SAG Mill Design and Benchmarking Using Trends in the JKTech Database

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Abstract

JKTech maintains a large database of comminution circuit data acquired from detailed surveys of grinding circuits in operations all over the world. Traditionally, this database has been used for internal benchmarking of projects against similar reference sites, as well as for validating the simulation outputs of the population-balance comminution models in JKSimMet. This has been undertaken with the use of power-based models regressed against the data, the forms of which have evolved over the years as the database has grown in size, and which delineate the underlying patterns otherwise camouflaged in the noise and variability of the dataset.

This paper presents the structure of the latest version of the JKTech autogenous and semi-autogenous (AG/SAG) mill specific energy model, which is an adaptation of that previously proposed by Morrell. While Morrell's model is well-known, historical publications have not provided insight into its behaviour or the trends that it predicts. These are described in this paper, where complex interactions between key feed, design, and operational variables that may not necessarily be evident in datasets of full-scale mills in production duty, are illustrated. The model's application in greenfield design scenarios and benchmarking of existing mills is demonstrated with a number of case studies.

Keywords

Comminution, SAG mill, specific energy, ball mill

Introduction

In 2009, a group of comminution practitioners published a paper discussing common, and typically unforeseen issues, that have led to problems with the correct interpretation of design-stage comminution testwork and analysis (Bailey et al., 2009). Broadly, these issues included the appropriateness of selected ore characterisation test procedures, the risk of laboratories employing non-standardised machine designs for common tests such as the Bond test suite, as well as limitations (and misuse) of various modelling philosophies that often underpin design selections. A follow-up publication detailed examples of where costly circuit modifications were required for throughputs to reach design targets, and how these projects have eroded the confidence of some financers in the ability of design engineers to size circuits that meet project requirements (Staples et al., 2015).

One of the recommendations in both Bailey et al. (2009) and Staples et al. (2015) was in the empirical benchmarking of mill selection (regardless of the modelling methodology that is used to arrive at a given mill sizing). At its most rudimentary, this involves comparisons with historical reference sites treating ores of similar hardness. Such an example was provided in 2005, when Newmont published observed specific energy (Ecs) data of their sites against the JKMRC SAG milling ore parameter, Axb, shown in Figure 1 (Veillette and Parker, 2005). A transformation of this trend was presented in Staples et al. (2015) where it was compared against projects that underperformed upon start-up, illustrating that these projects had insufficient installed power to treat the hard ores being processed at each site. Other *ad hoc* data are available in the public domain for benchmarking purposes where operations have published the results of detailed surveys and corresponding ore hardness tests on circuit feed (often forgotten about). Some recent examples are described in Kanchibotla et al. (2015), Esen et al. (2015), and Engelhardt et al. (2015).

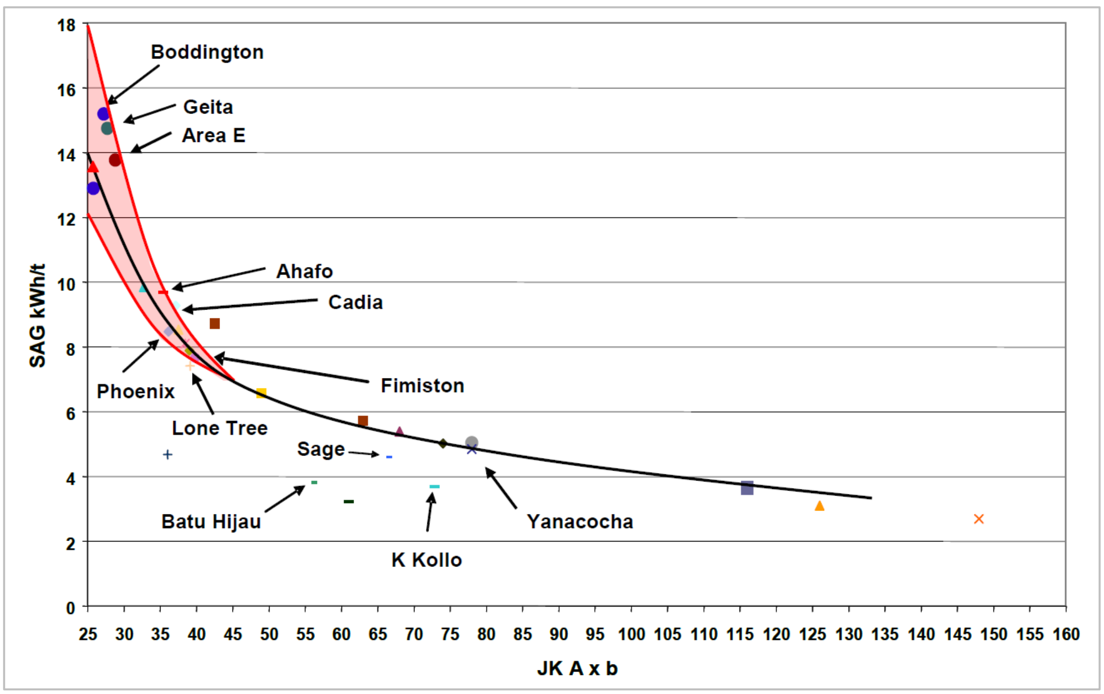


Figure 1—Observed SAG Mill Ecs vs. Axb as reported in Bailey et al. (2009), adapted from Veillette & Parker (2005)

Data of this type facilitate broad, high-level comparisons of Ecs requirements, although Figure 1 probably belies the true extent of variability that is evident with larger datasets. This paper describes some of the major trends in JKTech's database of comminution circuit surveys, and how the variability inherent in data obtained from production-scale mills can be accounted for with modelling approaches.

JKTech Database

For almost four decades, JKTech has been undertaking detailed surveys of comminution circuits, primarily for the purposes of obtaining the requisite data for modelling these circuits in JKSimMet. The so-called *population-balance* models in JKSimMet are very granular, necessitating the acquisition of field data including (but not limited to):

- Full size distribution measurements of fresh feed, final product, and internal circuit streams
- Stream tonnages, flowrates and pulp densities
- Ore hardness testwork
- Mill total filling and ball load measurements
- Equipment design and operating variables.

Key metrics from the surveys have been captured in a database containing the results of unique testwork rarely undertaken as part of full-circuit audits with corresponding ore hardness measurements. These include pebble crusher on vs. off comparisons, assessments of the effect of primary vs. secondary crushed feed, as well as surveys of mills operating fully autogenously and then with progressively higher ball loads to conventional ranges >12%. The database is regularly maintained and continues to grow as JKTech undertakes more of these types of surveys (Table 1).

Table 1—Summary of JKTech AG/SAG mill database ('open-circuit' subset)

Variable	Units	Min	Max
F_{80}	mm	20	153
Axb	-	25	90
M_{ia}	kWh/t	10	28
Ball load	%	0	22
Mill diameter	m	4	12
Speed	% critical	67	83
Aspect ratio (Diameter:Length)	-	0.6	3.0
Ecs	kWh/t	3.7	18.0

Note: F_{80} = 80% passing size; kWh/t = observed kilowatt hours per tonne; m = metre; mm = millimetre.

The data have been invaluable for benchmarking Ecs requirements in both the context of greenfield design, as well as in process improvement initiatives when there has been a need to make assessments of overall circuit efficiency. Historically, this has been undertaken either through comparisons against 'similar' sites treating 'similar' ore (with professional judgement required to define what constitutes 'similar'), as well as through the use of models that have been regressed against the data. This allows the effect of each variable to then be trended in isolation, which is usually not feasible in a full-scale production circuit. Uncertainties regarding scale-up (e.g., from lab or pilot-scale testwork) are also circumvented in this manner. The summary in Table 1 pertains to a subset of the database comprising 67 surveys of 27 different mills that were included in the analysis described in the following section.

Similarly to Figure 1, observed SAG mill Ecs vs. Axb is plotted in Figure 2, except this time with data from JKTech's database. The Axb data were obtained from measurements on feed samples collected during each survey. The figure shows subset data from 'open-circuit' SAG mills (i.e., classified with relatively coarse screens or trommels greater than ~10 mm aperture and with relatively low recirculating loads less than ~25%), which is the focus of this paper. More evident from the scatter in this chart than in Figure 1 is the degree of variability that is possible when inferring Ecs requirements from ore hardness alone.

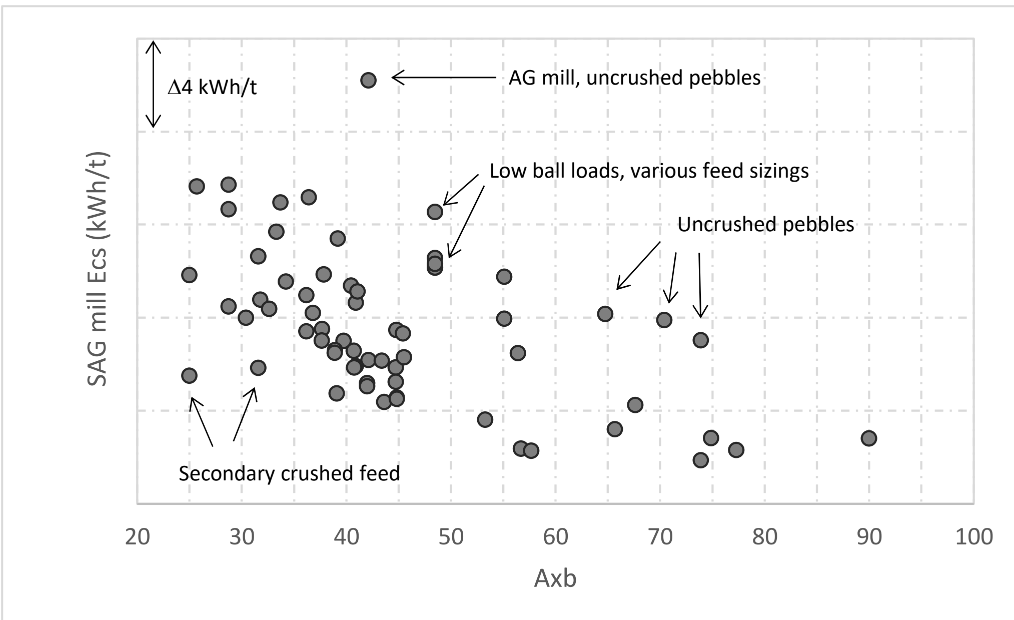


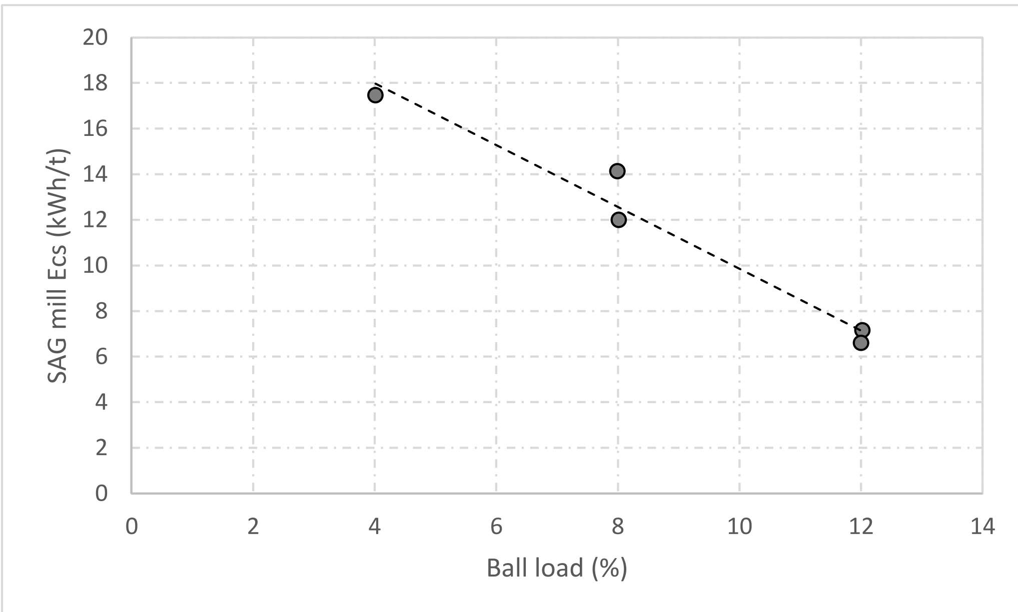
Figure 2—SAG mill Ecs vs. Axb Trend from JKTech Database ('Open-Circuit' AG/SAG Mills Only)

Annotations of circuit conditions causing several observations to deviate significantly away from the main group of observations are also shown. These include the effects of secondary crushing, AG-mode milling, and operating without pebble crushers (i.e., legitimate, and conventional processing strategies). The variability in Figure 2 is therefore not an artefact of 'outliers', but a wide variety of circuit-specific conditions that are effectively absorbed into the noise of the trend. This illustrates one of the risks of rudimentary benchmarking, in that there is often inherent difficulty in undertaking 'like-for-like' comparisons. As an example, Figure 2 shows that it is entirely possible for a relatively 'soft' ore with Axb ~70 to have similar SAG milling Ecs requirements as a relatively competent ore with Axb ~40, depending on the cumulative differences in circuit conditions.

The challenge with data obtained from production-scale mills is that 'one-variable-at-a-time' trials are rare (although the JKTech database does contain observations from such trials); these would otherwise delineate the effect of a manipulated variable upon SAG milling performance. With pilot-scale testing, these types of sensitivity tests can be undertaken in controlled, laboratory environments, to yield the types of trends shown in Figure 3a (Ecs vs. ball load in this instance), although the very shape of common pilot units in themselves can lead to large discrepancies between pilot vs. full-scale milling Ecs (Morrell, 2007).

The same plot, generated using production-scale data from JKTech's surveys, is shown in Figure 3b. The relationship between the two variables is nowhere near as discernible as they are when compared to controlled pilot-scale tests, again due to the wide range in site-specific processing conditions and ore types that otherwise camouflage the underlying patterns in the database. Conditions are shown for some observations that do not conform to the broad trend – none of these are necessarily abnormal in any respect; therefore, benchmarking would be crude (and potentially misleading) if these effects were not accounted for.

(a)



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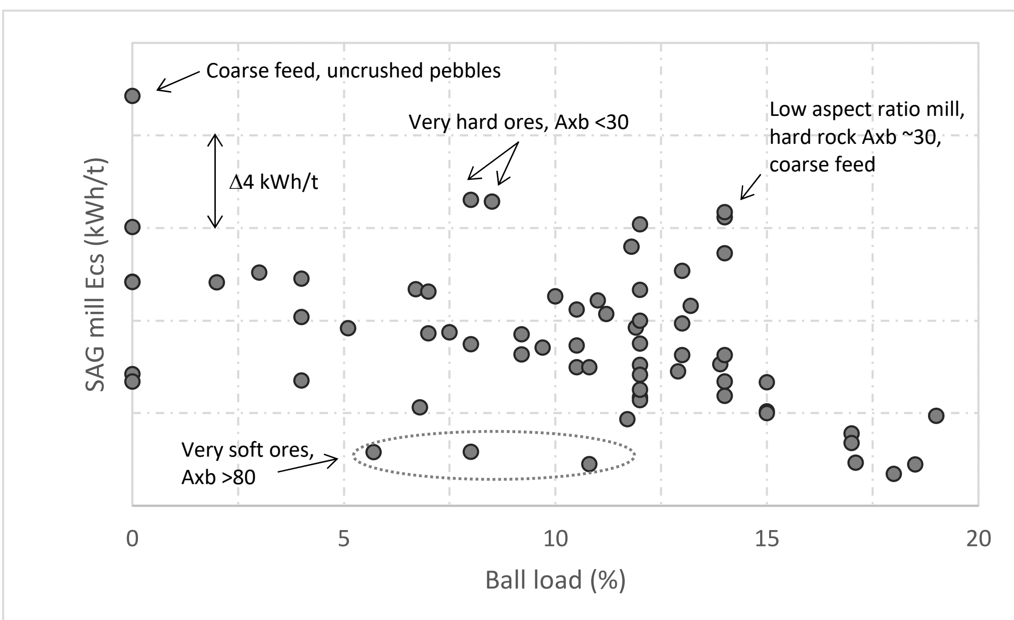


Figure 3(a)—Pilot SAG mill Ecs vs. Ball Load, Reproduced from Morrell (2006a); (b) SAG Mill Ecs vs. Ball Load for 'Open-Circuit' SAG Mills in JKTech Database

JKTech AG/SAG Mill Specific Energy Model

About the only way to account for so many competing factors that affect Ecs (in the absence of one-variable-at-a-time testwork at each site in the database) is to use multi-variable models that can be fitted to the data, which 'mathematically' disentangle these variables from one another. There have been several iterations of such models used by JKTech internally over the years. The structure of the latest version is an adaptation of that originally proposed in Morrell (2004):

$$SAG\ Ecs\ =\ KF_{80}{}^{a}M_{ia}{}^{b}\left(1+c\left(1-e^{-dJ}\right)\right)^{-1}\phi^{e}f(Ar)g(x) \tag{1}$$

where:

SAG Ecs = SAG mill Ecs (kWh/t)

K = function dependent on the absence or presence of a pebble crusher

F_{80} = 80th percentile fresh feed size (mm)

M_{ia} = coarse Morrell work index (kWh/t)

J = ball load (%)

ϕ = mill speed (fraction critical)

f(Ar) = function of the mill aspect ratio

g(x) = function of the SAG trommel or screen size

a, b, c, d, e are constants.

It should be noted that the original model form as reported in Morrell (2004) used the Drop Weight Index (DWi), as measured with the SMC Test, to represent SAG milling ore hardness. A similar model by Orway Mineral Consultants (OMC) was reported in Scinto et al. (2015), which instead used the JK-parameter, Axb, as the ore hardness index. JKTech's adaptation of Morrell's model in Equation (1) uses M_{ia}, the 'coarse' particle hardness parameter as measured with the SMC Test, to represent ore hardness as it resulted in the best overall fit to the JKTech database.

It should be highlighted that Equation (1) is applicable only to SAG mills classified with relatively coarse trommels or screens with apertures greater than about 10 mm (Morrell, 2006b) and with correspondingly low recirculating loads up to ~25%. Mills with non-standard configurations, or single-stage mills closed with hydrocyclones and with correspondingly high recirculating loads, do not conform to the predictions of Equation (1).

The goodness-of-fit is shown in Figure 4 (standard error = 1.5 kWh/t, 95% confidence interval = 3.0 kWh/t) with a comparison against the Morrell and OMC fits.

(a)

(b)

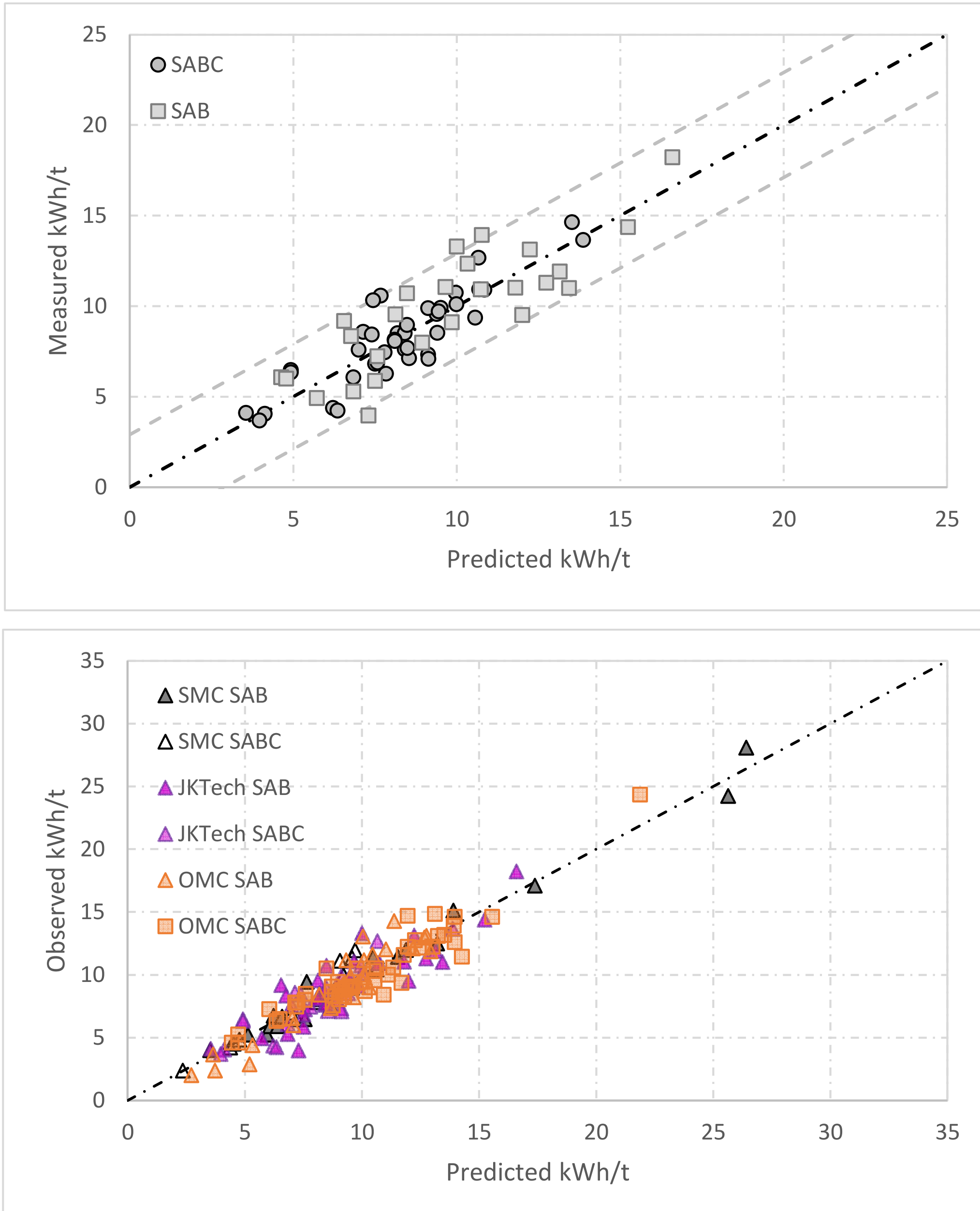
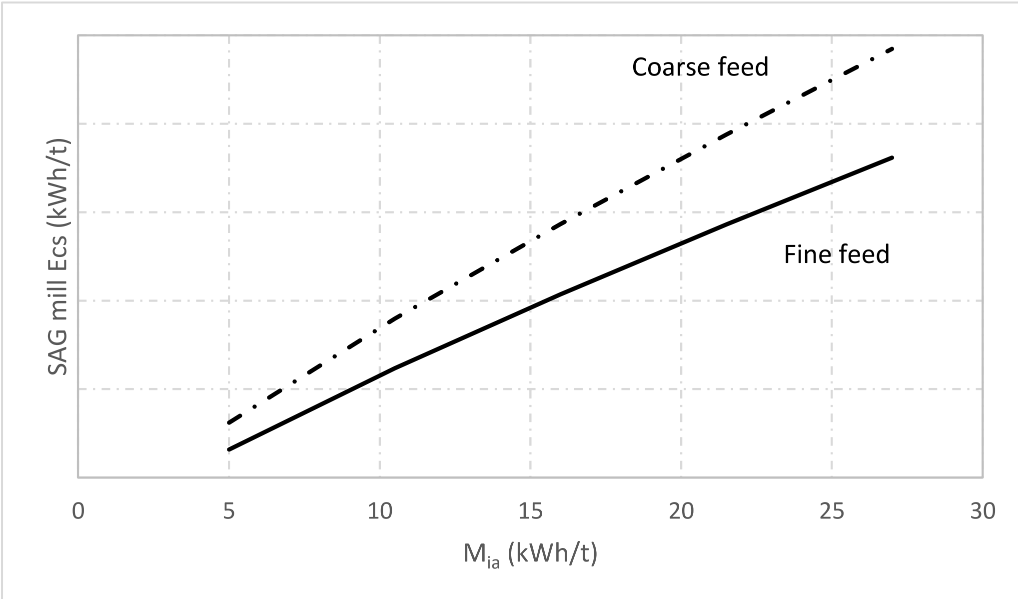


Figure 4(a)—Validation of JKTech AG/SAG mill Ecs equation; (b) comparison of Morrell, OMC and JKTech AG/SAG mill Ecs equation fits. Only the 'open' AG/SAG mill circuit subset is shown in the OMC series

While the form of Morrell's model is well-known, the behaviour of the model and its predicted trends have not been described in any publication thus far. Some example-predicted trends of Equation (1) are illustrated in Figures 5 to 7. In each figure, the y-axes have been supressed but are otherwise scaled identically to facilitate comparisons.

(a)



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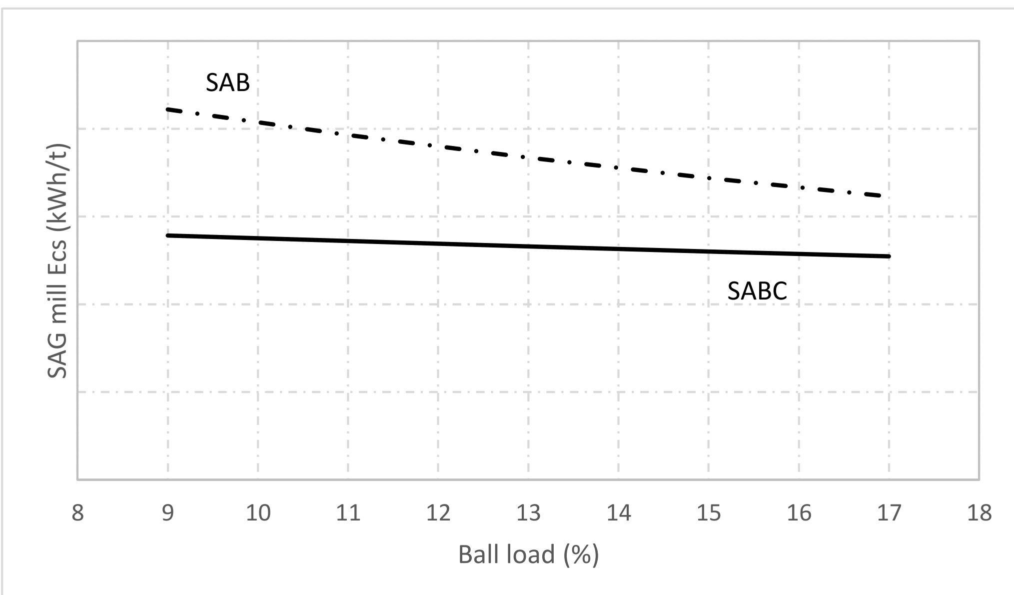


Figure 5—Example Trends of Predicted SAG mill Ecs Requirements with (a) M_{ia}; and (b) Ball Load

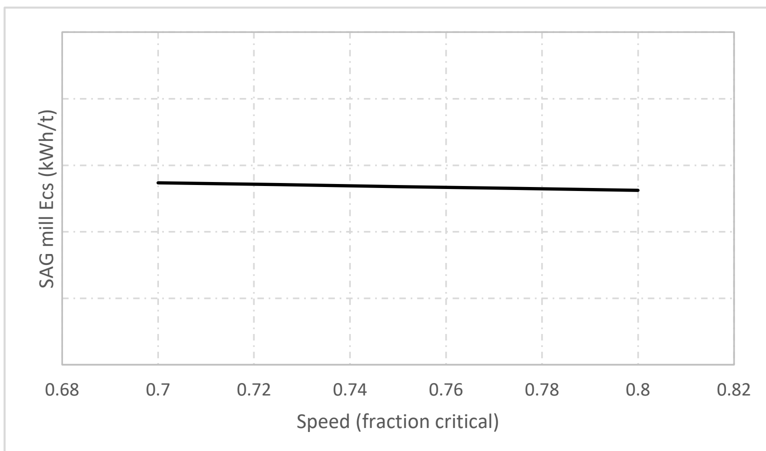
Ecs requirements trend almost linearly with M_{ia} (with mills treating coarse feed being more sensitive to changes in ore hardness) in a manner very dissimilar to that with Axb shown previously in Figure 1. While the M_{ia} is a direct measurement of ore competence, the A and b parameters are 'softness' indices that control the response of the Variable Rates SAG milling model in JKSimMet to changes in breakage energy. This response changes non-linearly with the two parameters. Consequently, their use outside of the JKSimMet software environment to describe ore hardness as the notional 'Axb' is prone to artefacts whereby a change from (say) 25 to 30 represents a substantial reduction in ore hardness, while a change in the very soft range from 125 to 130 would be almost indistinguishable within the error limits of the JKDWT experimental methodology.

In some circles, this led to confusion with the interpretation of the Axb. This prompted the development of the SAG Circuit Specific Energy (SCSE) metric, to assist with the interpretation of A and b outside of the application for which they were originally intended (i.e., the JKSimMet Variable Rates model) (Matei et al., 2015). While the SCSE has units of kWh/t, it was emphasised in Matei et al. (2015) that it should be used only to facilitate comparisons between different ores, and does not necessarily equate to the SAG mill power split in a particular application since other relevant site-specific feed and milling conditions are not considered in its derivation.

With respect to ball filling (Figure 5b), SAG mills without pebble crushers are predicted to be more sensitive to changes in ball load compared to those with pebble crushers. It is possible that the different sensitivities of mills in SAB vs. SABC configurations to ball load is due to the role of steel media in breaking pebbles. In the absence of pebble crushers, this would make mill performance more susceptible to variations in ball load. For mills in SABC configuration, recycle crushers would absorb the extra load of pebbles that would otherwise be produced with reduced quantities of steel media, resulting in a much more 'forgiving' Ecs response to changes in ball filling.

The speed and screen aperture effects (Figure 6) are quite weak.

(a)



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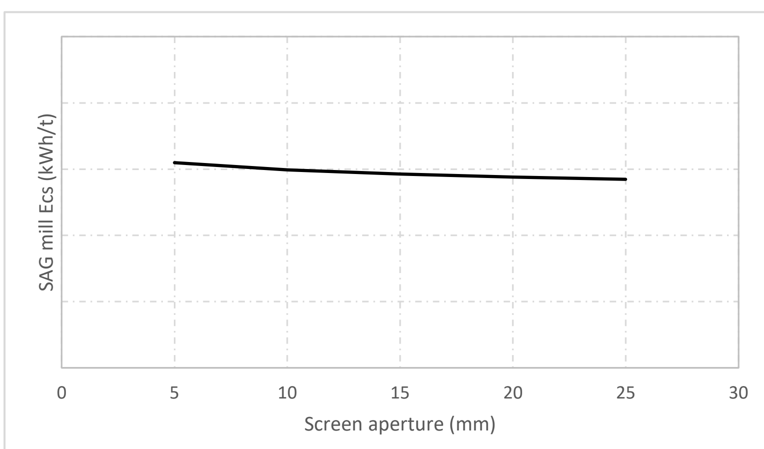
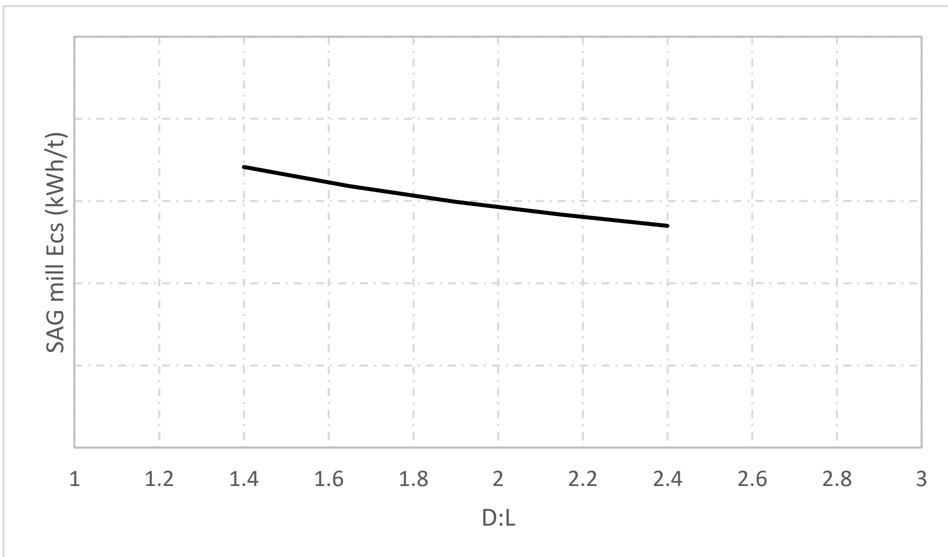


Figure 6—Example Trends of Predicted SAG Mill Ecs Requirements with (a) Mill Speed; and (b) Screen or Trommel Aperture

The weakness of the screen aperture effect is due to AG/SAG mill discharge streams typically being comprised of large quantities of fine particles. With typical closing screen apertures at fairly coarse sizes >10 mm, recirculating loads are usually very low (less than ~25%) and changes in this aperture have little effect on AG/SAG mill Ecs (Morrell, 2011). Interpreting the relatively insensitive response with speed was difficult; it is possible that faster speeds proxy liner wear in the database and that the benefit of faster speeds in promoting impact breakage is tempered by the effect of worn liners. The database contains no liner wear data, however, and so this remains a point of speculation.

The aspect ratio trend (Figure 7a) aligns with that reported in Morrell (2007), and Adam and Hirte (1973), and is predicted by JKSimMet's Variable Rates SAG mill model in that mills with high diameter-to-length ratios generally require less power to achieve a given throughput, though at the expense of a coarser transfer size.

(a)



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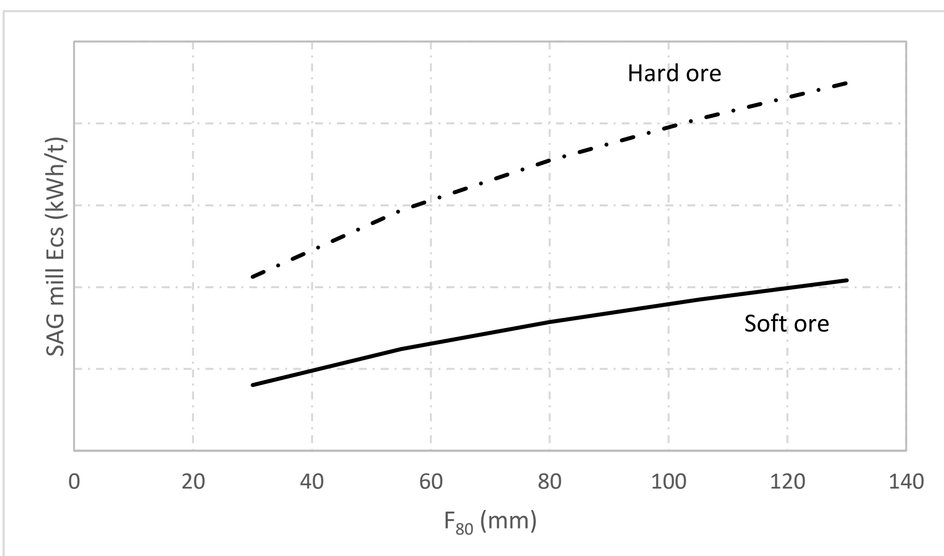


Figure 7—Example Trends of Predicted SAG Mill Ecs Requirements with (a) Aspect Ratio; and (b) F_{80}

The implication is that a strategy of targeting higher mill power draws by selecting mills with longer lengths will not result in commensurate increases in throughput. There are also implications for the interpretation of pilot-scale testwork data, which are most frequently obtained using mills with very high aspect ratios (6 ft. diameter [D] × 2 ft. length [L], D:L = 3), while typical North American 'pancake' mills in production duty have a D:L ratio ~ 2. That is, with all else being equal, full-scale mills will typically have higher Ecs requirements than their pilot-scale analogues simply due to differences in geometry. These increased Ecs requirements do not imply inherent inefficiencies, however, as lower-aspect ratio mills will discharge finer products; that is, the increased power consumption needed to achieve a throughput target is not 'wasted', but produces more fine particles (Adam and Hirte, 1973; Morrell, 2007).

The F_{80} effect is strong (Figure 7b), showing the alleviation of SAG milling Ecs requirements with progressively finer feed sizes, whether through 'Mine-to-Mill' philosophies or more aggressive strategies such as secondary crushing. The sensitivity of Ecs to changes in F_{80} is shown to be more severe for 'hard' feed compared to 'soft' feed. The difficulty in greenfield projects is often with the selection of an appropriate F_{80} to use as the basis of the design, with different modelling packages typically arriving at different predictions of what this may be. A relationship between SAG mill F_{80} and ore hardness was published in Bailey et al. (2009), the predictions of which are often finer than corresponding vendor predictions. That measured SAG mill feed sizings are often finer than expected has long been reported (e.g., Morrell and Morrison, 1996), with discrepancies attributed to blasting practices in mining as opposed to quarrying, the origins of vendor crushing models, ore friability (Chandramohan et al., 2015), and the often-unappreciated comminution effect of primary crusher stockpiles (Morrell and Valery, 2022). In any case, the strategy of reducing SAG milling Ecs requirements by reducing SAG mill feed sizing has downstream implications which become apparent when Equation (1) is used in conjunction with total circuit Ecs models, as described in the next section.

Applications

Equation (1) is the latest in a series of power-based models that JKTech has used internally to validate simulation outputs from JKSimMet, as well as to benchmark the performance of existing mills. When used in conjunction with a total circuit specific energy model, Ecs requirements for ball mills following AG/SAG mills can also be determined. JKTech does not use the Bond method for power-based ball milling calculations, and instead uses an approach advocated in Morrell (2011), Lane et al. (2013) and Scinto et al. (2015) where ball milling requirements are calculated by the difference between total milling and AG/SAG milling Ecs:

$$Ball\ mill\ Ecs = Total\ Ecs - SAG\ mill\ Ecs \tag{2}$$

where:

Ball mill Ecs = ball mill Ecs requirements (kWh/t)

Total Ecs = Ecs requirements of both AG/SAG and ball milling circuits (kWh/t)

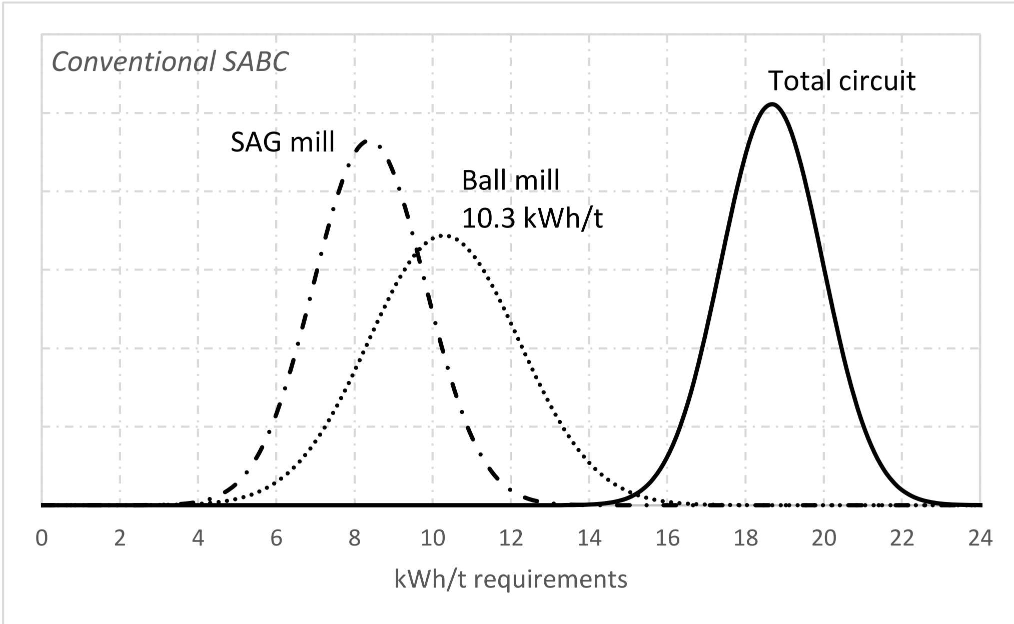
SAG mill Ecs = given by Equation (1) (kWh/t).

Total Ecs in Equation (2) can be obtained with published Morrell equations (Morrell, 2008) that have been endorsed by the Global Mining Guidelines Group (GMG, 2021), although Ausenco and OMC use their own approaches to calculate this term as detailed in Lane et al. (2013) and Scinto et al. (2015) respectively. Regardless, the benefit of this overall approach of obtaining ball milling requirements by difference is that it circumvents complications with defining and predicting the transfer size distribution between AG/SAG milling and ball milling circuits, which remains contentious.

An example of the application of Equation (2) is shown in Figure 8, which demonstrates the change in a SAG-ball mill power split following the introduction of fine SAG feed (F_{80} 35 mm) compared to a baseline circuit with conventional feed F_{80} 100 mm. These are represented as histograms to illustrate the uncertainties in each model's predictions.

With a conventional feed sizing, the SAG-to-ball mill power ratio was 45:55. With secondary crushed feed, the power split changed to 30:70, with the ball mill Ecs requirements increasing from 10.3 to 11.8 kWh/t for the target P_{80} to be maintained. In greenfield scenarios, this could obviously be accommodated with the selection of larger ball mills. In circumstances where this is not possible (e.g., existing circuits), the lack of required ball milling power would necessitate either a reduction in throughput to maintain the target grind, or alternatively, a coarsening of the final grind at the target throughput. This is a common experience in sites that utilise secondary crushing ahead of SAG mills, and is a consequence of the coarsened transfer size between SAG and ball mills (Needham and Folland, 1994; Nelson et al., 1996; Powell et al., 2015; Sulianto et al., 2016). The strategy, in effect, reduces SAG mill Ecs but increases the burden on downstream ball milling.

(a)



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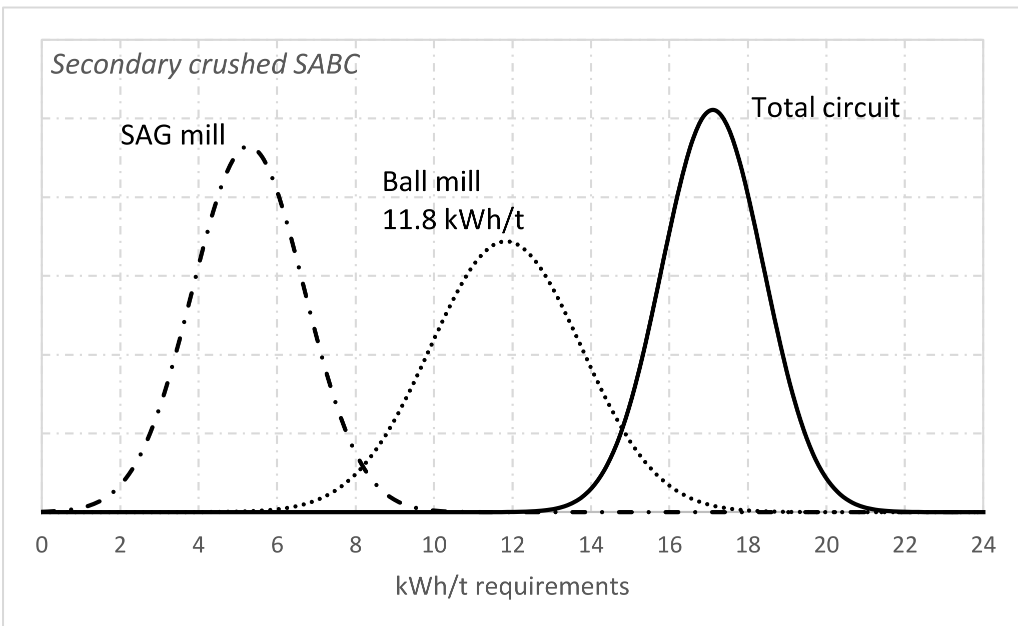


Figure 8—Tumbling mill Ecs requirements of (a) conventional SABC circuit with F_{80} 100 mm; (b) SABC circuit with secondary crushed feed F_{80} 35 mm

Apart from greenfield studies, Equation (1) is also useful for benchmarking existing mills, and assessing whether their performance aligns with what would typically be expected for a given set of ore and milling conditions. Figure 9 shows theoretical SAG mill Ecs requirements as a histogram calculated with Equation (1) against the much higher Ecs measured for a SAG mill in a gold operation. The mill was fed by a stockpile subject to severe segregation, and while the measured F_{80} 102 mm was typical, the size distribution was depleted in fines content with less than 5% of the SAG mill feed consisting of -10 mm material (usually ~15-30% in this F_{80} range).

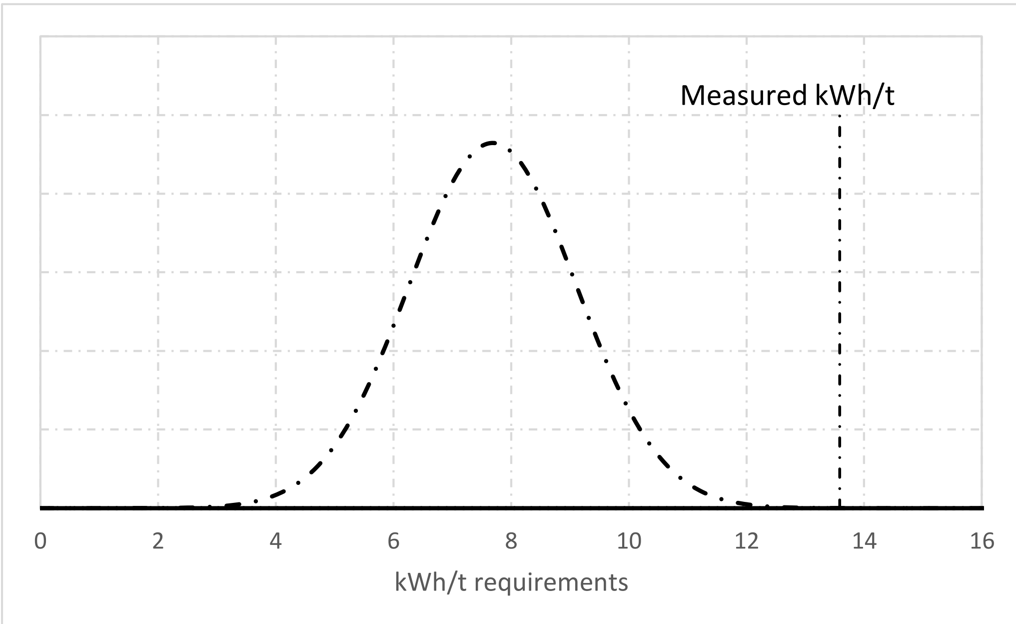
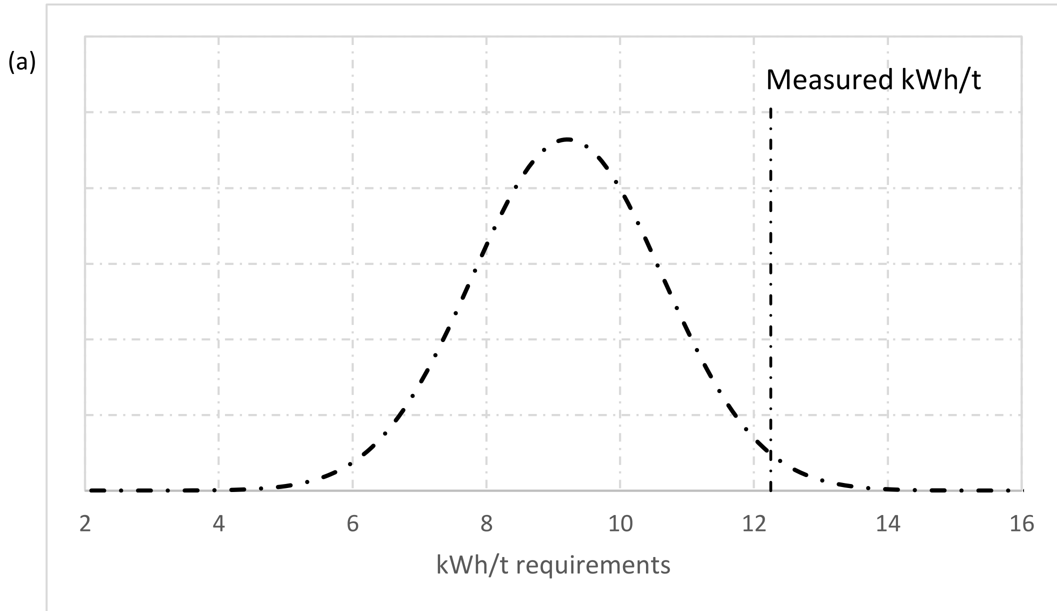


Figure 9—SAG Mill Ecs Requirements for SAG Mill Fed by Highly Segregated Stockpile

Figure 10a shows the measured SAG mill Ecs in another gold operation, against the corresponding prediction of Equation (1), shown again as a histogram. The relatively high Ecs of the mill was largely due to poor size reduction across the pebble crusher, with the closed-side setting (CSS) measured to be 25 mm (originally reported by the control system as 12 mm).

This excessively large CSS was rectified, and a follow-up survey undertaken with the SAG mill performance shown in Figure 10b. The position of the Equation (1) histogram shifted to lower ranges largely due to a softer ore and finer SAG mill feed sizing being processed. Importantly, the vertical line better aligned with the position of the histogram peak as the performance of the operation more closely matched what would normally be expected for a mill undertaking this particular duty.



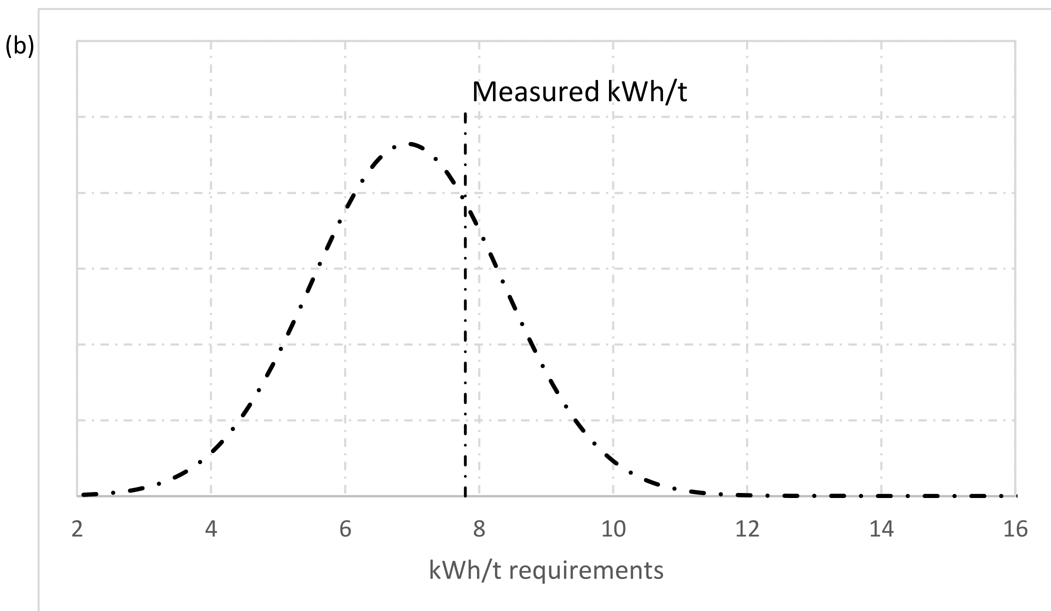


Figure 10—SAG Mill Ecs Requirements for (a) SAG Mill with Poor Pebble Crushing Performance; (b) SAG Mill with Good Pebble Crushing Performance

Conclusions

A modified version of Morrell's AG/SAG mill Ecs model has been fitted to the JKTech comminution survey database. The model can be used for benchmarking, either to de-risk greenfield milling designs, or to assess whether existing mills are performing as expected when compared to mills in similar duties. When used in conjunction with total circuit Ecs calculations, the model can also be used to determine appropriate ball mill sizing.

It is worth noting that the model in itself will not diagnose the root cause of throughput bottlenecks, and its application is limited in identifying remedial strategies that resolve circuit constraints. These assessments are best undertaken with population-balance models such as those in JKSimMet that describe the behaviour of individual size fractions flowing around a circuit, and their role in suppressing overall circuit performance. All models have strengths and weaknesses, and the ability of practitioners to use models that complement each other is a powerful approach to facilitate process improvement, and de-risk design selections.

Acknowledgements

The work of JKTech personnel, past and present, in undertaking grinding circuit surveys in production plants all over the world, formed the basis of this paper, which would not have been possible without their efforts.

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