted in a higher utilization of the expert system from the initial implementation stages of the project. This was made possible through continual operational confidence in the expert's actions, even when critical instrumentation was not available.

The objective of the expert system was to first stabilize and then optimize the grinding circuit. This was done though adjustments in the setpoints of the feed rate, water flow rate to the mill and the water flow rate to the hydrocyclone feed sump, which resulted on maximization of plant throughput while keeping the product size within operational specifications.

In this project, the use of multi pronged, flexible logic strategies compensated for outages of online particles size readings. Three different sets of logic (i.e. logic arms) were considered; the first logic consisted of a hierarchical control structure with the full range of instrumentation available in the plant, including the PSI. The second logic arm activates when the quality of the PSI readings goes "bad" and replaces them with estimated values from PI soft sensors. Findings showed that two hours after the quality of the PSI readings had gone "bad" the soft sensors lost accuracy and therefore, a third logic kicks in. This third logic is comprised of relative loading indicators such as ball mill power, pump amperes, sump levels and hydrocyclone pressure.

The grinding Expert System was coded in the SGS' expert platform called MEC (Mineral Expert Console) which runs on the Gensym software. The connectivity between the expert system and the Distributed Control System (DCS) is via an OPC server. Cuajone selected the MEC platform due to its reliability and wide usage across the industrial sector.

Process description

The Cuajone Mine is located 840 km south from the city of Lima in Moquegua, Peru. The site is owned by Grupo Mexico and operates a concentrator plant with a processing capacity of 32 million tpa of ore to produce 624,000 tpa of copper concentrate.

The comminution process consists of a crushing circuit receiving ROM from an open-pit mine; the crushed product is tipped onto a stockpile and then transferred to the primary grinding stage which is comprised of:

- Eight 16.5 ft dia x 20 ft long Alice Chalmers ball mills and one 16.5 ft dia x 20.8 ft long Polysius ball mill with an installed power capacity of 3000 HP each.

- Two 20 ft dia x 33.5 ft long Svedala ball mills with installed capacity of 9000 HP each.

All eleven primary ball mills operate in a closed loop circuit with a hydrocyclone classifier where the cyclone overflow reports to flotation and the underflow is recycled back to the ball mill as shown in Figure 1.

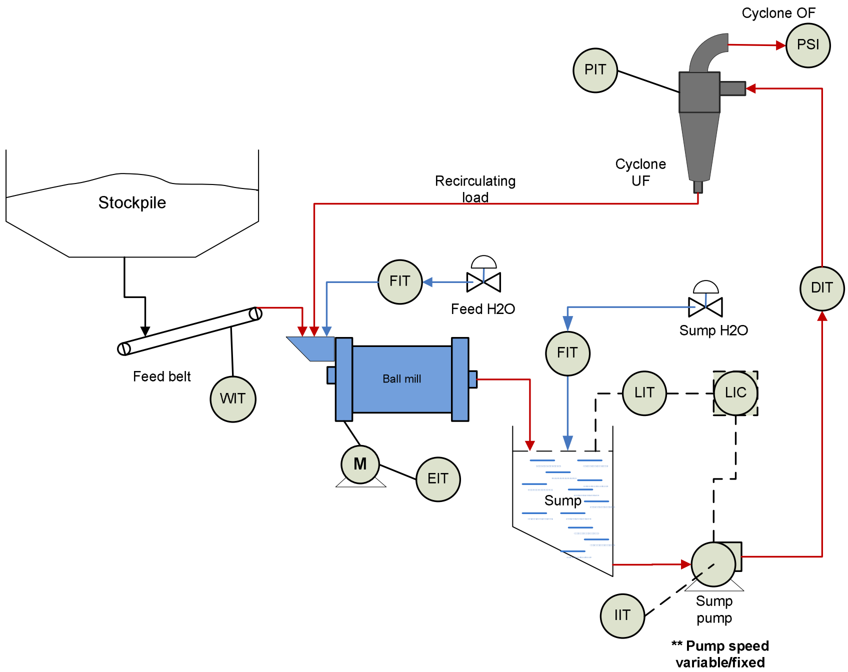


Figure 1 Ball Mill circuit

This paper describes the steps followed for the integration of the grinding expert system in this large scale plant, as well as the benefits achieved in terms of increased throughput and stable grinding product quality. Of particular importance to this project is how existing secondary and tertiary estimation models allowed temporary replacement of actual field readings.

METHODOLOGY

The methodology used for the design and implementation of this expert system was inclusive and progressive. The application contained Cuajone's operational knowledge in a tangible format to ensure sustainability and longevity of the expert system. The commissioning methodology consisted of three main steps: 1) knowledge capture; 2) application coding, installation and coarse tuning and 3) fine tuning and Site Acceptance Test (SAT). These steps will be expanded upon in this section.

Knowledge Capture

The knowledge capture step was initiated with a series of interviews in which the SGS team met with site personnel to review and discuss their current operating practices. Key operational scenarios for inclusion in the expert control strategy were identified from this review. It also made evident that the expert control logic would require the implementation of parameters to handle ore competency (i.e. hard, medium and soft) and liner conditions (i.e. new, worn-in and worn-out).

Key instrumentation readings as well as their availability were determined over time. The product particle size was identified as a key parameter used in the expert system logic; however, its availability was limited in comparison to other field readings. This low availability represented a project risk with potential negative effects on system utilization and it had to be mitigated with the use of soft sensors.

Application coding:

The conventional single-arm logic of the expert system contains several operational scenarios such as ball mill Overload (OL), Slight Overload (SO), Active Process Constraints, Optimization, Stability and Low Load (LL). This logic structure is hierarchical (i.e. risk-related importance) and characterized by ball mill circulating load, mill power draw and grinding product size as shown in Figure 2.

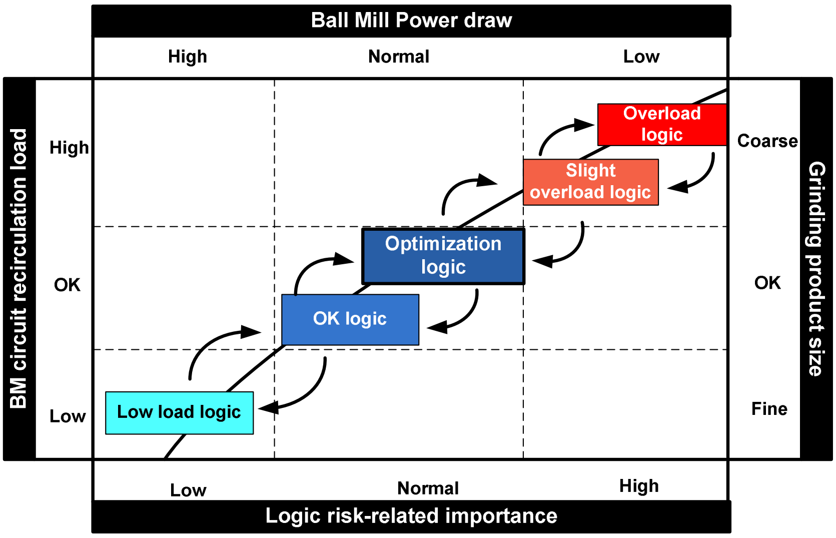


Figure 2 Operational states considered in the expert logic

The expert control dynamics first drive key grinding process variables into the OK state of its logic hierarchy. In this logic state, stability of the ball mill power draw and grinding particles size are continuously monitored and their statistical deviation reduced. Once the system is considered stable, then the optimization stage kicks in by adding small but sequential step changes in tonnage, mill feed water addition and water addition to the hydrocyclone feed sump. The ultimate goal of the expert system is to keep its optimization logic controlling the grinding circuit as much as the process allows.

The Slight Overload (SO) logic is oriented to correct any sudden increase of circulating load (normally followed by power decreasing and coarser grinding product). This correction is done by acting first on mill densities followed by the reduction of tonnage as final measure. The Overload (OL) logic entails more aggressive actions to correct higher circulating loads giving tonnage reduction equal priority to density manipulation.

As previously mentioned, the lack of reliable and constant PSI readings were identified as a constraint during early stages of the project; thereby negatively impacting the expert system utilization. To mitigate this risk, the SGS team modified the conventional single arm expert logic (shown in Figure 2) to a multi-set of logics (i.e. logic arms) seen in Figure 3. These additional arms contained the same operational scenarios considered in the first and principal logic but additionally contained two compensating techniques such as soft sensors and relative process indicators separately. The multi-input logic allows the expert system to adapt its control strategy to different levels of available instrumentation without compromising its usage. The three logic arms included in this control strategy were the following: 1) Arm 1 - PSI signal is OK; 2) Arm 2 - PSI signal is NOT OK but virtual sensor signal is OK and finally; 3) Arm 3: whenever PSI signal and virtual sensor signals are both NOT OK.

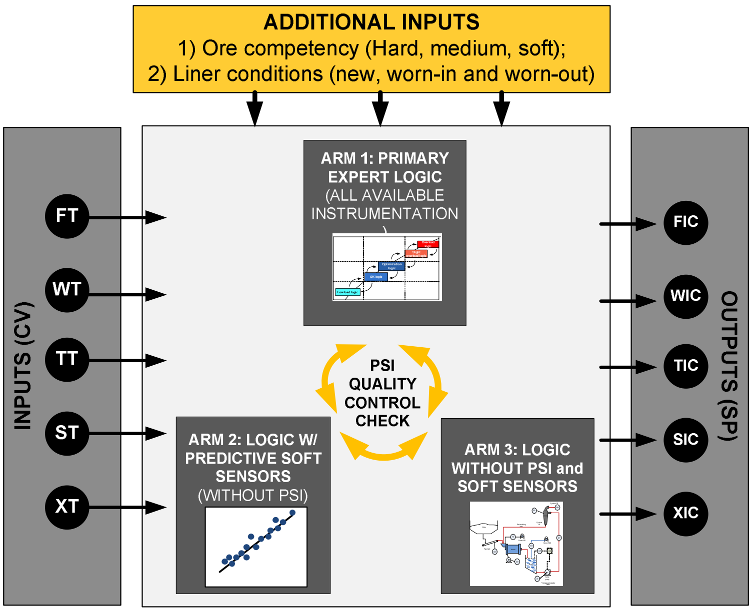


Figure 3 Multi-pronged expert system design

The control logic has additional components implemented to monitor other operational aspects of the grinding circuit such as: high (close to overflow) sump levels, high pump amps, high or low cyclone pressures, etc.

Soft sensors

The twenty two soft sensors used in the expert system were built by the Cuajone Process Control Department. These sensors determine particle size of the cyclone overflow stream as well as overflow percent solids in each ball mill circuit. They are calculated using a commercial multivariable statistical software built on the PI platform called SCAN Online.

The creation of the soft sensors started with sensitivity and contribution analyses which served to identify key operational parameters affecting the product particle size and solids as well as their importance weights. These parameters were also analyzed using a Partial least Squares regression (PLS-regression) which is a statistical method that bears some relation to principal components regression. During these analyses, data outliers were eliminated and different operational sub-groups or operational regions identified. The soft sensors were then created considering the variables with greater contribution to the “estimation” objective (i.e. particle size and solids) as well as the number of sub-groups identified in the process. The final step was the definition of time delays for each of the model variables (i.e. time required to see any effect on the predicted sensor after making step changes on each of its model variables) and these were defined based on plant tests.

The created soft sensors were launched online to assess estimation ranges, which shown to be fairly good; however, their prediction quality decreased down to unacceptable levels after two hours for most of the models. These estimations are sent to the DCS via OPC for other purposes.

Relative process indicators

The relative process indicators were built to allow expert control under scenarios with faulty PSI and soft sensor readings. These indicators are a combination of primary process variables such as ball mill power draw, sump level and cyclone pressure as well as their process slopes; this is done to estimate relative changes of mass-recirculation within the ball mill circuit. The main assumption behind these estimations is that mass changes will indeed affect grinding particle size levels. Basically, whenever mass-recirculating flow increases then coarser product particle size will output the process and viceversa. The relative indicators will only be used within the third arm of the logic by replacing PSI and soft sensor inputs; which are considered more absolute measurements. To validate expert control under these conditions, plant tests were performed and results indicated that assumptions made were acceptable as long as ore competency does not suffer drastic changes.

The switching between logic arms is based on a quality control logic implemented in the expert system shown in Figure 4. This logic analyzes quality of PSI and soft sensor readings using online statistics as well as their moving averages, variable limits and process slopes. The logic is simple and triggers automatically as signals become unavailable and restores control to the principal arms (i.e. Logic arm 1 and 2) as readings show OK quality.

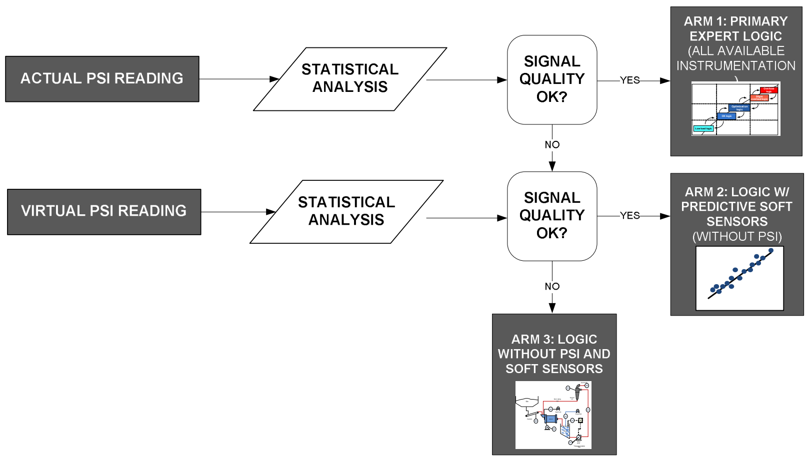


Figure 4 PSI & Soft sensor quality control logic

Installation of Application – Set up of interface and coarse tuning

Once site has set up the interface as per the functional specification, the connectivity was tested and consequently the manipulated and measured variables were checked for proper validation and filtering so as to provide inputs to the logic. After completion of these commissioning checks, the application tuning could commence. During tuning, site feedback was a key factor to confirm all logic. The initial collaboration with the site personnel with a "live" application uncovered additional opportunities for improvement. Training of the operators and administrators starts. At the end of this stage the application ran with the on-site assistance of the administrators and a period of testing began.

Final tuning of Application

The third and final stage in the process was to finalize the tuning and complete operator and administrator training. The expert operating trends and data were reviewed and the logic analyzed for possible "holes".

Following the final site visit, the Site Acceptance Testing (SAT) period began. The SAT test is a period in which site runs the expert system in ON/OFF periods to quantify the benefits of its implementation. A set of Key Performance Indicators (KPIs) are defined with site to measure expert system performance and confirm that it has effectively reached its objectives. The expert system installed at Cuajone had the following performance objectives: 1) Increase throughput by 1%; 2) Maintain the product particle size within specifications (<25% below +65 mesh) and; 3) Utilization above 90%.

RESULTS AND DISCUSSION

The objectives were exceeded. Figure 5 shows the impact of each project stage on monthly throughput as compared to an initial benchmark of 1% increased throughput. The overall increase in throughput from April to December of 2009, the year of project implementation, was an average of 4.8%. Cuajone started to benefit from the expert implementation from start of tuning in April 2009. The second tuning visit was delayed until September 2009, at this time the system was fine tuned with soft/OK ore type.

The SAT from November to early December 2009 yielded a throughput increase of 6.65%. An additional site visit was scheduled right after the SAT test to further tune the system under hard ore conditions, which brought up the average tonnage increase up to 7.6%.

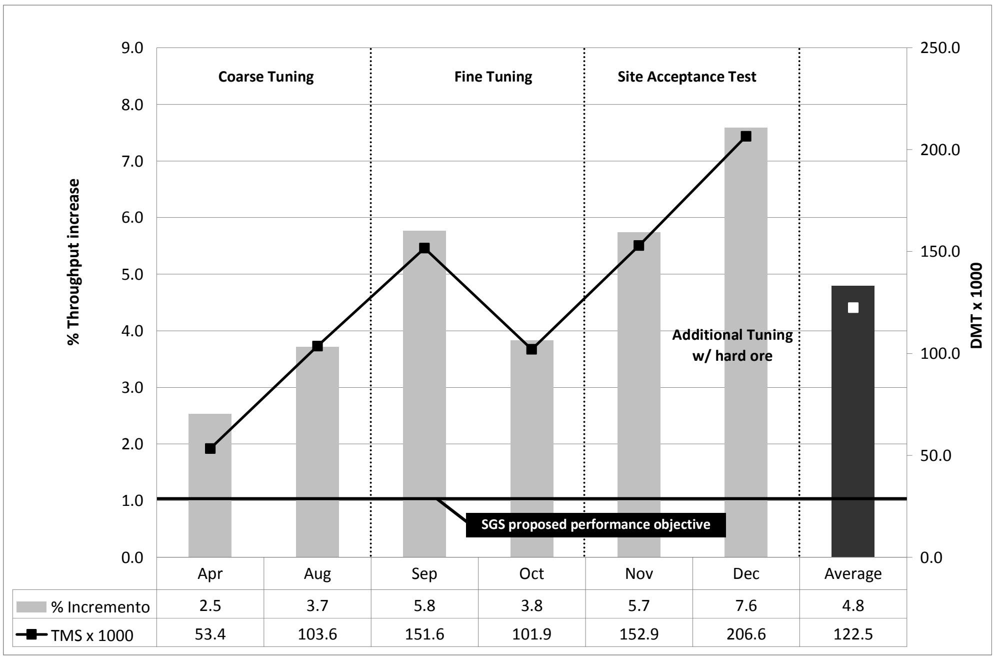
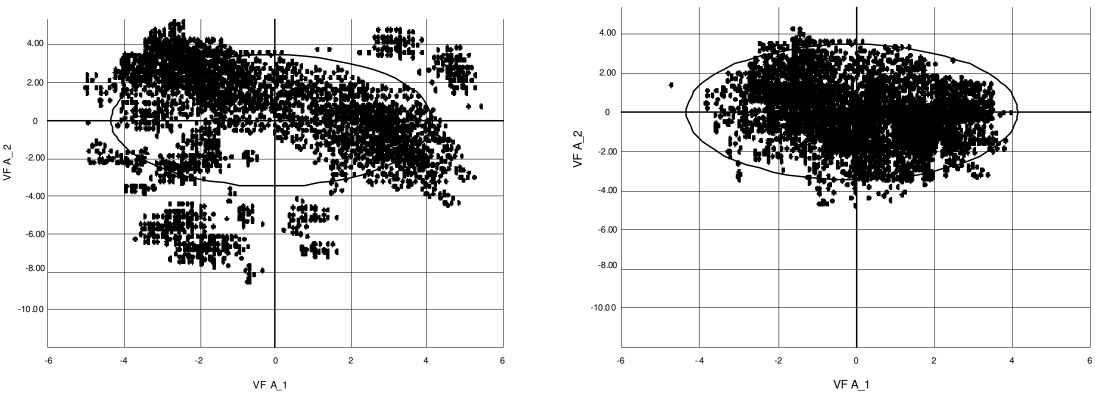
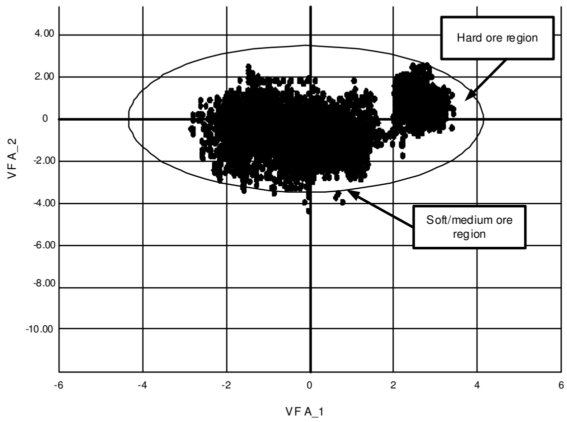


Figure 5 Expert System's performance during the project life-cycle

Figure 6 shows the dispersion of process data clusters for one of the eleven ball mills in Cuajone. This cluster analysis was done over a period of 4 months and covers different stages of the expert project. Figure 6A shows cluster dispersion levels before the expert system was implemented; the observed dispersion suggests multiple operational regions with low process stability. As the expert system is commissioned and tuned, the data dispersion becomes more centralized (Figure 6B and 6C) achieving higher degree of process consistency and stability. This enhanced stability in combination with consistent grinding product size (i.e. kept at an average of 24.7% 65 mesh) had a positive effect in the downstream flotation circuit. The grinding product size was closely monitored by operations personnel during the expert implementation and was also validated with shift lab results. Similar data clusters were observed for the other ten grinding circuits.



(A) (B)



(C)

Figure 6 Data cluster dispersion for ball mill No. 1B operating without Expert system (A); with Expert coarse tuned (B) and; with Expert fine tuned (C)

The expert utilization for the eleven ball mill circuits averaged 94.7% from April to December 2009. It should be mentioned that high utilization of the expert system by operations personnel was observed since it was first installed at site, which was a result of two main factors 1) The multi-arm logic approach that allowed the expert system to still run under instrumentation-constrained scenarios and 2) The support from local management.

This implementation also provided secondary benefits such as the reduction of grinding power consumption by almost 10% at an average of 8.7 kW/Ton (2009) compared to the 9.5 kW/Ton value reported for 2008. Overall water consumption was also reduced by 2.4% reporting an average consumption of 1.32 m3/Ton in 2009 compared to the average 1.36 m3/Ton in 2008.

The three logic arms achieved different levels of stabilization and optimization in controlling these eleven grinding circuits; the first logic arm being the most effective at bringing and maintaining the grinding circuit within optimal levels; followed by the secondary arm. The third arm also showed an enhanced ability to stabilize the system and slightly optimize its throughput when compared to the manual operation.

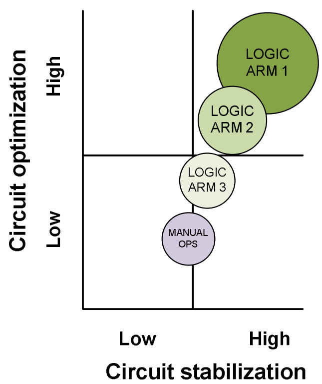


Figure 7 Degree of stability/optimization achieved by expert logic arms

It should also be mentioned that Cuajone has improved the PSI availability, which represents higher utilization of the primary logic arm during expert online periods.

Further calculations to quantify overall expert benefits from April 2009 up to July 2010 have been performed by site personnel. Results have shown an average tonnage increase of 4.3%; this percentage is equal to an additional production of 1.8 million tons.

CONCLUSIONS

- Results have shown an overall throughput increase of 4.3% from April 2009 to July 2010. The increased production was achieved without affecting grinding product size, which was kept within specifications as provided by Cuajone.
- Flotation performance was marginally affected by the increased throughput. From April 2009 to July 2010, flotation statistics showed a drop in recoveries of 0.5% from an average of 87.2% down to 86.7%. This slight drop in recoveries is considered to be marginal by site management based on the substantial benefits achieved in grinding capacity.
- Secondary benefits such as reduced power and water consumption were also achieved by the expert system.
- The use of multi-input logic arms has allowed the expert system utilization to remain high and constant since it was first installed averaging 94.7%.
- The grinding expert system implementation resulted on a new standardized way of operating the grinding plant across different shifts; this combined with the high utilization has resulted on less production variability between shifts and a more stable daily production.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude and acknowledgement to all the personnel at site involved in the expert system for their continued support and assistance during the project commissioning. A special thanks to Nelver Benavides, Gary Jarama and Rene Llerena for sharing their knowledge and experience with SGS.

NOMENGLATURE

MEC	Mineral Expert Console
SPCC	Southern Peru Copper Corporation
PSI	Particle Size Indicator
BM	Ball Mill
KPI	Key Performance Indictor
SAT	Site Acceptance Test

REFERENCES

1. A. Festa, F. Cornejo, F. Orrante, R. Alanis, B. Gutiérrez, “Implementation of Expert Systems at Penoles Group Concentrators”, 2009 Canadian Mineral Processing Conference, Ottawa, Canada, 191-204.
2. G. Metzner, F. Cornejo, J. Steyn, C. M. Westcott, A. Festa., Britts, E. Barnard, “Implementation of a SAG Expert System at Barrick North Mara – Tanzania”, 2009 World Gold Conference, Johannesburg, South Africa, October 2009.
3. Cornejo F., Festa A., Gomez A., Yaroshak P. “Expert Control of Crushing Circuits at Barrick South America” – Proceedings of the Conference of Metallurgists 2009, Canada, August 2009.
4. Sloan R., Parker S., Craven J., Schaffer M., 2001 Expert Systems on SAG Circuits: Three Comparative Case Studies. Proceedings of the International SAG Conference 2001. 346-356
5. Jonas, R., 2007. Advanced Control for Mineral Processing: better than Expert Systems. CMP 2007. 421-443.
6. T.J. Napier-Munn, S. Morrel, R.D. Morrison, R.D. Kojovic, Mineral Comminution Circuits – Their Operation and Optimisation, T. Julius Kruttschnitt Mineral Research Centre, Australia, 1996.