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Model development for prediction of autogenous mill power consumption in Sangan iron ore processing plant

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ABSTRACT

The variables including ore hardness based on the SAG power index (SPI), the particle size of mill product (P_{80}), trunnion pressure of the mill free head (p), and working time period of mill liner (H) were considered as variables for the development of an adequate model for the prediction of autogenous (AG) mill power consumption in Sangan iron ore processing plant. The one-parameter models (SPI as a variable) showed no adequate precision for the prediction of Sangan AG mill power consumption. Two-parameter models (SPI and P_{80} as variables), proposed by Starkey and Dobby, showed no adequate precision for the Sangan AG mill power consumption. Nonetheless, by exerting an adjustment factor in the model (0.604513 which was obtained by what-if analysis using the Solver Add-Ins program), the model precision increased significantly (an error of 7.11%). Finally, a four-parameter model in which the Sangan AG mill power consumption is predicated as a function of SPI, P_{80}, p, and H was developed. Hence, initially, the relationship between the mill power consumption and each of the variables was obtained and then the four-parameter model was developed by summation of these four equations and applying a similar coefficient of 0.25 for all of them. This model was modified by finding the best coefficients by what-if analysis using the solver Add-Ins program by minimizing the ARE error function. The error function for the training and testing data sets was determined to be 2.93% and 2.39%, respectively.

Keywords: *Autogenous mill, Power consumption, Modeling, What-if analysis.*

1. Introduction

Most of the energy consumption (more than 50%) in the mineral processing plants is related to the grinding stage [1, 2]. As the average grade of ore decreases in most mining sites of the world, energy consumption per ton of ore processed will increase even more [3]. Hence, optimization of the energy consumption in the grinding circuit reduces the operating costs of the process [4] and it has received much research attention in recent years.

Many parameters are effective in the power consumption of AG and semi-autogenous (SAG) mills, including hardness and fragility and the other characteristics of feed ore, mill product size, mill feed flow rate, mill filling percentage, mill circulating load rate, solid percentage, and mill lifter height [5-8].

Ore hardness and other ore characteristics have a great influence on the energy consumption of AG/SAG mill [9]. Bond work index (W_i) estimates ore hardness in rod/ball mills which is used with Bond's third theory of comminution to calculate net power requirements [10]. It cannot be used in AG/SAG mills since the geometric structure and the grinding mechanism of these mills are quite different from ball/rod mills. Therefore, Starkey et al. proposed the SPI index for measuring ore hardness in AG/SAG mills, which was universally accepted [11]. The particle size of the mill product also has a great influence on the mill power consumption since more mill power consumption is required for more reduction of mill product size [12]. The mill weight is dependent on the mill feed rate, mill filling percentage, circulating load, and mill percent solids. There is a direct relationship between the trunnion pressure of the free head of the AG mill and the mill weight so that it increases by increasing the mill weight [13, 14]. The trunnion pressure of the free head of the AG mill is recorded in the control room, and it can be considered as a parameter in the prediction of mill power consumption instead of several parameters including mill feed rate, mill filling percentage, circulating load, and mill percent solids. Another parameter that can affect the mill power consumption is the height of the lifters (elevators) installed on the mill's inner shell. The mill lifters are responsible for raising the load to a certain height inside the mill [15]. Newly installed lifters have an initial height of 30 cm. Their height gradually decreases due to attrition, hence the load inside the mill rises to a lower height, and as a result, when it falls on the ore on the heel of the mill, it strikes with less energy, resulting in less grinding. It is also known that by reducing the height of the mill lifter due to the lower efficiency of the grinding process, the residence time of the load inside the mill increases. Continuous measurement of the height of mill lifters is difficult and in many cases impossible. Considering that the working time period of mill lifters is recorded in the control room and it is directly related to the height of the lifters. Hence, it can be said that the power consumption of the AG mill is a function of the working time period of mill lifters.

Modeling the mill power consumption plays a significant role in predicting and optimization of the mill power consumption at various plant operating conditions. There are two approaches for modeling the performance of AG/SAG mills including computational and empirical schemes. The Discrete Element Method (DEM) is a computational scheme for predicting the flow of particulates [16-18]. Since milling is predominately a process involving collisions between particles and between particles and the milling machine, it has been used extensively to investigate different aspects of mill performance such as charge distribution, material flow patterns, energy utilization, and power draw

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[16-18]. Nonetheless, mills are one of the more difficult applications to model using DEM because of the scale of the mill, the huge numbers of particles present in the mill, the presence of water, and the timescales involved in the comminution processes [16-18]. An exact match between predicted and actual ball trajectories is difficult to obtain due to simplifying assumptions made in the DEM model [16-18]. These assumptions inevitably lead to differences between experimental and simulated charge profiles. The other approach is an empirical scheme in which the mill operating parameters that fully describe the mill operating conditions must be included in the model. It may have more precision and simplicity than the computational scheme which is the focus of this research for modeling the Sangan AG mill power consumption.

Akbari-Nasab et al. modeled the power consumption of the AG mill of Golgohar iron ore processing plant based solely on the SPI index [19]. The sampling was performed from the AG mill feed and the samples were subjected to the SPI test. They also received data on the AG mill's power consumption from the control room. Finally, based on the results, they proposed a one-parameter equation to predict the mill power consumption. Starkey and Dobby (1996) proposed a two-parameter equation (SPI and P80 as variables) to predict the power consumption of SAG mills [9]. In 2001, Dobby et al. proposed a new two-parameter equation, including the SPI and P80 as variables, to predict SAG mill power consumption by studying data from industrial SAG mills in several mineral processing plants [20]. Azimi used four variables including SPI, P80, p, and H to predict the power consumption of Sarcheshmeh Copper Complex SAG mill [21]. For this purpose, the feed and product of the SAG mill were sampled and the data about the power consumption of the mill, trunnion pressure of the free head of AG mill, and working time period of the mill liner were received from the control room. Finally, a four-parameter model was proposed for the prediction of power consumption of the SAG mill in the Sarcheshmeh copper complex.

This research aims to model the power consumption of the AG mill of Sangan Iron Ore Processing Plant (Opal Parsian Company) in an empirical scheme. For this purpose, the power consumption of Sangan AG mill is modeled by one-, two- and four-parameter empirical models. After that, the adjustment of the models has been examined by applying the what-if analysis using the Solver Add-Ins program, Microsoft Excel.

2. Materials and Methods

2.1. Plant description

The feed of the Sangan iron ore processing plant (Opal Parsian Co.) is supplied from two mines (B and C_N mines). The ore extracted from these two mines with the particle size of d80=1200 mm is fed into a gyratory crusher. The crusher product with the particle size of d80 = 200 mm is conveyed to a stockpile and then to the AG mill feeding. Figure 1 shows the flowsheet of the grinding circuit of Sangan iron ore processing plant. The AG mill product is classified into two size fractions of -75+8 mm and -8 mm by a scalper screen. The coarse-grained fraction (-75+8 mm) is returned to the mill as a circulating load, and the fine-grained fraction (-8 mm) is pumped to the Banana screen. It is responsible for classifying particles into two size fractions of +1-8 mm and -1 mm. The oversize materials (+ 1-8 mm) are transferred back into the AG mill as circulating load, and the fine-grained materials (-1 mm) proceed to the first step of upgrading, which is low-intensity magnetic separation (Cobber LIMS separators).

2.2. Sampling

Sampling of the AG mill feed was performed on several days from October 2018 to January 2019. At each sampling stage, the AG mill feed conveyor belt was stopped and the entire load was discharged at a distance of 30 meters. The samples were subjected to the SPI test. In order to determine the particle size distribution of the AG mill product, samples were taken from the feeding pipe of the Cobber LIMS separators by using an automatic sampler. Sampling started two hours after sampling of the AG mill feed and for six hours, the pulp was sampled several times, and finally, samples were mixed and subjected to the particle size analysis. The control room information including AG mill power consumption, trunnion pressure of the free head of AG mill, AG mill fresh feed rate, and circulating load rate were gathered two hours after sampling from the AG mill feed and continued for six hours, and their average values were used in modeling.

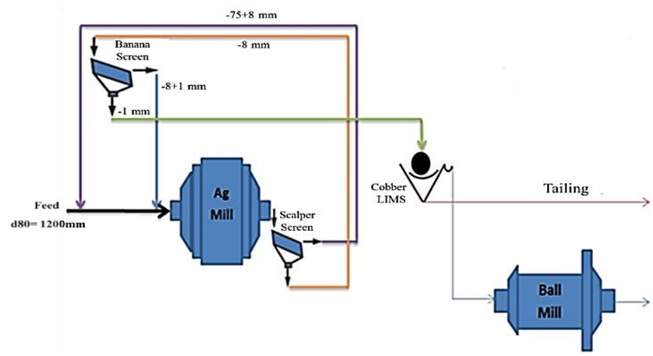

Figure 1. Flowsheet of the grinding circuit of Sangan iron ore processing plant.

2.3. Determination of SPI index

Determination of the SPI index was performed according to the standard method proposed by Starkey and Dobby by a standard laboratory mill known as the Starkey mill [9]. Figure 2a shows the image of the Starkey mill made in our lab. The diameter of this mill is 304.8 mm (12 inches) and its length is 101.6 mm (4 inches) [22]. The diameter of this mill is equal to the diameter of the band mill and the ratio of diameter to length is equal to 3 to 1 [22]. There are 6 lifters inside the mill for easy load movement. The dimensions of the lifters are 2.5 x 2.5 cm and cover the entire length of the mill. To install the lifters, the interior perimeter of the mill is divided into 6 equal parts and the lifters are completely welded to the mill shell to prevent the passage and accumulation of materials in the empty spaces behind them [22]. The detail of the mill structure has been presented elsewhere [22]. The mill is placed on the rolls that are rotated by an electric motor (Figure 2b). Rotation is provided by a single-phase electric motor with a power of 75 kW. Given that the standard rotation speed is 70% of the critical speed, the mill speed should be set at 56 rpm [9].

At each stage of sampling from Sangan AG mill feed, the sample weight was in the range of 50 to 70 kg. The sample was crushed by a jaw crusher up to 100% passing through a 19 mm sieve. The crushed material was sieved by a 12.7 mm sieve. 400 g remaining materials on the sieve and 1600 g materials passing from the sieve was taken homogeneously, mixed, and considered as SPI test sample. 15% by volume of the Starkey mill was filled with 35 mm steel balls and the sample was poured into the mill. The first grinding time was considered according to the estimation of the sample hardness in the range of 2-3 min. After that, the material in the mill was discharged and sieved by a 1.7 mm (10 mesh) sieve. The weight of material passed through this sieve was determined. At the first grinding step, the particle size of the mill product should not reach the desired amount (80% less than 1.7 mm). In the next step, the material together with the steel balls is returned to the mill for further grinding. After a certain time of grinding, the above step was repeated and this operation continued until the weight of the material passed through the 1.7 mm sieve reached 1600 g (80% of feed). Finally, the summation of these grinding times is considered as SPI of the sample (min.) [20].

3. Results and discussion

3.1. one-parameter models

Although many parameters are involved in the power consumption of AG mills, the properties of feed ore such as ore hardness, are the most effective parameter. Therefore, in one-parameter models that predict the power consumption of AG mills, the variable is considered SPI. AkbariNasab et al. modeled the power consumption of the AG mill of Golgohar iron ore processing plant [19]. They performed a series of sampling from the AG mill feed and then, they carried out an SPI test on the samples. They also received data about the mill power consumption from the plant control room. Finally, they proposed Eq. 1 to predict the power consumption of Golgohar AG mill by training data.

$$P = 0.0025\,SPI2 - 0.0663SPI + 5.6358 \quad (1)$$

where SPI is the power index in minutes, and P is the mill power consumption per ton of fresh feed ore (kWh/t).

Modeling power consumption of the Sangan AG mill was performed by this one-parameter model. The SPI values related to 17 series of sampling were placed in the model and the amount of AG mill power consumption was predicted by the model (P_{model}). Then, the modeling error was determined based on the average relative error (ARE) function (Eq. 2).

$$\%ARE = \frac{100\sum\left|\frac{P(real) - P(model)}{P(real)}\right|}{n} \quad (2)$$

in which ARE is the modeling error value (%), P_{real} is the real power consumption of the Sangan AG mill obtained from control room data, P_{model} is the predicted power consumption by the one-parameter model, and n is the number of collected data.

The ARE error value was calculated to be 126.87% for the training data and 123.83% for the validation data. As can be seen, the error is very high for both modeling and validation data series, which indicates that the model is not able to predict the power consumption of Sangan AG mill. Hence, a model which predicts mill power consumption only based on one variable cannot be used in other circuits.

3.2. Two-parameter models

Starkey and Dobby (1996) used data from AG mills in five mineral processing plants in Canada for modeling the power consumption [9]. They used two independent variables of SPI and P_{80} to predict the power consumption of SAG mills. They proposed the following equation for the prediction of power consumption of the AG/SAG mills [9].

(a)

(b)

Figure2. a) The Starkey mill made in our lab, b) The Starkey mill on the rolls.

$$P = \frac{2.2 + (0.1\,SPI)}{P_{80}^{0.33}} \quad (3)$$

In this equation, P is the power consumption of AG/SAG mills (kWh/t), P_{80} is the mill product size (μm), and SPI is the ore hardness (min.).

In 2001, Dobby et al. proposed a new two-parameter equation for predicting AG/SAG mill's power consumption by studying data from several plants [20]. Eq. 4 shows the equation proposed by Dobby et al [20].

$$P = 5.9\,\left(\frac{SPI}{\sqrt{P_{80}}}\right)^{0.55} \quad (4)$$

This equation is proposed for SAG mills in a closed circuit without a pebble crusher with a nominal feed of 6 inches. An adjustment factor is required for circuits that use finer grain feed or if a pebble crusher is located in an AG/SAG mill circuit. This adjustment factor (f_{SAG}) is added to Eq. 4 and the new equation is obtained as follows:

$$P = 5.9\left(\frac{SPI}{\sqrt{P_{80}}}\right)^{0.55} f_{SAG} \quad (5)$$

By including the data related to 17 independent sampling series from Sangan AG mill circuit (training data) in Starkey and Dobby equation (1996) which is presented in Eq. 3, the ARE error function of this modeling was determined to be 81.97%, which indicates the inefficiency of this model to predict the power consumption of Sangan AG mill. Comparing the performance of this model with the one-parameter model of Akbari Nasab et al. shows that the two-parameter model is more efficient for predicting the power consumption of AG mills.

Another two-parameter model examined in this study was the Dobby et al. (2001) model shown in Eq. 4. The data relating to 17 series of sampling from the Sangan iron ore processing plant were placed in the model. The ARE error function was calculated to be 60.23% for this modeling. The high value of the error function indicates that it is not a suitable model to predict the power consumption of the Sangan AG mill. To increase the compatibility of this model with other circuits, Dobby et al. proposed that an adjustment factor (f_{SAG}) be applied to this equation. In this research, in order to find the best adjustment factor, the Solver Add-Ins program was applied. Solver is a Microsoft Excel add-in program that can be used for what-if analysis. By using Solver, we can find an optimal (maximum or minimum) value for a formula in one cell (called the objective cell) subject to constraints, or limits, on the values of other formula cells on a worksheet. The objective cell was considered the ARE error function. By changing the adjustment factor, it was tried to minimize the ARE error function. The minimum value of ARE error function was obtained to be 7.11% at an adjustment factor of 0.604513 by using the Solver Add-Ins program. Therefore, the Dobby et al. (2001) model was modified in the form of Eq. 6 for the Sangan AG mill.

$$P = 5.9\left(\frac{SPI}{\sqrt{P_{80}}}\right)^{0.55} f_{SAG}; \quad f_{SAG} = 0.604513 \quad (6)$$

The value of the ARE error function was determined to be 7.11% for the training data. Furthermore, the value of ARE error function related to the validation data was 10.87%, which indicates the precision of the Dobby et al. (2001) model for predicting the power consumption of Sangan AG mill increases by exerting an appropriate adjustment factor.

Fig. 3 shows the efficiency of Dobby et al. model with and without adjustment factors in predicting the power consumption of Sangan AG mill. As can be seen, although the model without adjustment factor has been able to predict the trend of power consumption of the Sangan AG mill, there is the nearly same difference between the actual and predicted power consumption values at different conditions. When this happens, it can be predicted that if the equation is multiplied by an appropriate adjustment factor, its precision to predict the mill's power consumption will be greatly improved. Fig. 3 shows the efficiency of the Dobby et al. model after applying an adjustment factor to predict the power consumption of Sangan AG mill. The precision of this model was further investigated by the validation data. As can be seen in Figure 3, the Dobby et al. model, after applying an adjustment factor, has a high ability to predict the Sangan AG mill power consumption.

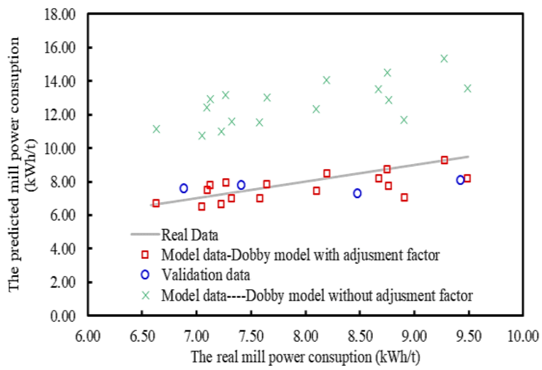

Figure 3. The real and predicted power consumption of Sangan AG mill by Dobby et al. model with and without adjustment factor.

3.3. Four-parameter models

The mill power consumption is a function of four parameters: SPI, P_{80}, trunnion pressure of the free head of AG mill (p), and working time period of mill liner (H), in other words, P = f (SPI, P80, p, H). To find the four-parameter equation predicting the mill power consumption, we first found a separate relationship between these four parameters and the mill power consumption.

Figure 4a shows the relationship between SPI and Sangan AG mill power consumption. As can be seen, there is a direct relationship between SPI index and mill power consumption, so the mill power consumption increases with increasing ore hardness. The relationship between SPI and mill power consumption using nonlinear regression by Minitab 18 software was obtained as Eq. 7.

$$P(kWh/t)= 0.5297SPI^{0.6111} \quad (7)$$

The relationship between the particle size of the mill product (P_{80}) and the power consumption of Sangan AG mill is shown in Figure 4b. As can be seen, the mill power consumption increases by decreasing the particle size of the mill product. The relationship between P_{80} and mill power consumption using nonlinear regression by Minitab 18 software was obtained as Eq. 8:

$$P(kWh/t)= 3.9411P_{80}^{0.1144} \quad (8)$$

The relationship between the working time period of mill liner (H) and mill power consumption is shown in Figure 4c. As can be seen, the mill power consumption increases by increasing the working time period of the mill liner. A linear relationship between the working time period of mill liner and mill power consumption was obtained in the form of Eq. 9:

$$P(kWh/t)= 0.0008\,H +5.7567 \quad (9)$$

The relationship between the trunnion pressure of the free head of AG mill and mill power consumption also showed a linear relationship in the form of Eq. 10, which shows that the mill power consumption increases with increasing trunnion pressure of the free head of AG mill (Figure 4d).

$$P(kWh/t)= 0.0032p-9.076 \quad (10)$$

Given that the four parameters SPI, P_{80}, H and p are independent variables, so the four-parameter model for predicting mill power consumption is considered as Eq. 11, which is actually the average of the values predicted by Eqs. 7-10:

$$P(kWh/t)=0.25[0.5297SPI^{0.6111}] + 0.25[3.9411P_{80}^{0.1144}] + 0.25[0.0008\,H +5.7567] + 0.25[0.0032p-9.076] \quad (11)$$

The modeling was performed based on Eq. 11 and the results are presented in Table 1. In this table, the real values of Sangan AG mill power consumption in different operating conditions and the prediction

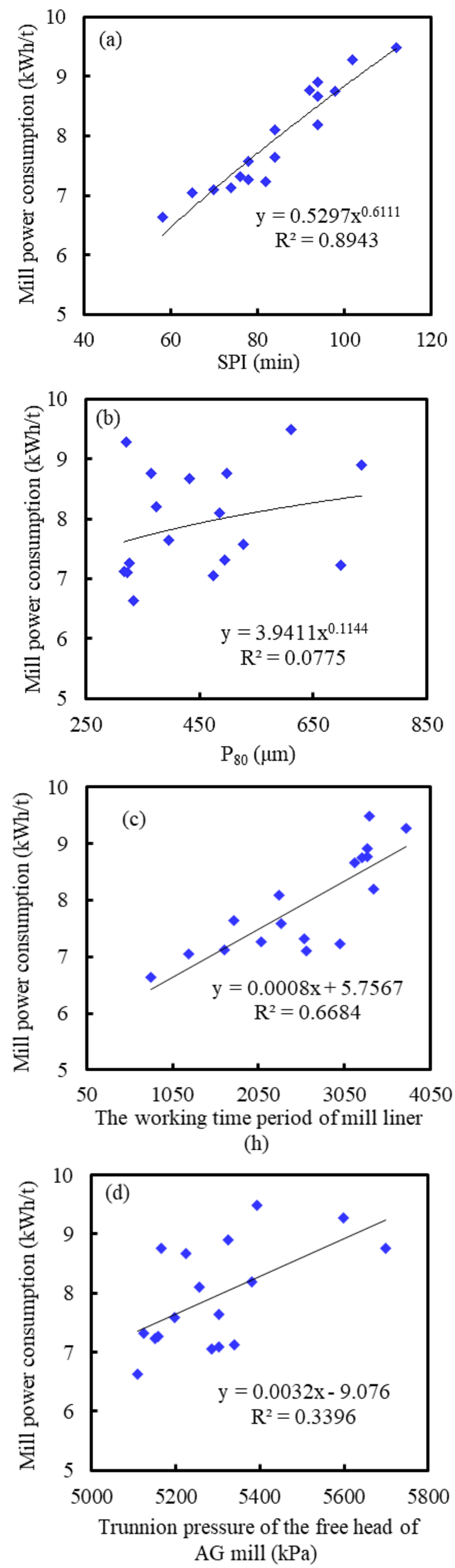

Figure 4. The relationship between the mill power consumption and the mill parameters including a. SPI, b. P_{80}, c. working time period of mill liner, and d. trunnion pressure of the free head of Sangan AG mill.

of these values by the four-parameter model with the same coefficients of 0.25 are shown. As can be seen, the value of the ARE error function for this modeling is equal to 53.94%, which shows that the model obtained based on constant coefficients of 0.25 cannot provide a good prediction of the AG mill power consumption.

In order to find suitable coefficients for one-parameter equations in the four-parameter model, what-if analysis by Solver Add-Ins program in Microsoft Excel 2010 software package was used. Using what-if analysis to minimize the ARE error function, the modified coefficients were determined. According to the new coefficients, Eq. 11 will be modified to the new form of Eq. 12.

$$P(kWh/t)=0.889[0.5297SPI^{0.6111}] + 0.199[3.9411P_{80}^{0.1144}] + 0.296[0.0008H +5.7567] + 0.334[0.0032p-9.076] \quad (12)$$

Table 2 shows the results of modeling the power consumption of the Sangan AG mill based on Eq. 12. As can be seen, the value of ARE error function for this model was calculated to be 2.93%, which shows that what-if analysis has been able to provide a suitable model for predicting the power consumption of Sangan AG mill by modifying the coefficients of Eq. 11.

Table 1. The real values of the Sangan AG mill power consumption at different operating conditions and prediction of these values by a four-parameter model with the same coefficients.

Test Num.	AG MILL POWER [kW]	NEW ORE [t/h]	P (real) [kWh/t]	OIL PRESSURE (TRUNION) [kPa]	P80 [µm]	H [h]	SPI [min.]	(model) (kWh/t)	$\left\lvert\frac{P(real)-P(model)}{P(real)}\right\rvert$
1	3211.51	370.31	8.67	5225	432	3175	94.00	3.9117	0.5490
2	3562.11	375.49	9.49	5393	611	3343	112.00	4.2661	0.5503
3	4927.75	601.24	8.20	5381	374	3393	94.00	3.9227	0.5214
4	2852.41	400.31	7.13	5339	317	1659	74.00	3.2494	0.5440
5	4263.13	459.62	9.28	5599	322	3764	102.00	4.0736	0.5608
6	3686.16	421.19	8.75	5166	365	3254	98.00	3.9448	0.5493
7	4009.77	495.07	8.10	5257	485	2293	84.00	3.6198	0.5531
8	4671.33	524.44	8.91	5326	736	3316	94.00	4.0641	0.5437
9	4290.57	561.08	7.65	5302	396	1762	84.00	3.4675	0.5466
10	3558.38	486.06	7.32	5124	494	2581	76.00	3.5632	0.5133
11	2946.86	415.19	7.10	5302	324	2603	70.00	3.3815	0.5236
12	3434.34	472.56	7.27	5158	327	2083	78.00	3.4011	0.5320
13	3563.07	492.96	7.23	5150	698	2999	82.00	3.8163	0.4720
14	4053.49	534.74	7.58	5197	527	2318	78.00	3.5556	0.5309
15	5987.72	683.18	8.76	5700	498	3312	92.00	3.9438	0.5500
16	3457.62	521.47	6.63	5111	335	791	58.00	2.8332	0.5727
17	3902.09	553.70	7.05	5285	475	1238	65.00	3.1152	0.5579
								Σ	9.1705
								ARE	53.9443

Table 2. The real values of power consumption of Sangan AG mill at different operating conditions and prediction of these values by the four-parameter model with coefficients obtained by Solver Add-Ins program.

Test Num.	AG MILL POWER [kW]	NEW ORE [t/h]	P (real) [kWh/t]	OIL PRESSURE (TRUNION) [kPa]	P80 [µm]	H [h]	SPI [min.]	P(model) (kWh/t)	$\left\lvert\frac{P(real)-P(model)}{P(real)}\right\rvert$
1	3211.51	370.31	8.67	5225	432	3175	94.00	8.5680	0.0120
2	3562.11	375.49	9.49	5393	611	3343	112.00	9.5268	0.0043
3	4927.75	601.24	8.20	5381	374	3393	94.00	8.5934	0.0485
4	2852.41	400.31	7.13	5339	317	1659	74.00	7.1239	0.0002
5	4263.13	459.62	9.28	5599	322	3764	102.00	9.0433	0.0250
6	3686.16	421.19	8.75	5166	365	3254	98.00	8.7519	0.0000
7	4009.77	495.07	8.10	5257	485	2293	84.00	7.8769	0.0275
8	4671.33	524.44	8.91	5326	736	3316	94.00	8.7003	0.0232
9	4290.57	561.08	7.65	5302	396	1762	84.00	7.7141	0.0088
10	3558.38	486.06	7.32	5124	494	2581	76.00	7.5288	0.0284
11	2946.86	415.19	7.10	5302	324	2603	70.00	7.1332	0.0050
12	3434.34	472.56	7.27	5158	327	2083	78.00	7.4435	0.0242
13	3563.07	492.96	7.23	5150	698	2999	82.00	8.0078	0.1079
14	4053.49	534.74	7.58	5197	527	2318	78.00	7.5849	0.0006
15	5987.72	683.18	8.76	5700	498	3312	92.00	8.5275	0.0270
16	3457.62	521.47	6.63	5111	335	791	58.00	6.0235	0.0915
17	3902.09	553.70	7.05	5285	475	1238	65.00	6.5980	0.0638
								Σ	0.4980
								ARE	2.9293

Table 3. The real values of power consumption of Sangan AG mill at different operating conditions and prediction of these values by the modified model (validation data).

Test Num.	AG MILL POWER [kW]	NEW ORE [t/h]	P (real) [kWh/t]	OIL PRESSURE (TRUNION) [kPa]	P80 [μm]	H [h]	SPI [min.]	P(model) (kWh/t)	$\left\lvert\frac{P(real)-P(model)}{P(real)}\right\rvert$
1	5403.13	637.29	8.48	5348	619	3369	92.00	8.5809	0.0002
2	3257.00	439.62	7.41	5307	335	1681	76.00	7.2464	0.0074
3	3889.08	565.35	6.88	5440	229	1437	60.00	6.2297	0.0668
4	4817.98	511.39	9.42	5710	588	3923	108.00	9.4720	0.0213
								Σ	0.0957
								ARE	2.39

Figure 5 shows the ability of the model with similar coefficients (initial model) and the modified model by what-if analysis with Solver Add-Ins program (modified model) to predict the power consumption of Sangan AG mill. As can be seen, the modified model has a much higher accuracy to predict the power consumption of AG mill than the initial model. Fig. 5 also shows the prediction of validation data with the modified model. As can be seen, there is very little difference between the real and predicted values for both the modeling and validation data series, which confirms the accuracy of the modified four-parameter model in predicting the Sangan AG mill power consumption.

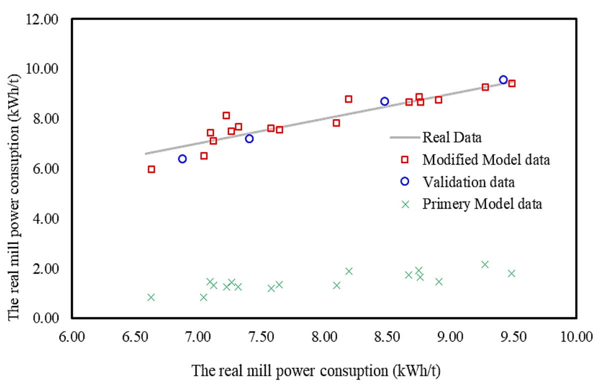

Figure 5. Comparison of the efficiency of the four-parameter model with the same coefficients (initial model) and modified by the Solver Add-Ins program (modified model) to predict the power consumption of Sangan AG mill.

4. Conclusions

One of the best ways for modeling the mill power consumption is by finding variables that can well describe the whole mill operating conditions and then finding suitable coefficients for these variables in the model by an appropriate method. It is believed that the AG mill performance can be well described by four parameters of ore hardness based on the SAG power index (SPI), the particle size of mill product (P80), trunnion pressure of the mill free head (p), and working time period of mill liner (H). Therefore, in this study, to obtain a four-parameter model, first, the relationship between AG mill power consumption and these four variables was obtained separately and then the four-parameter model which integrates univariate models by applying the same coefficient of 0.25 for each equation was obtained. The four-parameter model did not have the necessary capability for the prediction of the Sangan AG mill power consumption. Therefore, the coefficients of this model (coefficients of univariate equations) were modified by the Solver Add-Ins program in Microsoft Excel 2010 software package by minimizing the ARE error function. Therefore, the best model for the prediction of the power consumption of Sangan AG mill is proposed as follows:

$$P(kWh/t)=0.889[0.5297SPI^{0.6111}] + 0.199[3.9411P_{80}^{0.1144}] + 0.296[0.0008H +5.7567] + 0.334[0.0032p-9.076]$$

The modified model has high efficiency for predicting the power consumption of Sangan AG mill so the ARE error function for the modeling and validation data was obtained to be 2.93% and 2.39%, respectively.

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