

A Method to Justify Process Control Systems in Mineral Processing Applications

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ABSTRACT: *The impact of installing process control systems can be expected in terms of performance improvements through reduced operating costs. Since these installations impose considerable capital expenditure, the profitability of the new systems should be economically justified. Controlled variable trend was reconstructed by a combination of simple waves, which provided a means to simulate the effect of installing a control system (feedback) by removing disturbance waves with high periods (> one cycle per hour). A method was proposed to evaluate the impact of installing a control system either by a reduction of difference between concentrate target quality and operating quality (i.e., bias reduction) or by reduction of scatter of product quality (i.e., variance reduction). Installing automatic control systems not only reduces operating costs, but also may increase revenue from washed coal sales by maintaining plant performance on designed or desired target. It was found that if an appropriate feedback control system is used at the flotation circuit of the Zarand coal washing plant, the variance of concentrate ash content could be decreased from the current value of 0.38 to 0.06. Based on the predicted metallurgical improvement, the payback time of installing a conventional control system for the flotation circuit of the Zarand plant size with the approximate cost of \$1,000,000 was found to be 2 years.*

KEY WORDS: *Control system, Justification, Zarand coal washing plant.*

INTRODUCTION

Process control has become widely recognized as an essential component of any processing operation [1-3]. It has direct impact on productivity, process efficiency and product marketability. The reported paybacks associated with successful installations underscore this

observation. As a consequence, many operators who have not utilized process automation are looking to initiate control projects, while those who currently use some level of automation are looking to upgrade existing control systems [4].

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Important advances have been made in the field of automatic control of mineral processing operations, particularly in grinding and flotation. The main reasons for this rapid development are [5]:

- The development of reliable instrumentation for process control systems. On-line sensors such as flowmeters, density gauges, chemical composition analyzers, and on-line particle size analyzers have been successfully used in many plants [6].

- The availability of sophisticated digital computers at very low cost. The development of the microprocessor allowed very powerful computer hardware to be housed in increasingly smaller units. The development of high-level languages allowed relatively easy access to software, providing a more flexible approach to changes in control strategy within a particular circuit.

- A more thorough knowledge of process behavior, which has led to more reliable mathematical models of various important unit processes being developed [7]. Often the improved knowledge of the process gained during the development of the model has led to improved techniques for the control of the system.

- The increasing use of very large grinding mills and flotation cells has facilitated control, and reduced the amount of instrumentation required.

Financial models have been developed for the calculation of costs and benefits of the installation of automatic control systems [8-12], and benefits reported include significant energy savings, increased metallurgical efficiency and throughput, and decreased consumption of reagents, as well as increased process stability [13-16].

The question most frequently asked is: "What will automation cost and what will the economic benefits be?" To answer this question a complete justification study is needed. If the project team has little related experience providing a good answer is challenging. In most cases the costs, benefits and time requirements are underestimated. Project cost and time requirements tend to be somewhat easier to define, once the project scope is properly defined. Benefits present a more difficult problem since they require the impact of control system on the process [4].

The purpose of this paper is to describe and demonstrate a method which can be applied to estimate these potential

benefits, for certain types of control objectives. The method is based on characterisation of the controlled variable fluctuation and the effect of control system on reducing the variation. The justification problem will be introduced in general terms, and the underlying theory then will be explained along with a practical example from a coal processing plant in Kerman area.

The justification problem: A background

A process control system can impose significant capital and operating costs on process economics. For example, a retrofit control system project on an operation with predominantly manual controls can incur capital costs in excess of one million dollars. A great deal of instrumentation, hardware and software must be purchased/developed, installed and maintained. Management must be convinced that the project has a high probability of meeting its stated improvement goals with an acceptable financial return. In completing a justification study, one must consider all of the costs and benefits of the proposed project to ensure that management's interests are well satisfied [10].

The control system justification study can be thought of as a three step process:

- Identify and prioritize the potential control applications in the plant. Choose the application with the greatest potential.

- Evaluate the technical merit of the proposed control system.

- Evaluate the economic impact of the proposed control system.

Although there can be many reasons for investigating process control, e.g. environmental, safety, etc., better economic performance is the principal driving force to look for improvements in this area.

Usually the project costs are relatively easy to estimate based upon supplier data and information available from consultants. The benefits are more difficult to deal with. In this paper the focus is on the evaluation of the benefits of process control and, in particular, on the notion of increasing operating efficiency by operating at target values for the major production variables, while minimizing the variations that occur due to disturbances. Although cost reductions can be significant and will sometimes be enough to justify a control project, operating efficiency generally provides for much larger returns [4].

The technical and the economic merit of a proposed control system application are very important. The technical merit is assessed using the signal variance spectrum and the economic merit is estimated using the results of improvement in the technical evaluation.

There are several methods to evaluate the benefits of process control. In the order of increasing cost and increasing confidence in the results, these are:

- analysis of historical data
- plant studies
- dynamic simulation studies
- prototype control system testing on a portion of the plant

Plant studies may include some of the elements of the analysis of historical data as well as some of the sampling work that would be associated with dynamic simulation.

The method to be described falls into the second category. It is similar in concept to the dynamic simulation approach although approximations are employed to characterize disturbances. In addition, the analysis is conducted in the frequency domain and not the time domain usually associated with dynamic simulation.

THEORETICAL SECTION

Characterizing Disturbances

Process disturbances can be characterized by source and pattern. It is sometimes necessary to identify the potential sources of disturbances by careful consideration of the process inputs and operating features. In the method described in this paper the disturbances are lumped into a single, undefined source. With regard to pattern, in most process control applications various theoretical disturbance patterns, e.g. step change, ramp change and sinusoidal change are considered. In the proposed approach of justification, process disturbances are assumed to follow sinusoidal patterns.

Under the assumption that the process is linear, sinusoidal disturbances will be reflected as sinusoidal variations in the controlled variable. In practice the characterization is accomplished by high frequency sampling of the controlled variable. A Fourier series is then fitted to the time series which allows for the transformation of the data in the time domain to a variance spectrum in the frequency domain [11].

One source of experimental error which is not always mentioned is that which derives from the measurements, e.g. sampling, preparation and analytical errors.

This error could introduce a bias in the variance spectrum. It is important that in all sampling campaigns to take every effort to minimize the measurement error [4].

Typically, manual control is associated with low frequency-wide range fluctuations on the controlled variable. It is an experimental fact that, for many kinds of waves, two or more waves can traverse the same space independently of one another.

The importance of the superposition principle physically is that it makes it possible to analyze a complicated wave motion a combination of simple waves. In fact it was shown by Fourier all that we need to build the most general form of periodic wave are simple harmonic waves. Fourier showed that any periodic motion of a particle can be represented as a combination of simple harmonic motions. The general expression of such a combination is called a Fourier series [17]:

$$y_i = a_0 + \sum_{k=1}^{k_{\max}} \left(A_k \sin \left[\frac{2\pi k i}{N} + \varphi_k \right] \right) \quad (1)$$

where:

y_i = predicted value of the controlled variable at time i

a_0 = average value of y_i

k = wave number and k_{\max} = last wave

A_k, φ_k = Fourier coefficients for frequency component k (A_k = Amplitude and φ_k = Phase)

N = number of data points in the controlled variable data record

If it is assumed that the disturbance affecting the process is a sawtooth wave (Fig. 1), it could be reconstructed by considering only first six terms of the Fourier series each being a simple harmonic wave (Fig. 2).

The Fourier series for the above sawtooth wave approximation is:

$$y(t) = -\frac{1}{\pi} \sin \omega t - \frac{1}{2\pi} \sin 2\omega t - \frac{1}{3\pi} \sin 3\omega t - \frac{1}{4\pi} \sin 4\omega t - \frac{1}{5\pi} \sin 5\omega t - \frac{1}{6\pi} \sin 6\omega t \quad (2)$$

where ω is angular frequency.

Determination of Fourier series coefficients

In order to produce simple harmonic waves their amplitude (A) and phase (φ) should be determined. Eq. (1) could be expanded to obtain:

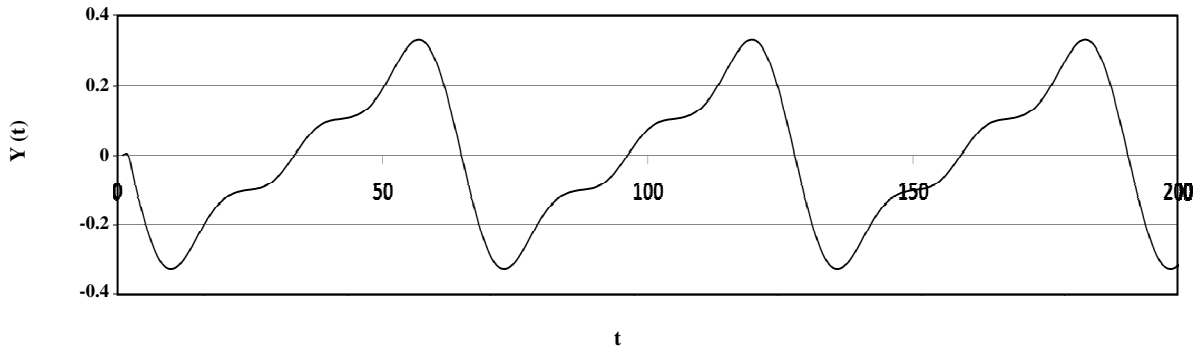


Fig. 1: A disturbance represented by a sawtooth wave.

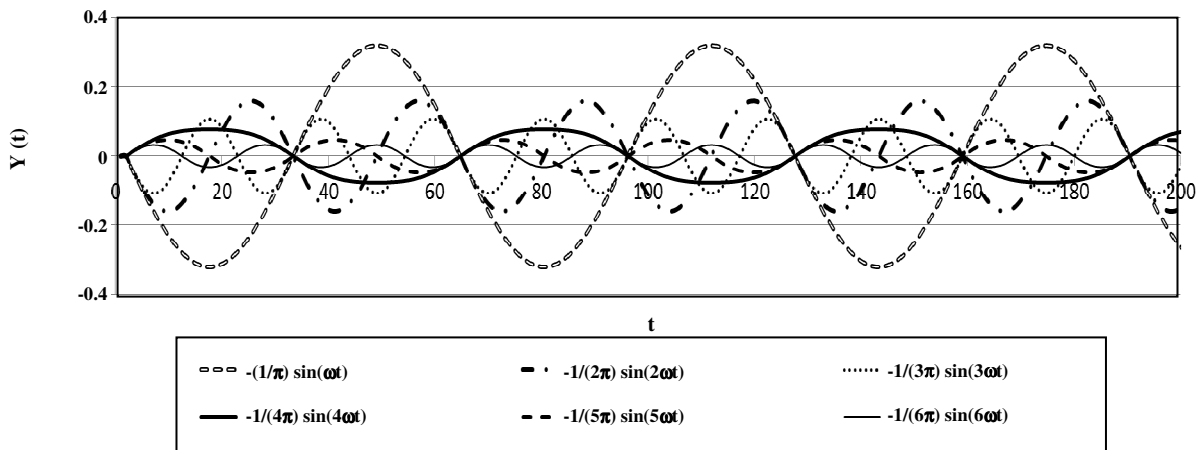


Fig. 2: The First six terms of the series.

$$y_i = a_0 + \sum_{k=1}^{k_{max}} \left(A_k \sin\left(\frac{2\pi ki}{N}\right) \cos\varphi_k + A_k \sin\varphi_k \cos\left(\frac{2\pi ki}{N}\right) \right) \quad (3)$$

If

$$A_k \cos\varphi_k = a_k \quad (4)$$

and

$$A_k \sin\varphi_k = b_k \quad (5)$$

then:

$$y_i = a_0 + \sum_{k=1}^{k_{max}} \left(a_k \sin\left(\frac{2\pi ki}{N}\right) + b_k \cos\left(\frac{2\pi ki}{N}\right) \right) \quad (6)$$

Eqs. 7 and 8 have been proposed to calculate a_k and b_k [18-19]:

$$a_k = \frac{2}{N} \sum_{i=1}^N y_i \sin\left(\frac{2\pi ki}{N}\right) \quad (7)$$

$$b_k = \frac{2}{N} \sum_{i=1}^N y_i \cos\left(\frac{2\pi ki}{N}\right) \quad (8)$$

Using Eqs. (4) and (5) one could arrive at:

$$A_k = \sqrt{(a_k^2 + b_k^2)} \quad (9)$$

$$\varphi_k = \arctan \frac{b_k}{a_k} \quad (10)$$

If N is an odd number then $k_{max} = (N-1)/2$ and a_k and b_k are computed by Eqs. (7) and (8). If N is even number $k_{max} = N/2$, $a_{k_{max}} = \frac{1}{N} \sum_{i=1}^N (-1)^i y_i$ and $b_{k_{max}} = 0$.

Variance spectrum

When a disturbance wave is reconstructed by superposition of simple harmonic waves, the total variance of the wave is summation of variance of each simple wave. If the variance of each simple wave is calculated then the variance spectrum could be obtained. In this research, the variance spectrum was calculated

Table 1: Twelve samples (N=12) taken from a controlled variable with time intervals of 20 min.

3.4	4.5	4.3	8.7	13.3	13.8
16.1	15.5	14.1	8.9	7.4	3.6

Table 2: Fourier coefficients of six simple harmonic waves approximating the signal.

k	a_k (Eq. 6)	b_k (Eq. 7)	A_k (Eq. 8)	$\delta_k^2 = \left[\frac{A_k^2}{2} \right]$	$f_k = k/N$	$p_k = 1/f_k$	$p_k/3$ (h)*
1	-5.30	-3.81	6.53	21.30	0.08	12.00	4.00
2	0.05	0.17	0.18	0.02	0.17	6.00	2.00
3	0.10	0.50	0.51	0.13	0.25	4.00	1.33
4	-0.52	-0.52	0.74	0.27	0.33	3.00	1.00
5	0.08	-0.59	0.59	0.17	0.42	2.40	0.80
6	0.30	0.00	0.30	0.05	0.50	2.00	0.67

* Note that since every 20 minutes samples were taken then to convert the period to hours they were divided by 3.

Table 3: Variance contribution of waves with various periods.

Lower-upper limits on period (hours)	Variance (mm ²)
2-4	21.32 (21.30+0.02)
1 - 1.9	0.40 (0.13+0.27)
0.67 - 0.9	0.22 (0.17+0.05)

using data collected from sampling of the process. The variance of each wave (δ_k^2) was calculated by [4]:

$$\delta_k^2 = \left[\frac{A_k^2}{2} \right] \quad \text{for } k = 1, 2, \dots, k_{\max} \quad (11)$$

Each δ_k^2 is a variance of a wave with a frequency of f_k (k/N) and a period of p_k ($1/f_k$). Therefore, k number of variances and periods are obtained. The total signal variance would then be:

$$\delta_{\text{Total}}^2 = \sum_{k=1}^{k_{\max}} \delta_k^2 \quad (12)$$

Variance spectrum calculation procedure

To illustrate the method it is assumed that 12 samples ($N=12$) with the time intervals of 20 minutes are collected from a controlled variable (Table 1). For $N=12$, $k_{\max}=6$ which means six waves could be superposed to approximate the controlled variable behavior.

Then Fourier coefficients and variances were calculated using Eqs. (6) to (8) as shown in Table 2.

The six waves could be grouped into three based

on the magnitude of their periods (Table 3). The grouping is arbitrary and does not affect the final results. The contribution of each group variance on the overall signal variance could then be calculated by summing the individual variances.

The variance spectrum of the signal (controlled variable) which could be approximated by six harmonic waves is shown in Fig. 3. The effect of installing a control system could be evaluated by removing variance contribution of the waves which could be eliminated by the control system [20].

Modeling the effect of control system on the process

It is assumed that both disturbance dynamics and the process control dynamics can be modeled as a simple first order linear system because linear approximations are often quite reasonable for control purposes. In these systems a sinusoidal disturbance will present a sinusoidal behavior in the process output. Feedback control system which is often used in plants is most effective for low frequency disturbance. In the high frequency, the process acts as a filter and reduces amplitude ratio. The low

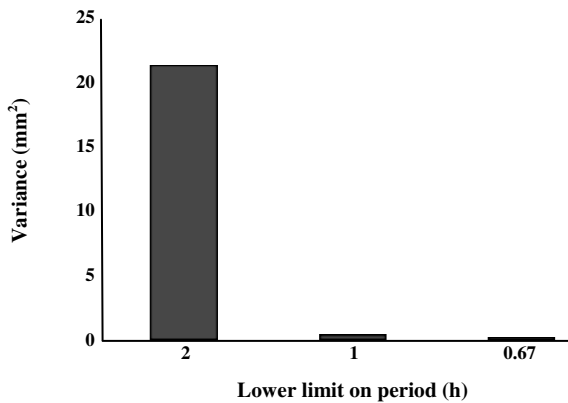


Fig. 3: Variance Spectrum of the controlled variable.

frequency level has been found to be 1 cycle per hour for most mineral and coal processing plants [10].

Process control can remove disturbances with frequencies lower than critical frequency (1 cycle per hour). This translates to a reduction in the variance; typically this variance reduction is substantial, about 90%.

QUANTIFYING ECONOMIC IMPACT OF VARIANCE REDUCTION

In most concentrate selling contracts either an average quality (a^* ; target value) or a limit for off-specification (a_L) products are defined. In other words, plants try to produce a concentrate with a minimum variation from the target value or try to reduce the amount of off-specification products by reducing the distribution of the concentrate quality values.

For further illustration, distributions of ash content (undesirable elements) of Dense Medium Separator (DMS) concentrate of the Zarand coal washing plant with and without control system are shown in Fig. 4. It is assumed that using a control system will reduce the spread of the concentrate ash content. The average ash contents (μ) and standard deviations (σ) of concentrates without and with control are 10.64%, 1.64% and 10.92%, 0.99%, respectively. This means that for the same amount off-specification products the target ash could be increased which translates to a higher yield (Fig. 4). If the acceptance limit of DMS concentrate ash (a_L) is assumed to be 11.5%, for no control case the amount of undesirable concentrate (off-specification) could be calculated using normal distribution curves characteristics (Z-score):

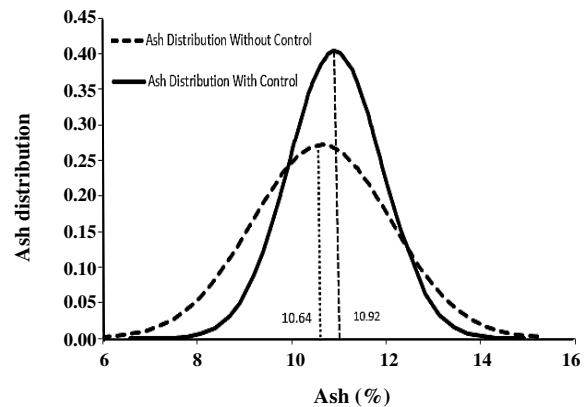


Fig. 4: Impact of a control system on ash distribution of a product at the Zarand coal washing plant.

$$Z = \frac{a_L - \mu}{\sigma} \rightarrow Z = \frac{11.5 - 10.64}{1.64} = 0.586 \quad (13)$$

The Z-score of 0.586 corresponds to a point where the area to the left side of the distribution is equal to 0.28 which means 28% of the concentrate in this case is out of limit and is unacceptable to the buyer. If the use of the control system results in a reduction of standard deviation from 1.64 to 0.99%, (assuming the same unacceptable area) then the new value of the target ash (μ_n) will be equal to 10.92%. In practice, this means that the weight of the product could be increased.

Modeling relationship between quality and quantity of products

A prerequisite to study the economic impact of a control system is to have a model to relate the quality to the quantity of the products. Each point in the relationship is a possible operating case which should be evaluated economically. By using a control system the operation moves to another location in this relationship which could be justified if it has a superior economic return over the no control case. It is then necessary to establish the relationship between controlled and other variables. Due to complexity, steady state models are used instead of dynamic models. It has been found that such approximation is appropriate when the disturbance frequency is low [9]. In this study, the quality of the product (ash content; a) and quantity (yield; y) relationship was used to justify the use of a control system.

At the steady state average yield (\bar{Y}) and ash (\bar{A}) can be computed by:

$$\bar{Y} = \frac{\int_0^T F(t)y(t)dt}{\int_0^T F(t)dt} = \frac{\sum_{i=1}^N F_i y_i \Delta t}{\sum_{i=1}^N F_i \Delta t} \quad (14)$$

$$\bar{A} = \frac{\int_0^T F(t)y(t)a(t)dt}{\int_0^T F(t)y(t)dt} = \frac{\sum_{i=1}^N F_i y_i a_i \Delta t}{\sum_{i=1}^N F_i y_i \Delta t} \quad (15)$$

where

T: sampling period

F(t), F_i: solid feed rate at time t or i

y(t), y_i: yield at time t or i

a(t), a_i: concentrate ash content at time t or i

N: number of samples

One method to solve these integrations is to transform time-dependent function (e.g., a(t)) to a probability density function (e.g., p(a)):

$$\int_0^T y(t)d(t) = T \int_{-\infty}^{\infty} y(a)p(a)d(a) \quad (16)$$

Expanding y(a) about the desired operating point (y*, a*) using Taylor series and ignoring terms with order three and above:

$$y(a) = y^* + \alpha(a - a^*) + \beta(a - a^*)^2 \quad (17)$$

where:

$$y^* = y(a^*) \quad (18)$$

$$\alpha = y'(a^*) \quad (19)$$

$$\beta = \frac{y''(a^*)}{2!} \quad (20)$$

y' and y'' are first and second derivatives of y(a).

Substituting Eq. (17) in Eq. (14) and using probability density functions properties and assuming constant feed rate (i.e., F(t)=F) will give:

$$\bar{Y} = \frac{\int_0^T y(t)dt}{\int_0^T dt} = \frac{T \int_{-\infty}^{\infty} y(a)p(a)d(a)}{T \int_{-\infty}^{\infty} p(a)d(a)} = \quad (21)$$

$$\int_{-\infty}^{\infty} [y^* + \alpha(a - a^*) + \beta(a - a^*)^2]p(a)d(a)$$

By integration and rearranging:

$$\bar{Y} = y^* + \underbrace{\alpha(\bar{a} - a^*)}_{\text{Offset}} + \underbrace{\beta(\bar{a} - a^*)^2}_{\text{Variation}} + \frac{\beta\sigma_a^2}{2} \quad (22)$$

where:

$$\int_{-\infty}^{\infty} ap(a)d(a) = \bar{a} \quad (23)$$

$$\int_{-\infty}^{\infty} (a - \bar{a})^2 p(a)d(a) = \sigma_a^2 \quad (24)$$

\bar{a} and σ_a^2 are the ash content average and variance, respectively. Inspection of Eq. (22) indicates that deviation of average yield (\bar{Y}) from the desired yield (y^*) could occur because of either low concentrate quality ($\bar{a} - a^*$; offset) or high variation of concentrate ash content (σ_a^2 ; variation). Since β (second derivate) is always negative any variation and offset will result in deviation of the average yield from the desired yield. The effect of poor control depends on the slope (α) and curvature (β) of yield-ash curve at the desired operating point (i.e., y^* , a^*). The use of a control system reduces or eliminates the bias ($\bar{a} - a^*$); in other words $\bar{a} = a^*$. Eq. (22) could be used to evaluate the effect of a control system by comparing the average yield with and without control. With no control case average yield will be lower than desired yield because of offset and variation effects. The difference between the yields of two cases should be higher than the costs of the control system in order to justify the use of control system.

Assuming a constant feed rate (F(t)=F) and substituting Eq. (22) in Eq. (15), the weighted average ash content could be calculated:

$$\bar{A} = \frac{\int_0^T y(t)a(t)dt}{\int_0^T y(t)dt} = \quad (25)$$

$$\frac{T \int_{-\infty}^{\infty} [y^* + \alpha(a - a^*) + \beta(a - a^*)^2] a p(a)d(a)}{T \int_{-\infty}^{\infty} [y^* + \alpha(a - a^*) + \beta(a - a^*)^2] p(a)d(a)}$$

By proper integration and ignoring order three and higher terms:

$$\bar{A} = \frac{y^* \bar{a} + \alpha(\sigma_a^2 + \bar{a}^2 - \bar{a}a^*) + \beta[\bar{a}(\bar{a} - a^*)^2 + \sigma_a^2(3\bar{a} - 2a^*)]}{y^* + \alpha(\bar{a} - a^*) + \beta(\bar{a} - a^*)^2 + \beta\sigma_a^2} \quad (26)$$

Note that \bar{a} is the average of ash contents during the sampling period (T) but \bar{A} is the weighted average of the ash contents in which the mass of the concentrates are also taken into consideration. The latter average is very close to the real average. Eq. (26) provides the average ash content with and without a control system through the use of different values for α and β .

Table 4: Fourier coefficients and variances calculated for ash content trend line.

k	a_k	b_k	A_k	δ_k^2	f_k	P_k	Period (min)	$\Sigma\delta_k^2$
1	0.0455	0.5386	0.5405	0.1461	0.0244	41.0	615.0	0.1906
2	-0.0239	0.2973	0.2982	0.0445	0.0488	20.5	307.5	
3	-0.0080	0.2704	0.2705	0.0366	0.0732	13.7	205.0	0.0596
4	-0.1889	0.1021	0.2147	0.0230	0.0976	10.3	153.8	
5	-0.1285	0.1724	0.2150	0.0231	0.1220	8.2	123.0	0.0360
6	0.0995	0.1257	0.1603	0.0129	0.1463	6.8	102.5	
7	-0.0863	0.0791	0.1171	0.0069	0.1707	5.9	87.9	0.0087
8	0.0569	-0.0228	0.0613	0.0019	0.1951	5.1	76.9	
9	-0.1000	0.1261	0.1610	0.0130	0.2195	4.6	68.3	0.0195
10	0.0538	0.1007	0.1142	0.0065	0.2439	4.1	61.5	
11	-0.0775	-0.0531	0.0939	0.0044	0.2683	3.7	55.9	0.0082
12	0.0586	-0.0647	0.0873	0.0038	0.2927	3.4	51.3	
13	-0.0882	-0.0665	0.1105	0.0061	0.3171	3.2	47.3	0.0141
14	-0.1265	0.0083	0.1268	0.0080	0.3415	2.9	43.9	
15	-0.0876	-0.0727	0.1139	0.0065	0.3659	2.7	41.0	0.0102
16	-0.0741	-0.0451	0.0868	0.0038	0.3902	2.6	38.4	
17	0.0180	0.0664	0.0688	0.0024	0.4146	2.4	36.2	0.0028
18	-0.0164	0.0253	0.0302	0.0005	0.4390	2.3	34.2	
19	-0.1119	-0.1370	0.1769	0.0156	0.4634	2.2	32.4	0.0249
20	-0.1341	-0.0239	0.1362	0.0093	0.4878	2.1	30.8	

EXPERIMENTAL SECTION

In order to use the proposed method, application of a control system for the flotation circuit of the Zarand coal washing plant was undertaken. Forty one samples of flotation concentrate were taken with the time interval of 15 min and analyzed for ash content.

The concentrate ash content was used as the controlled variable (y_i) and Fourier coefficients along with variances were calculated using Eqs. (6) to (10). The variance spectrum was then obtained and disturbances with the frequency lower than 1 cycle per hour (periods larger than 1 hour) were removed to simulate the effect of using a control system. The removal process was carried out by assigning $A_k=0$ in Eq. (6). The controlled variable (concentrate ash content; y_i) was then predicted with the new coefficients and average and standard deviation of predicted values were calculated.

In order to obtain steady state yield-ash curve in a period of 3 months 9 sampling campaigns were conducted and flotation circuit concentrate, tailing and feed samples were analyzed for the ash content. The data

then was fitted with Eq. (17) to obtain α and β . The average yield and ash were calculated using Eqs. (25) and (26) for with and without control systems. The predicted revenue when using the control system was calculated considering the plant tonnage and the coal market price.

RESULTS AND DISCUSSION

The results of sampling of concentrate over a period of 615 minutes are shown in Fig. 5. The variation of the concentrate ash content is rather high and has a decreasing trend. The average ash content and variance were calculated to be 10.17% and $0.38 (\%)^2$, respectively.

Fourier coefficients and variance spectrum were calculated using the procedure explained in theoretical Section are shown in Table 4.

The variance contribution of various waves on the overall trend line variance was calculated by grouping waves based on their periods.

The variance contribution and the lower limit of the period of each group were drawn in Fig. 6 which is known as variance spectrum.

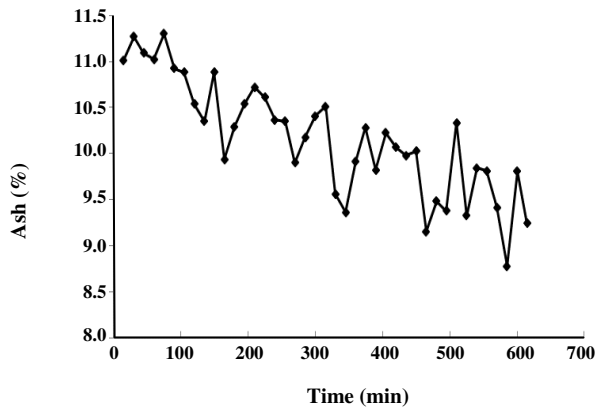


Fig. 5: Variation of ash content of flotation concentrate of the Zarand coal washing plant.

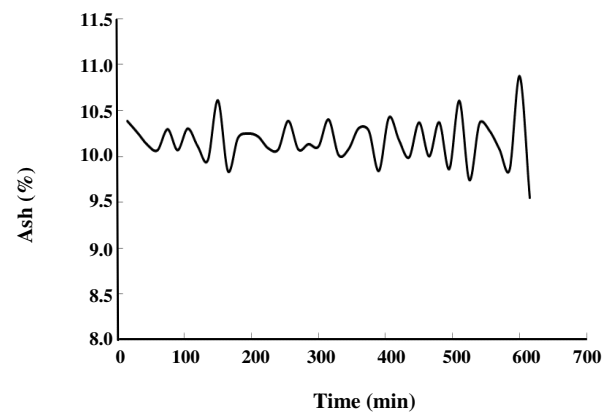


Fig. 7: Predicted variation of ash content of flotation concentrate of the Zarand coal washing plant after using a control system.

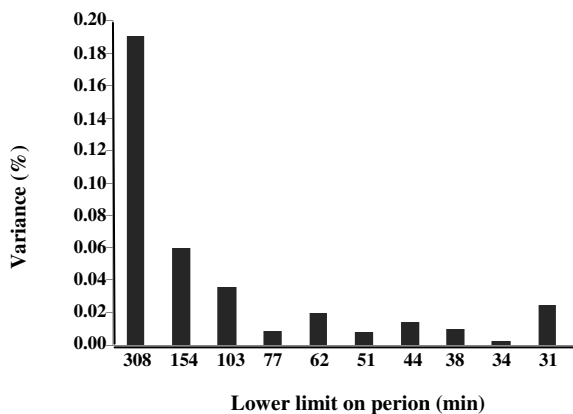


Fig. 6: Variance spectrum of the concentrate ash content trend line of the Zarand coal washing plant.

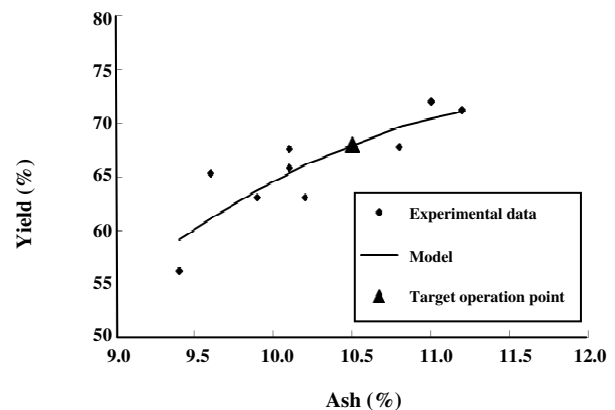


Fig. 8: Steady state yield-ash relationship for the samples taken along with desired (target) operating point and the model fit.

The highest variance contribution is associated with disturbances with high periods. If the use of a control system results in the removal of waves with periods of more than one hour (~62 min), the overall variance will decrease from 0.38 to 0.06 which indicates a relative reduction of 84%.

In order to implement the removal of high period disturbances from the signal (ash vs. time curve), the coefficients of k from 1 to 10 in Table 4 was set to zero. Using the remaining coefficients, the ash content was predicated over the sampling periods. The predicated ash content trend which is the simulated behavior of the system when the control system is used is shown in Fig. 7. The average and variance of ash contents were obtained to be 10.17 % and $0.06 (\%)^2$, respectively. Comparison of ash content trends shown in Figs. 5 and 7 verifies lower variation when the control system is used.

The steady state yield-ash relationship for the samples taken along with desired (target) operating point and the model fit is shown in Fig. 8.

The desired operating point of the plant was selected to be 10.5% for ash content (a^*) and 68% for yield (y^*) based on the operating and economic considerations. The economic factors involved coal price, processing and transportation costs. Fitting the data to Eq. (17) provided Eq. (27) which then used as the model to predict yield for any given ash content.

$$y(a) = 68 + 5.9(a - 10.5) - 2.0(a - 10.5)^2 \quad (27)$$

If the effect of the control system is taken into account only through the variance reduction (bias reduction ignored), the yield with and without the control system using Eq. (22) will be equal to 65.98 and 66.62%, respectively. Since the use of a control system is also

accompanied by a reduction in bias, which means that the operating ash content becomes closer to the desired value, the improvement in the efficiency of the process is more than what is estimated here. The increase of 0.64% in flotation circuit yield translates to yearly increase of 2560 t of concentrate. If the market price of coal is assumed to be \$250 per ton, the yearly revenue due to installing a control system will be over \$500,000. A conventional control system for a flotation circuit of the Zarand plant size with one controlled variable and four control loops is about \$1,000,000 which results in a payback time of 2 years.

CONCLUSIONS

- Controlled variable trend (i.e., concentrate ash content) was reconstructed by a combination of simple waves, which provided a means to simulate the effect of installing a control system (feedback) by removing disturbance waves with low frequency (> one cycle per hour).

- Metallurgical impact of installing a control system in mineral processing applications was proposed to be evaluated either by a reduction of difference between concentrate target quality and operating quality (i.e., bias reduction) or by reduction of scatter of product quality (i.e., variance reduction).

- It was found that if an appropriate feedback control system is used at the flotation circuit of the Zarand coal washing plant, the variance of concentrate ash content could decrease from the current value of 0.38 to 0.06.

- Based on predicted metallurgical improvement installing a conventional control system for the flotation circuit of the Zarand plant size with the approximate cost of \$1,000,000, the payback time was found to be 2 years.

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