AN UPDATED DATA SET FOR SAG MILL POWER MODEL CALIBRATION

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ABSTRACT

This paper expands the SAG mill survey database published by the Author at Procemin 2013. The new database includes 49 published SAG/AG mill surveys and includes mills from all over the world. The paper will compare the survey database to SAG mill models by Austin, Morrell and Hogg & Fuerstenau with the purpose of demonstrating the degree of fit of the models to surveys and validating any empirical "fitting factors" used in the models.

SAG mill power draw models are used in mill design and grinding circuit modelling to predict how much power will be consumed by a particular mill geometry and operating configuration. The importance of conducting surveys suited to model calibration will be highlighted because the review of literature shows that survey information important to modelling is often missing or omitted. A recommendation for the collection of data during a mill survey is presented, along with some assumptions used by the Author in the absence of certain data. The benefit to mining companies of publishing their survey data, and thereby allowing modellers to improve their model calibration, is discussed.

The comparison of models requires a discussion of the measurement of power in a mill drive system as the models use slightly different position in the electrical network for "where power is measured". The benchmarking of models against plant operations requires a similar discussion of power measurement.

KEYWORDS

SAG mill, power model, power draw, Austin model, Morrell C-model, Hogg & Fuerstenau model

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INTRODUCTION

Sizing the mills for a new grinding circuit requires a determination of how much energy is required for grinding (using test results such as Bond work indices) and then finding the mill sizes to draw that required amount of energy. There are several mill power draw models available to perform the second task, though generally each model is specific to a type of tumbling mill. This paper is an update to an earlier paper, Doll (2013), that described three SAG mill models (Austin, Morrell and Loveday & Barratt) and compares their default results against 25 mill surveys.

Because these models are used in the design of new plants, operating companies will benefit from improved designs (less “design fat” and risk) when consultants and model designers have better data to calibrate models against. Operating companies who publish detailed surveys allow modelling consultants to improve the models and benefit the next generation of plant designs.

METHODS

A data set of mill operating data is collected from published information and compared to predictions made by two published mill power draw models for SAG mills (Austin's SAG model and Morrell's C-model). A third model (Hogg and Fuerstenau) is fit to each survey and the principal fitting parameter is tabulated.

Power measurement

The nature of electrical and mechanical networks is that power is lost to various types of inefficiency as one observes power flowing through a network. A mill drive system consists of electrical components that have inherent inefficiency, such as a motor or variable frequency drive, and often include mechanical components such as gears and pinions that have inefficiencies. These network losses can be significant, and in order to equalize the models to one basis, the power as measured at the mill shell (or pinion output) is used in this Paper. The factors used to convert between a DCS power measurement (which may be based on a MCC cabinet or the motor input taps) and the mill shell are those presented in Doll, 2012. All motors are assumed to operate at unity power factor.

Operating data

Mill operating data, including mill dimensions, charge levels and mill speed has been collected from numerous publications. The operating data corresponds to the typical input parameters for grinding mill power draw models, including:

- ***D*, mill effective diameter**, (m) the nominal diameter inside the liners of the mill. Determined as the diameter of a circle equal to the area of the cross section of the mill inside the shell minus the cross section area of the liners and lifters.
- ***L*, mill effective grinding length**, (m) the length along the mill belly between the head liner plate and the front of the discharge grate, not including lifters or deflector vanes.
- **J_{total}, mill charge filling**, (v/v) the proportion of the internal volume of the mill that is consumed by the mill charge. This is the combined charge of grinding balls and ore solids and would be measured in a mill crash-stop.
- **J_{balls}, ball charge filling**, (v/v) the proportion of the internal volume of the mill that is consumed by the balls within the mill charge, as would be measured in a mill grind-out.
- **ϕ_C, mill speed,** the rotational speed of the mill as a fraction of the critical speed of the mill based on the effective diameter, *D*.
- **ρ_{ore}, ore density**, (kg/L) the density of the ore solids in the mill charge.

- w_C**, pulp slurry percent solids**, (w/w) the weight percent solids of the solid component of the pulp slurry, as measured at the mill discharge.
- P_{DCS}**, power draw at DCS**, (kW) the power draw of the mill as observed on the plant distributed control system.
- P_{shell}**, power draw at mill shell**, (kW) the power draw of the mill corrected to the power consumed at the shell of the mill.
- **drive system efficiency**, the cumulative electrical and mechanical losses between the power measurement point (P_{DCS}) and the power available at the shell of the mill (P_{shell}).

Austin SAG Model

The SAG mill model by proposed by Leonard Austin (1990) was largely based on modifications of earlier tumbling mill models by Hogg & Fuerstenau and F. Bond. The model is loosely structured as a kinetic and potential energy balance to describe the power draw of a mill charge. The power drawn from a cylindrical (shell-supported) mill is given by Equation 1.

$$P = K D^{2.5} L \left(1 - A J_{total}\right) \left[\left(1 - \varepsilon_B\right) \left(\frac{\rho_{solids}}{w_C} \right) J_{total} + 0.6 J_{balls} \left(\rho_{balls} - \frac{\rho_{solids}}{w_C} \right) \right] \phi_C \left(1 - \frac{0.1}{2^{9 - 10\phi_C}} \right) \tag{1}$$

Where:

- A and K are empirical fitting factors
- D is the mill diameter inside the liners, m
- J_x is the mill filling of component x, as a fraction of total mill volume (e.g. 0.3 for 30%)
- L is the mill effective grinding length, m
- P is the power evolved at the mill shell, kW
- w_C is the charge %solids, fraction by weight (e.g. 0.80 for 80%)
- ε_B is the porosity of the rock and ball bed, as a fraction of total bed volume (e.g. 0.3 for 30%)
- ρ_x is the density of a component x, t/m³
- ϕ_C is the mill speed, as a fraction of the mill critical speed (e.g. 0.75 for 75%)

The power result of the Austin model is relative to the “mill shell”, also referred to as power “at the pinion”.

Austin proposed a geometric factor be applied to the formula for use in cone-ended mills. The author's experience from fitting this model to published surveys suggests that Austin's factor adds too much power (approximately 14%), and proposes that 5% extra power should be added instead (based on Barratt, Brodie & Pfeifer, 1999).

An unusual feature of Austin's model is the pulp %solids appearing in the denominator of two of the terms, meaning that the power draw drops as the pulp density increases. This is the opposite of what the other models predict – higher pulp %solids gives higher power draw in both the Morrell and Hogg & Fuerstenau models. Austin's paper recommends using a fixed value of 0.80 for this term and not varying it as the mill water addition rate changes. All calculation use the published “tuning parameters”, except as noted.

1. Austin model calibration and configuration:
    a. A = 1.03, K = 10.6; ε_B = 0.3
    b. use a fixed pulp %solids w_C = 0.80;
    c. use 5% allowance for cone ends instead of the published formula.

Morrell C-Model

The C-model was developed by Steve Morrell at the University of Queensland as part of his PhD thesis. The Morrell C-Model is a generalised tumbling mill model and is not specific to SAG mills. The model was adopted for use in the JK SimMet™ software package and this paper is based on the description in a JK Mineral Research Centre publication (Napier-Munn et al, 1996).

The model contains too many equations and sub-equations to replicate here. In summary, the model consists of a friction balance between concentric layers within the rising part of the mill load. The model contains a great deal of physics and geometry, and uses some empirical parameters that have been fit to laboratory or industrial scale mills. The mathematics develops the power draw of a charge geometry and motion, and then applies a fitting factor k to convert the power draw of the mill charge into the observed gross motor power (the motor input). The highly-simplified formula is given in Equation 4:

$$\textit{Gross power} = \textit{no-load power} + k \times (\textit{Cylinder motion power} + \textit{Cone motion power}) \qquad (4)$$

The Morrell C-model provides a power draw relative to a motor input, and it must be converted to the same basis as the Austin model (mill shell basis) to perform meaningful comparisons. The Author assumes the mills that the published k factor was fit against consisted largely of Australian and African mills that typically have pinions (0.985 efficiency), gearboxes (0.985 efficiency) and induction motors (0.960 efficiency). Multiplying these efficiency values together suggests a conversion factor of 0.931 between motor input (C-model result) and mill shell (Doll, 2012).

2. Morrell model calibration and configuration:
    a. k = 1.26 (conversion to gross power at the input of a wound-rotor induction motor);
    b. J_{voids} = 0.40 (different from ε_B in the Austin equation);
    c. use 0.931 conversion between gross power and shell power.

Hogg & Fuerstenau Modelling

The grinding model proposed by Hogg & Fuerstenau is a variation on older models by Fischer (1904), White (1904) and Davis (1919), and assumes that the surface of the charge of the mill that is in contact with the mill shell can be approximated as a chord of a circle connecting a charge “shoulder” to a charge “toe”. This charge geometry is calculated by the mill charge level and a manually-input angle that corresponds to the “lever arm” connecting the centre of the geometric mill and the mass centroid of the charge.

The model used in this paper comes from the Moly-Cop Tools (version 3.0) software, where the power at the mill shell is given by:

$$P_{shell} = 0.238\,(D \times 3.28)^{3.5}\,(L/D)\,\phi_C\,\rho_{\text{charge}}\,(J - 1.065\,J^2)\sin\alpha \qquad (5)$$

This model is extremely sensitive to the angle α chosen by the operator of the calculation. This angle is not measurable and is based on a hypothetical mill charge geometry that assumes a charge shape that generally is not observed in operating mills. Moreover, the equation assumes the angle α is independent of the other parameters; it is possible that the angle is affected by, for example, the speed of the mill ϕ_C.

Instead of using the Hogg & Fuerstenau model to predict a power draw with a manually specified angle (how the Austin model and Morrell C-model are used), the Hogg & Fuerstenau model will be run to determine what the angle α "must be" to satisfy the measured power draw of the mill. A range of angles will be determined that can then be compared with other model parameters to check for independence.

RESULTS

The tabulated mill operating results are given in Table 1. Corresponding predictions by the models are given in Table 2. These tables are available for download as a LibreOffice spreadsheet from the author's website: https://www.sagmilling.com/articles/25/view/?s=1 .

It is easier to observe the fit of the models by charting the difference (as percent) of the model power draw versus operating parameters (Figures 1 to 6). An arbitrary ±5% threshold is indicated on charts to indicate an acceptable "insignificant" deviation between a model and the survey information. Linear trends are also indicated to demonstrate if a model has a particular bias to a parameter.

DISCUSSION

Both the Austin model and Morrell C-model give good agreement with the overall dataset, with average and median differences of no more than 1.5%. The standard deviations are significantly higher, which the Author attributes to individual surveys likely containing incorrect measurement of important parameters. The large quantity of surveys is useful for blending out these measurement errors and suggests that the overall form and configuration of the two models is generally very good. There is no reason to change any of the default configuration values of either model.

The mill speed (ϕ_C) is the only parameter where the two models show substantially different power predictions. The differences are minimal in the speed range of 75% to 80% of critical, but the models diverge as speed falls below 70% of critical. The Author suggests this difference is more a function of liner design or wear patterns than it is an intrinsic flaw in the models – both Austin and Morrell would have calibrated their models to different mill liner designs. Slowing a mill below the normal operating range could reasonably affect the position of the charge and the power consumed in the mill differently for different liner designs.

The power predictions for fully autogenous mills are highly sensitive to the density of the mill charge. The largest source of autogenous surveys are for the Boliden LKAB mills in Sweden (Bueno et al, 2011 and Powel et al, 2011). These surveys give a range of density for soft, high density iron ore and hard, low density silicates. Because the hard material will build up in the mill charge, the models must use a density lower than the measured ore density of the feed. Powell gives an estimate for the charge density of one case (line number 20 in Table 1) which is believed to be atypical due to the very high mill charge being operated. The equilibrium charge density for the other LKAB case (line number 19) are assumed to be a 30%–70% blend of hard waste and soft ore.

The Hogg-Fuerstenau model shows no relationship to the mill speed (Figure 5), suggesting the lever-arm angle α is not significantly affected by mill speed. The angle α is affected by the aspect ratio of the mill (Figure 6), with longer mills, D/L ≤ 1, having angles slightly above 40°, whereas "pancake" mills, D/L > 2, have typical angles around 47° to 50°.

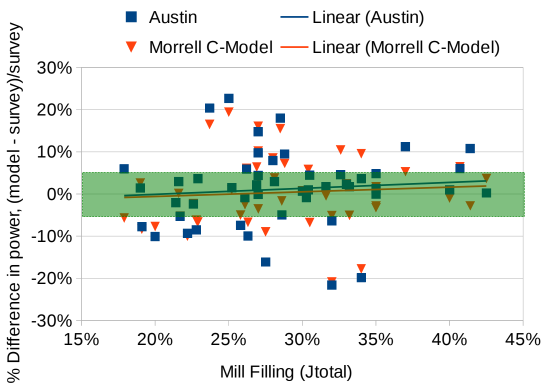

Figure 1. Model difference versus J_{total}

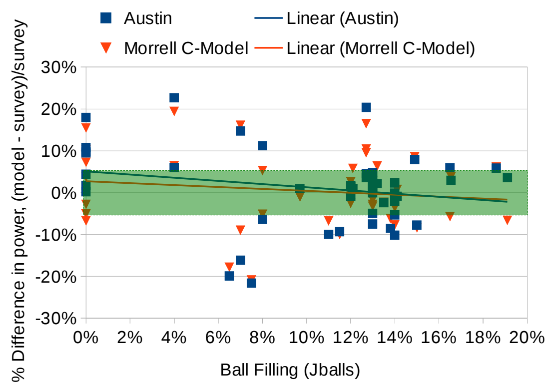

Figure 2. Model difference versus J_{balls}

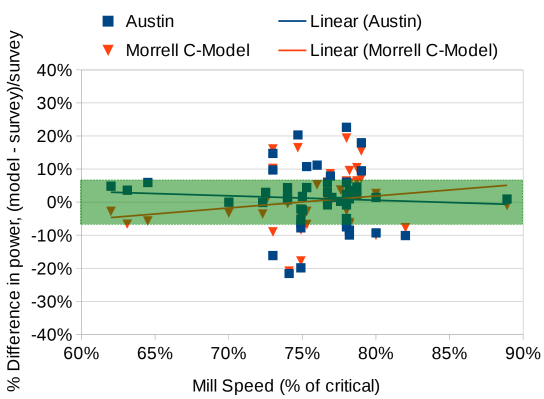

Figure 3. Model difference versus ϕ_C

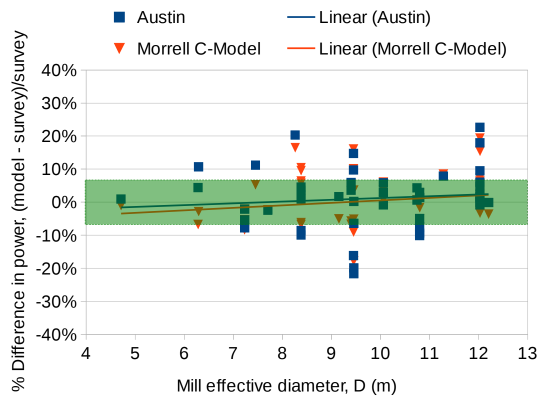

Figure 4. Model difference versus D

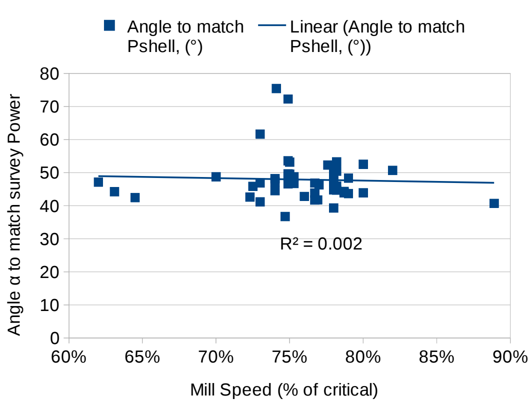

Figure 5. Hogg-Fuerstenau angle α versus ϕ_C

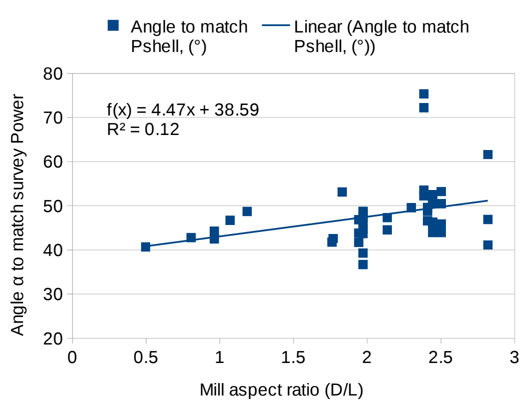

Figure 6. Angle α versus mill D/L ratio

	Mine	D, m	L, m	Survey J_{total}	Survey J_{balls}	ϕ_C	ρ_{ore}	w_C	P_{DCS} kW	Survey conver-sion	P_{shell} kW	Reference
1	Meadowbank	7.70	3.35	0.226	0.135	0.750	2.93	0.75	3,374	0.9456	**3,190**	Muteb & Allaire, 2003
2	Cadia *	12.02	6.10	0.288	0.000	0.790	2.60	*0.70*	11,189	0.9600	**10,741**	Radziszewski & Valery, 1999
3	Cadia *	12.02	6.10	0.285	0.000	0.790	2.60	*0.70*	10,321	0.9600	**9,908**	Radziszewski & Valery, 1999
4	Cadia *	12.02	6.10	0.250	0.040	0.780	2.60	*0.70*	10,824	0.9600	**10,391**	Radziszewski & Valery, 1999
5	Cadia *	12.02	6.10	0.407	0.040	0.780	2.60	*0.70*	14,945	0.9600	**14,347**	Radziszewski & Valery, 1999
6	Cadia *	12.02	6.10	0.316	0.120	0.740	2.60	*0.70*	17,586	0.9600	**16,883**	Radziszewski & Valery, 1999
7	Cadia *	12.02	6.10	0.261	0.120	0.780	2.60	*0.70*	17,963	0.9600	**17,244**	Radziszewski & Valery, 1999
8	Fimiston	10.80	4.42	0.216	0.130	0.725	2.90	0.66	9,255	0.9456	**8,752**	Nelson et al, 1996
9	Fimiston	10.80	4.42	0.252	0.130	0.770	2.90	0.63	10,374	0.9456	**9,810**	Nelson et al, 1996
10	Fimiston	10.80	4.42	0.222	0.115	0.800	2.90	0.60	10,976	0.9456	**10,379**	Nelson et al, 1996
11	Fimiston	10.80	4.42	0.200	0.140	0.820	2.90	0.75	11,684	0.9456	**11,048**	Nelson et al, 1996
12	Fimiston	10.80	4.42	0.286	0.130	0.780	2.90	0.75	11,610	0.9456	**10,978**	Nelson et al, 1996
13	Fimiston	10.80	4.42	0.258	0.130	0.780	2.90	0.75	11,571	0.9456	**10,942**	Nelson et al, 1996
14	Fimiston	10.80	4.42	0.190	0.120	0.800	2.90	0.75	9,408	0.9456	**8,896**	Nelson et al, 1996
15	Phoenix	10.74	5.03	0.300	0.130	0.740	*2.70*	*0.75*	10,965	*1.0000*	**10,965**	Cole et al, 2006
16	Phoenix	10.74	5.03	0.270	0.130	0.740	*2.70*	*0.75*	10,304	*1.0000*	**10,304**	Cole et al, 2006
17	Yanacocha	9.40	9.76	0.179	0.165	0.645	2.52	0.73	12,286	*1.0000*	**12,286**	Burger et al, 2011
18	Yanacocha	9.40	9.76	0.229	0.191	0.631	2.52	0.80	13,992	*1.0000*	**13,992**	Burger et al, 2011
19	LKAB KA2 (FAG)	6.28	5.30	0.305	0.000	0.753	*3.75*	0.75	2,800	*0.9456*	**2,648**	Bueno et al., 2011
20	LKAB KA3 (FAG)	6.29	5.88	0.414	0.000	0.753	4.33	0.76	3,857	*0.9456*	**3,647**	Powell et al., 2011
21	Porgera	8.38	3.35	0.263	0.110	0.782	2.73	*0.75*	4,550	*0.9267*	**4,216**	Grundstrom, 2001
22	Porgera	8.38	3.35	0.304	0.121	0.782	2.73	*0.75*	4,350	*0.9267*	**4,031**	Grundstrom, 2001
23	Porgera	8.38	3.35	0.228	0.138	0.782	2.73	*0.75*	4,650	*0.9267*	**4,309**	Grundstrom, 2001
24	Porgera	8.38	3.35	0.340	0.127	0.782	2.73	*0.75*	4,400	*0.9267*	**4,077**	Grundstrom, 2001
25	Porgera	8.38	3.35	0.269	0.132	0.787	2.73	*0.75*	4,310	*0.9267*	**3,994**	Grundstrom, 2001
26	Porgera	8.38	3.35	0.326	0.127	0.787	2.73	*0.75*	4,350	*0.9267*	**4,031**	Grundstrom, 2001
27	Cadia *	12.02	6.10	0.330	0.140	0.780	2.60	*0.70*	19,320	0.9600	**18,547**	Dunne et al, 2001
28	Cadia *	12.02	6.10	0.350	0.130	0.620	2.60	*0.70*	15,200	0.9600	**14,592**	Dunne et al, 2001
29	Cadia *	12.02	6.10	0.350	0.130	0.700	2.60	*0.70*	17,800	0.9600	**17,088**	Dunne et al, 2001
30	Cadia *	12.02	6.10	0.350	0.130	0.780	2.60	*0.70*	19,200	0.9600	**18,432**	Dunne et al, 2001
31	Driefontein RoM	7.45	9.25	0.370	0.080	0.760	*2.70*	*0.70*	7,400	0.9310	**6,889**	Powell, 2002
32	St Ives, sec crush	7.23	3.00	0.191	0.150	0.749	2.80	*0.70*	2,710	0.9310	**2,523**	Atasoy et al, SAG 2001; Clark, Mawby Vol Ed 2
33	St Ives, c/circ	7.23	3.00	0.214	0.140	0.749	2.80	*0.70*	2,565	0.9310	**2,388**	Atasoy et al, SAG 2001; Clark, Mawby Vol Ed 2
34	St Ives, o/circ	7.23	3.00	0.217	0.140	0.749	2.80	*0.70*	2,665	0.9310	**2,481**	Atasoy et al, SAG 2001; Clark, Mawby Vol Ed 2
35	Navachab	4.71	9.49	0.400	0.097	0.889	2.84	0.73	3,034	0.9310	**2,825**	Powell & Smit, 2001; Powell & Valery 2006
36	Los Bronces sag1	8.26	4.19	0.237	0.127	0.747	2.59	0.65	3,917	0.9361	**3,667**	Powell & Valery 2006
37	LB Confluencia	*12.20*	6.90	0.270	0.140	0.723	2.64	0.75	18,812	1.0000	**18,812**	Jordan et al, 2014
38	Inco Clarabelle	9.45	3.96	0.425	0.000	0.776	2.75	0.72	5,720	0.9014	**5,156**	McDonald & Strong, 1992
39	Inco Clarabelle	9.45	3.96	0.320	0.080	0.749	2.75	0.72	6,803	0.9014	**6,132**	McDonald & Strong, 1992
40	Inco Clarabelle	9.45	3.96	0.320	0.075	0.741	2.75	0.72	7,953	0.9014	**7,169**	McDonald & Strong, 1992
41	Inco Clarabelle	9.45	3.96	0.340	0.065	0.749	2.75	0.72	7,780	0.9014	**7,013**	McDonald & Strong, 1992
42	Santa Rita	9.15	5.00	0.332	0.000	*0.750*	3.24	*0.70*	6,667	0.9312	**6,208**	Latchireddi & Faria, 2013
43	Sossego	11.28	6.40	0.280	0.149	0.769	2.86	*0.70*	16,635	*0.9600*	**15,970**	Delboni et al, 2010
44	El Soldado	10.06	5.18	0.262	0.186	0.767	*2.70*	0.77	11,062	0.9456	**10,460**	Iglesias, Vicuña & Becerra, 2014
45	El Soldado	10.06	5.18	0.281	0.166	0.767	*2.70*	0.77	10,977	0.9456	**10,380**	Iglesias, Vicuña & Becerra, 2014
46	El Soldado	10.06	5.18	0.303	0.141	0.767	*2.70*	0.79	10,900	0.9456	**10,307**	Iglesias, Vicuña & Becerra, 2014
47	Bagdad AG 1,2	*9.45*	3.35	0.270	0.000	0.730	*2.70*	*0.70*	3,297	0.9219	**3,039**	Clements, Bender & Apland, 1996
48	Bagdad SAG 3	*9.45*	3.35	0.275	0.070	0.730	*2.70*	*0.70*	5,480	0.9219	**5,052**	Clements, Bender & Apland, 1996
49	Bagdad SAG 3	*9.45*	3.35	0.270	0.070	0.730	*2.70*	*0.70*	4,073	0.9219	**3,755**	Clements, Bender & Apland, 1996

Table 1. Published survey information (model inputs)

Italic indicates assumed values

* grinding ball density reported as 7.85 t/m³ (versus default 7.80)

LKAB (19) density assumed to be 30% hard (silicate) and 70% soft (iron)

	Austin				Morrell C-Model					Hogg-Fuerstenau
	$P_{cylinder}$ kW	P_{cone} kW	P_{shell} kW	Difference	$P_{cylinder}$ kW	P_{cone} kW	P_{gross} kW	P_{shell} kW	Difference	Angle to match P_{shell}, (°)
1	2,965	148	**3,113**	-2.4%	2,233	215	3,349	**3,119**	-2.3%	49.6
2	11,199	560	**11,759**	9.5%	8,235	708	12,372	**11,521**	7.3%	48.4
3	11,131	557	**11,688**	18.0%	8,179	699	12,289	**11,444**	15.5%	43.7
4	12,139	607	**12,746**	22.7%	8,988	722	13,326	**12,409**	19.4%	39.3
5	14,488	724	**15,212**	6.0%	11,026	1,124	16,401	**15,273**	6.5%	48.7
6	16,354	818	**17,172**	1.7%	12,342	1,152	18,049	**16,807**	-0.4%	48.2
7	16,280	814	**17,094**	-0.9%	12,438	1,023	18,052	**16,810**	-2.5%	47.6
8	8,580	429	**9,009**	2.9%	6,245	702	9,414	**8,767**	0.2%	45.9
9	9,478	474	**9,952**	1.5%	7,053	840	10,639	**9,907**	1.0%	46.3
10	8,961	448	**9,409**	-9.3%	6,668	725	10,031	**9,341**	-10.0%	52.5
11	9,456	473	**9,929**	-10.1%	7,367	743	10,950	**10,197**	-7.7%	50.7
12	9,935	497	**10,432**	-5.0%	7,673	971	11,593	**10,796**	-1.7%	50.5
13	9,642	482	**10,124**	-7.5%	7,413	888	11,162	**10,394**	-5.0%	51.6
14	8,591	430	**9,021**	1.4%	6,563	651	9,805	**9,131**	2.6%	43.9
15	10,510	526	**11,036**	0.6%	8,003	844	11,864	**11,048**	0.8%	47.3
16	10,242	512	**10,754**	4.4%	7,760	775	11,471	**10,682**	3.7%	44.5
17	12,400	620	**13,020**	6.0%	8,913	334	12,443	**11,587**	-5.7%	42.5
18	13,806	690	**14,496**	3.6%	10,075	446	14,033	**13,067**	-6.6%	44.2
19	2,765	0	**2,765**	4.4%	1,925	0	2,651	**2,469**	-6.7%	48.7
20	4,039	0	**4,039**	10.7%	2,826	0	3,807	**3,545**	-2.8%	46.7
21	3,615	181	**3,796**	-10.0%	2,780	311	4,224	**3,933**	-6.7%	53.2
22	3,876	194	**4,070**	1.0%	3,011	363	4,581	**4,266**	5.8%	45.9
23	3,753	188	**3,941**	-8.5%	2,886	298	4,342	**4,043**	-6.2%	50.5
24	4,024	201	**4,225**	3.6%	3,146	401	4,798	**4,468**	9.6%	44.7
25	3,886	194	**4,080**	2.2%	3,019	340	4,563	**4,250**	6.4%	44.3
26	4,014	201	**4,215**	4.6%	3,142	391	4,782	**4,453**	10.5%	43.9
27	18,069	903	**18,972**	2.3%	14,024	1,300	20,400	**18,996**	2.4%	44.8
28	14,564	728	**15,292**	4.8%	10,272	1,098	15,231	**14,183**	-2.8%	47.1
29	16,266	813	**17,079**	-0.1%	12,079	1,219	17,755	**16,533**	-3.2%	48.7
30	17,781	889	**18,670**	1.3%	13,801	1,315	20,138	**18,753**	1.7%	45.8
31	7,296	365	**7,661**	11.2%	5,521	239	7,790	**7,254**	5.3%	42.8
32	2,216	111	**2,327**	-7.8%	1,650	151	2,483	**2,312**	-8.4%	49.6
33	2,227	111	**2,338**	-2.1%	1,662	163	2,513	**2,339**	-2.1%	46.6
34	2,237	112	**2,349**	-5.3%	1,670	165	2,526	**2,351**	-5.2%	48.8
35	2,836	0	**2,852**	1.0%	2,200	0	3,004	**2,797**	-1.0%	40.7
36	4,203	210	**4,413**	20.3%	3,148	213	4,588	**4,272**	16.5%	36.7
37	17,898	895	**18,793**	-0.1%	13,488	1,106	19,483	**18,142**	-3.6%	42.6
38	4,922	246	**5,168**	0.2%	3,681	496	5,741	**5,346**	3.7%	52.3
39	5,467	273	**5,740**	-6.4%	4,096	495	6,248	**5,818**	-5.1%	53.5
40	5,350	268	**5,618**	-21.6%	3,986	484	6,092	**5,673**	-20.9%	75.4
41	5,350	268	**5,618**	-19.9%	4,044	501	6,194	**5,767**	-17.8%	72.2
41	6,014	301	**6,315**	1.7%	4,220	398	6,330	**5,895**	-5.0%	53.1
42	16,412	821	**17,232**	7.9%	12,529	1,031	18,063	**17,341**	8.6%	41.7
43	10,547	527	**11,074**	5.9%	8,221	720	11,921	**11,101**	6.1%	41.7
44	10,176	509	**10,685**	2.9%	7,941	722	11,570	**10,774**	3.8%	43.8
45	9,732	487	**10,219**	-0.9%	7,615	719	11,156	**10,388**	0.8%	46.8
47	3,177	159	**3,336**	9.8%	2,237	297	3,596	**3,349**	10.2%	46.9
48	4,034	202	**4,236**	-16.2%	3,172	416	4,938	**4,599**	-9.0%	61.6
49	4,103	205	**4,308**	14.7%	2,997	398	4,681	**4,359**	16.1%	41.1

Table 2. Model predictions

Spreadsheet containing Tables 1 & 2 may be downloaded from https://www.sagmilling.com/articles/25/view/?s=1

Recommended data for a mill survey publication

Consultants and academics who perform mill design and modelling rely on data from mill operators to calibrate their models. Because these models are used in the design of new plants, operating companies benefit from improved designs (less risk and less cost due to “design fat”) when consultants and model designers have better data. Therefore, operating companies who publish detailed surveys are important influencers of the next generation of plant designs.

An ideal published mill survey provides the following information:

- D, L, J_{total}, J_{balls}, ϕ_C, ρ_{ore}, w_C and P_{DCS};
- A description of the motor and drive system and a description of where in the electrical system the DCS power indication is measured;
- Ball metallurgy (e.g. “forged steel” or “high-chrome”) or ρ_{balls};
- Liner thickness estimate.

CONCLUSIONS

Published survey information is frequently missing pulp density, a description of the electrical and drive system, and an indication of how thick the liners are at the time of the survey. Including a description such as “gearless motor with DCS indicating the motor output” or “induction motor with gearbox” allows model operators to choose appropriate factors for power conversions.

The **Austin SAG model** is in good agreement with the surveys across a wide range of mill filling and mill speeds. It is also suitable for a typical range of ball fillings, between 8% and 18%.

- Difference between model & survey: average 1.1%; median 1.5%; standard deviation 9.0%.

The **Morrell C-Model** is in good agreement with the surveys across a wide range of mill filling and mill speeds. It is also suitable for a typical range of ball fillings, between 7% and 18%.

- Difference between model & survey: average 0.3%; median -0.4%; standard deviation 8.2%.

The **Hogg & Fuerstenau model** should be run with an angle α of 43° for mill with a D/L ratio equal to or less than one, angle α of 47° for D/L ratio of two, and 47° to 50° for D/L ratios greater than two.

The Author recommends using the Austin SAG model for greenfield mill designs as the model requires fewer parameters and less geometry than the Morrell C-model. The specification of a trunnion diameter, for example, is not required in the Austin model, removing an unnecessary degree of freedom from early-stage mill designs. The Morrell C-model is recommended for model-fitting to an existing SAG mill installation where a more detailed geometry (especially of the cone ends) can give higher fidelity predictions than the simpler Austin SAG model.

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NOMENCLATURE

A empirical fitting factor for the Austin SAG model

D mill diameter inside the liner, m

J_{balls} ball filling level, as a fraction of the total mill volume (e.g. 0.10 for 10%)

J_{ore} ore filling inside a mill, as a fraction of the total mill volume (e.g. 0.20 for 20%)

J_{total} total filling inside a mill, as a fraction of the total mill volume (e.g. 0.30 for 30%)

J_{voids} interstitial void space between balls and coarse rocks in a mill charge (e.g. 0.04 for 4%)

k empirical fitting factor in Morrell C-model to convert charge power draw to motor input power draw

K empirical fitting factor for the Austin SAG model

L mill effective grinding length, m

P the power evolved at the mill shell, kW

w_C charge %solids, fraction by weight (e.g. 0.75 for 75%)

α empirical angle of the "lever arm" for the Hogg & Fuerstenau model, degrees

ε_B porosity of the rock and ball bed, as a fraction of total bed volume (e.g. 0.3 for 30%)

ρ_x density of a component *x*, t/m³

ϕ_C mill speed, as a fraction of the mill critical speed (e.g. 0.75 for 75%)

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