Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Grinding Mill Circuits - A Survey of Control and Economic Concerns

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Abstract: A worldwide survey on grinding mill circuits in the mineral processing industry was conducted. The aims of this survey are to determine how milling circuits are currently controlled, and to find out how key process variables are linked to economic benefits. The survey involves background information on the circuits, the choice of controlled and manipulated variables, the economic impact of the controlled variables, adopted control technologies, and assessment of control performance. 68 responses were received as a whole. Survey results are contrasted to the milling control literature.

Keywords: Grinding mill circuits, survey, process control, performance assessment, economic benefits, costs, performance functions.

1. INTRODUCTION

Grinding mill circuits are the most energy and cost intensive unit processes in the mineral processing industry and therefore the study of the control systems for grinding circuits remains important. The primary objective of control systems is to maximise benefits. A technically successful control system is not necessarily an economic success. The economic performance assessment of control systems is receiving increasing attention and a relevant framework, which provides a systematic procedure for the economic assessment of process control, was proposed in Bauer and Craig (2008). In this framework, performance functions, which relate controlled variables to profit/loss, play a crucial role.

A survey on the current practice of process control and (economic) performance assessment as applied to grinding mill circuits was conducted to capture industry guidelines and standards. The survey also highlights performance functions that could be used for a systematic economic performance assessment of grinding circuits. The questions in the survey that were used to derive the performance functions were also intended to facilitate generating some ideas on how to develop performance functions for other processes. The main survey results are given in this paper. Furthermore, a number of publications on milling control are examined and the content relevant to the survey is used to contrast the survey results.

The organisation of this paper is as follows. Firstly the research methodology that was used in the survey and the questionnaire design are given in Section 2. The main survey results are then elaborated on in Sections 3, 4, and 5 in line with the questionnaire structure. The main survey conclusions are given in Section 6.

2. RESEARCH METHODOLOGY AND QUESTIONNAIRE DESIGN

The survey was carried out via a web-based questionnaire at *http://millingsurvey.ee.up.ac.za* and the distribution and collection of an MS Word document. Data were then collected from the middle of April until the middle of June 2007. In total, 68 responses were received, of whom the positions are shown in Fig. 1. Several channels were used to target the respondents, ensuring that the relevant experts were chosen.

At the end of April 2007, the survey was sent to 850 relevant professionals. It was also sent to members of the South African Institute of Mining and Metallurgy. Furthermore, professionals who had published literature on control of grinding mill circuits were contacted directly. The extensive search for respondents ensured that the respondents came from all over the world, as can be seen in Fig. 2.

The questionnaire was designed to cover various aspects of grinding mill circuits. The first part identifies the respondents and the second part is aimed at obtaining background information on the circuits. The third part

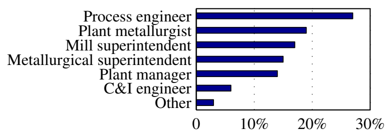


Fig. 1. The positions of the respondents

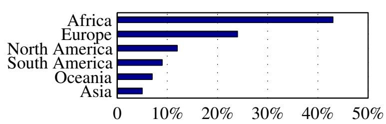


Fig. 2. Continent distribution of the respondents

involves the choice of key process variables and their economic impact. Part four is concerned with the control of milling circuits and control loop performance and part five covers economic concerns.

Most questions were posed as close-ended responses that allow the respondent to choose an answer and to analyze the results in a straightforward manner. A glossary at the end of the questionnaire explained the terminology used in the questionnaire.

3. CHOICE OF CRUCIAL PROCESS VARIABLES AND THEIR ECONOMIC IMPACT

3.1 Choice of key process variables

Choice of controlled variables: The respondents were asked to specify which variables are most often controlled. It can be seen in Fig. 3 that the product particle size, slurry level in the sump, and sump discharge slurry density are the three most frequently used controlled variables. The product particle size is often considered as a major controlled variable, see e.g., Hodouin et al. (2001), Niemi et al. (1995), Yahmedi et al. (1998), Ramasamy et al. (2005), Pomerleau et al. (2000), Muller et al. (2003), Craig and Macleod (1995, 1996), Ivezić and Petrović (2003), and Hulbert et al. (1990). The mill load and slurry level in the sump are usually open-loop unstable, requiring some form of control (Craig et al., 1992a). The slurry level in the sump is used as a controlled variable in Muller et al. (2003), Craig and Macleod (1995, 1996), and Hulbert et al. (1990). The sump discharge slurry density is controlled in Niemi et al. (1995), Muller et al. (2003), and Hulbert et al. (1981). The mill throughput is controlled in Yahmedi et al. (1998) and Ramasamy et al. (2005) and mill load is controlled in Craig and Macleod (1995, 1996), Muller et al. (2003), and Hulbert et al. (1990). The 'Feed ratio' in Fig. 3 means the feed ratio between feed of solids and water to the mill.

It can be seen in Fig. 3 that the respondents did not select all the variables. In the following questions concerning each controlled variable (Sections 3.2 to 3.5), the proportions are based on the respondents who selected that variable as a controlled variable.

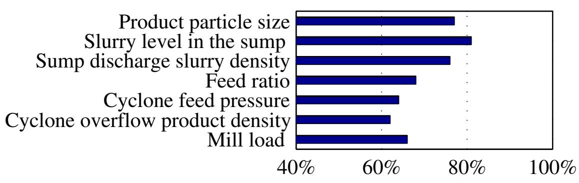


Fig. 3. Choice of controlled variables

Choice of manipulated variables: Fig. 4 shows the choice of manipulated variables. The flow rate of water to the sump, flow rate of water to the mill, feed rate of solids to the mill, and flow rate of slurry from the sump are all frequently adopted as manipulated variables. The flow rate of water to the sump is used as a manipulated variable in Hodouin et al. (2001), Niemi et al. (1995), Yahmedi et al. (1998), Ramasamy et al. (2005), Pomerleau et al. (2000), Muller et al. (2003), Ivezić and Petrović (2003), Hulbert et al. (1981), and Hulbert et al. (1990). The flow rate of water to the mill is used as a manipulated variable in Muller et al. (2003) and Hulbert et al. (1981). The usage of the feed rate of solids to the mill as a manipulated variable is discussed in Hodouin et al. (2001), Niemi et al. (1995), Ramasamy et al. (2005), Pomerleau et al. (2000), Muller et al. (2003), Ivezić and Petrović (2003), Galán et al. (2002), and Hulbert et al. (1990). The flow rate of slurry from sump is manipulated in Muller et al. (2003) and Hulbert et al. (1990). The 'Other' in Fig. 4 comprises the mill speed and the mill feed size.

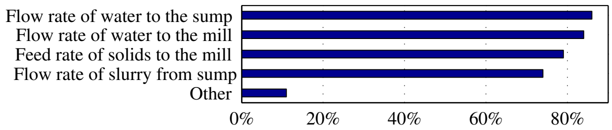


Fig. 4. Choice of manipulated variables

3.2 Setpoint choice, corrective action, and economic impact of the product particle size

The respondents were asked to state the considerations when determining the setpoint for the product particle size. The efficiency of the downstream process is of primary importance (89%). Circuit throughput is also an important factor (53%).

Two main actions taken to grind finer than expected are to decrease the feed rate of solids to the mill and to increase the flow rate of water to the sump. These actions are mainly performed manually (62%). Two main actions taken to grind coarser are to increase the feed rate of solids to the mill and to decrease the flow rate of water to the sump.

The main economic consequences of grinding finer than the setpoint were given as better extraction downstream and a reduced throughput. Grinding coarser than the setpoint has the opposite effect.

3.3 Setpoint choice, corrective action, and economic impact of the sump level

As for the considerations when choosing the setpoint for the sump level, the stability of the system is the first priority (78%). Maintaining a margin of safety is the second choice (67%).

The most frequent action taken, when the sump level is too low, is to increase the feed rate of water to the sump (47%). To reduce the feed rate of slurry from the sump discharge is of secondary importance (39%). When the sump level is too high, reducing the feed rate of water to the sump is the first priority (44%). The other two often used actions are to increase the feed rate of sump discharge slurry and to investigate whether the controller runs normally. These actions are mainly done automatically (83%).

The respondents were asked to specify the qualitative economic impact of the sump level deviating from the setpoint. When the sump level is higher than the setpoint, most (94%) of the respondents indicated that spilled slurry needed to be handled, which would lead to some costs. When the sump level is lower than the setpoint, the largest percentage of the respondents state it will adversely affect the normal operation. 15% of the respondents indicated that the throughput could be adversely affected.

3.4 Setpoint choice, corrective action, and economic impact of the mill load

The efficiency of power consumption is the first priority (80%) when considering the choice of the setpoint of the mill load. The stability of the system is also regarded as an important factor (67%).

The most frequently taken action, when a mill load is too low, is to increase the feed rate of solids to the mill (73%). In some milling circuits, the mill speed is decreased (29%) or water addition to the mill feed is reduced (27%). When mill load is too high, the opposite actions are taken. These actions are mainly conducted manually (53%).

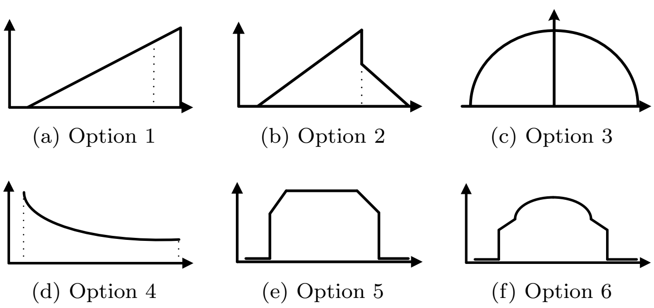
The qualitative economic impact of the mill load deviating from the setpoint is investigated. When the mill load is too high, stoppage of the mill to reduce the load and thus interrupting production is chosen by 47% of the respondents. Additional manpower required to reduce the mill load manually is taken into account by 22% of the respondents. When the mill load is too low, the largest percentage of the respondents (87%) indicated it would lead to excessive ball-on-liner contact and therefore to damage of the mill liners. Consuming more steel and a decreased throughput are both regarded as serious consequences. Around half of the respondents stated that a too low mill load would result in a waste of power.

3.5 Setpoint choice, corrective action, and economic impact of the sump discharge slurry density

The stability of the system is the first priority when determining the setpoint of the sump discharge slurry density (53%). Smooth running of the system is regarded as important by almost half of the respondents (47%). Avoiding cyclone choking is also considered significant by 41% of the respondents.

When the sump discharge slurry density is too low, the three most frequently taken actions are to decrease the flow rate of water to the sump, to increase the feed rate of solids to the mill, and to reduce the flow rate of water to the mill. When it is too high, the opposite actions are adopted. These actions are primarily conducted automatically (65%).

The qualitative economic impact of the sump discharge slurry density deviating from the setpoint is now considered. When the density is too high, downstream process inefficiency and decreased production are regarded as the most important consequences by the largest percentage



(a) Option 1 (b) Option 2 (c) Option 3

(d) Option 4 (e) Option 5 (f) Option 6

Fig. 5. The options of performance functions

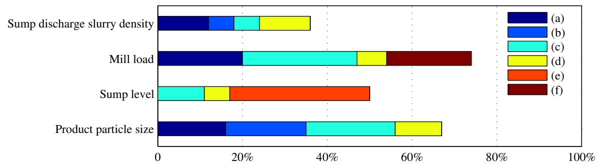


Fig. 6. Economic impact of the controlled variables deviating from the setpoints. The (a), (b), (c), (d), (e), and (f) here refer to the subplots in Fig. 5 respectively

of the respondents (chosen by 73% and 53% of the respondents respectively). When the density is too low, the impact is primarily the potential wastage of reagents in downstream processing and losses in recovery (76%).

3.6 Performance functions of the controlled variables

The respondents were asked to specify the relationships between the controlled variables and the relevant economic impact. Several sample performance functions are provided in Fig. 5 that are used frequently for economic assessment of control systems (Bauer et al., 2007). Option 4 can be found in Craig et al. (1992b) to relate residue (money) and product particle size. The respondents could also come up with their own relationship. The y coordinate is used to represent revenue or cost, and the x coordinate is for the controlled variables.

The results are shown in Fig. 6. It can be seen that the majority of the respondents selected options describing the economic impact of the mill load (74%), but only one-third did so for the sump discharge slurry density (36%). 68% of the respondents indicated the economic impact of the product particle size, and 50% of the respondents did so for the impact of the sump level.

For all the controlled variables in Fig. 6, more than one figure was selected to describe the economic impact. The investigation of the physical meanings of the monetary value indicates that different curve types are usually accompanied by different definitions of the monetary value. That means that when considering the economic impact of one controlled variable, the types of the performance function may depend on how the revenue or cost is specifically defined for particular milling circuits.

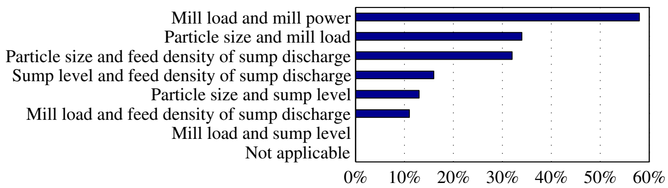


Fig. 7. Dependence of controlled variables

3.7 Dependence of controlled variables

The respondents were asked to specify which variables are dependent when the control system is in place. When the multivariate nature of a system is considered, performance functions of the individual controlled variables can become joint performance functions, which can lead to a more accurate estimation of the system's economic performance

(Wei et al., 2007). The results are shown in Fig. 7. The mill load and the mill power are regarded as dependent by over half of the respondents (58%). Another two pairs of variables that are regarded as dependent by a considerable percentage of respondents are the particle size and the mill load, and the particle size and the density of slurry of the sump discharge.

4. CONTROL OF GRINDING CIRCUITS

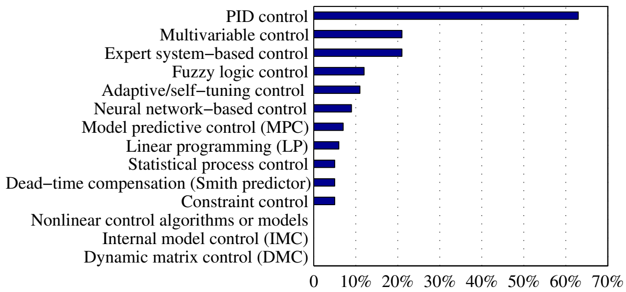


Fig. 8. Control technologies used in milling circuits

Choice of control technology: Control techniques used by the survey respondents to control their grinding circuits are shown in Fig. 8. The majority of the respondents use PID control (63%). This is in contrast to the process industries in general where model predictive control dominates (Bauer and Craig, 2008). Ivezić and Petrović (2003) declares that more than half of all industrial controllers are of the PID-type. PID control is discussed in Edwards et al. (2002) and Pomerleau et al. (2000). Multivariable control and expert system-based control are less frequently used but more often than other control technologies. Multivariable control is discussed in Yahmedi et al. (1998), Pomerleau et al. (2000), Hulbert et al. (1981), Hulbert et al. (1990), Craig and Macleod (1995, 1996). Expert system-based control is discussed in Herbst et al. (1989) and Lo et al. (1996). Fuzzy logic control is discussed in van Dyk et al. (2000). Adaptive control is investigated in Desbiens et al. (1997). Model predictive control is becoming increasingly popular (Muller and de Vaal, 2000; Cipriano et al., 1989; Niemi et al., 1995; Ramasamy et al., 2005; Coetzee and Craig, 2007).

Frequency of monitoring the control loop performance: In most of the grinding mill circuits, the control loop performance is frequently monitored (online: 40%, daily: 32%). Weekly monitoring is mentioned by 18% of the respondents. There is basically no mill circuit without control loop monitoring, which is in line with recent trends (Jelali, 2006).

Satisfaction with control loop performance: Only a few of the respondents are **completely** satisfied with the control loop performance (8%). A significant percentage of the respondents (38%) indicated that there was room for performance improvement. This could be due to the fact that PID control is used predominantly for a process that is inherently multivariate.

5. ECONOMIC PERFORMANCE ASSESSMENT FOR THE GRINDING CIRCUITS

5.1 Benefit types and methods of estimating benefit

The respondents were asked to indicate three main contributors to the benefits of a process control system. Process stability improvement was regarded as the primary contributor (71%). Throughput increase and energy consumption reduction are also seen to be main contributors (54% and 50% respectively). This is similar to what was reported in Bauer and Craig (2008) for the process industries as a whole. The contribution of the throughput increase to benefits is discussed in Herbst et al. (1989), Hulbert (2002), Galán et al. (2002), Perry and Hall (1994), and van Dyk et al. (2000). Energy consumption reduction is regarded as an important source of benefit in Lo et al. (1996) and Galán et al. (2002).

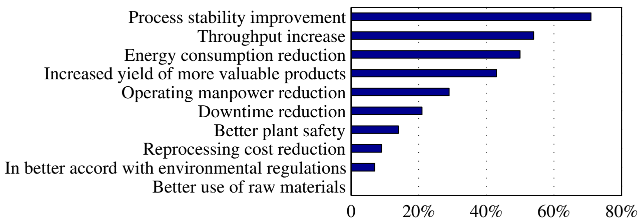


Fig. 9. Benefit types due to a process control system

As for the methods of estimating the benefits before the control system is implemented, past experience with similar projects is more often used (86%). Before control variance estimation is another frequently used method (78%). As for the methods of calculating the benefits when the control system is in place, in most of the milling circuits (89%), experiments are conducted where respondents switch between the old and new control system, similar to what is described in Craig and Koch (2003). 17% of the respondents indicated that qualitative estimate was performed.

5.2 Cost types and estimation methods

The respondents were asked to state three main contributors to the costs of a control system, which are shown in Fig. 10. The main contributors are control hardware, consultant manpower cost, and cost of technology. These are chosen by 73%, 57%, and 55% of the respondents respectively. The cost types are discussed in Herbst et al. (1988). This is in contrast to results reported in Bauer and Craig (2008) where manpower cost was dominant and control hardware played a lesser role.

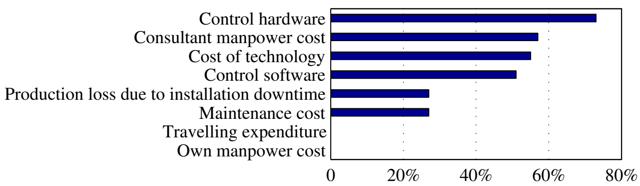


Fig. 10. Cost types of a process control system

As far as the methods of estimating the cost of a control project for milling circuits are concerned, two frequently used methods are past experience with similar projects (91%) and installation cost quoted by the vendor (83%).

5.3 Importance and accuracy of, and satisfaction with economic assessment

The importance of economic analysis at different stages of control system implementation is considered. Fig. 11 indicates that cost/benefit analysis is indispensable before the system implementation for half of the respondents. After-control analysis is also important, but not as important as before-control analysis.

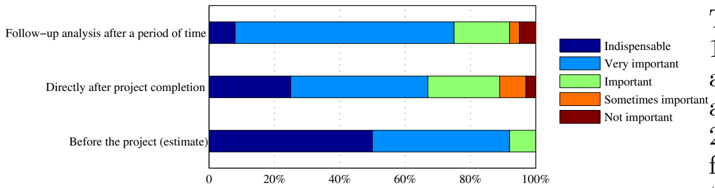


Fig. 11. Importance of economic analysis

The respondents were asked to state how accurate the economic analysis should be at different stages of control system implementation. The requirement of being as accurate as possible before system implementation is not as strong as directly after implementation. Overall, the economic analysis needs to be at least accurate before and directly after implementation.

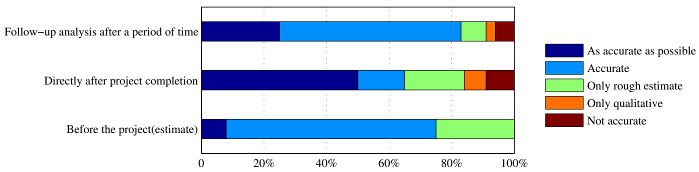


Fig. 12. Accuracy of economic analysis

The respondents were asked to declare how satisfied they were with the current economic analysis technique at different stages of a control system implementation. Less than half of the respondents were satisfied with their cost/benefit analysis methods. Some respondents clearly expressed dissatisfaction with their analysis methods used.

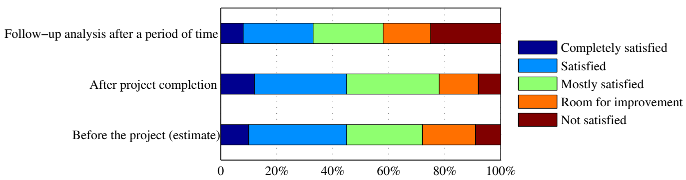


Fig. 13. Satisfaction with economic analysis

5.4 Most important topics requiring additional development

The respondents were asked to specify the three most important topics requiring additional development. Fig. 14 shows that a lookup table as reference guide is the most popular (61%). Combined analysis for process control and real time optimization was regarded as important by a majority of the respondents (59%). Base case benefit estimation from historical data was also selected by almost half of the respondents (47%).

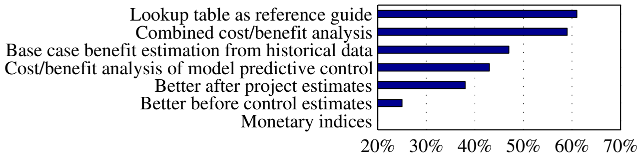


Fig. 14. Future trends: survey results

6. MAIN CONCLUSIONS OF THE SURVEY

The main conclusions from the survey are as follows:

1. The three variables that are most frequently controlled are the product particle size, the slurry level in the sump, and the sump discharge slurry density.
2. The most commonly used manipulated variables are the flow rate of water to the sump, the flow rate of water to the mill, the feed rate of solids to the mill, and the flow rate of the sump discharge slurry.
3. The following are the main considerations when choosing setpoints for the controlled variables: the efficiency of the downstream process (product particle size), system stability (sump level and sump discharge slurry density) and efficient power usage (mill load). Economic considerations are not explicitly stated.
4. There is usually some economic impact when the setpoints of controlled variables are violated.
5. Fewer than half of the respondents quantified the economic impact of the controlled variables deviating from their setpoints in terms of mathematical functions. Different mathematical functions were sometimes chosen for the same controlled variable. This implies that there is some confusion regarding the exact relationship between milling circuit controlled variables and money.
6. More than half of the respondents indicated that controlled variables were dependent on each other. This is not surprising as milling circuits are known to be candidates for multivariable control owing to the interaction of variables.
7. PID controllers are predominantly used in the grinding mill plants, and more than half of the respondents are satisfied with the performance of their control loops. This fact tends to counter point 6, and appears to imply that respondents are happy to live with the interactions that do exist.
8. Process control system benefits arise mainly from process stability improvements, an increase in throughput, and a reduction in energy consumption. The most popularly used method of estimating benefits is past experience with similar projects. The main elements of cost for a control system are control hardware, consultant manpower cost, and technology cost. The costs are mainly estimated from experience by similar projects and installation cost as quoted by a vendor.
9. Cost/benefit analysis is considered important at all stages of a control system implementation, with the analysis before a controller is implemented considered to be more important than the after-controller implementation and the follow-up analysis.
10. One-third of the respondents indicated the economic assessment of grinding control needed to be improved.

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