BENCHMARKING COMMINUTION CIRCUIT PERFORMANCE FOR SUSTAINED IMPROVEMENT

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Abstract

Newmont has a demonstrated history as a leading investor in comminution technology developments. Most notably the cornerstone high pressure grinding rolls (HPGR) demonstration plant at the Lone Tree operation in 2003, which paved the way for the subsequent adaptation of the HPGR technology in the hard rock mining industry. Newmont continuously evaluates grinding circuit performance at its global operations, allowing continuous improvement of operating facilities and practical insights to be applied to new plant designs. This approach was demonstrated by a global mine-to-mill operations review in 2009, incorporating circuit sampling and standard ore characterisation testwork to facilitate the assessment of circuit performance efficiency and increased circuit productivity. This effort, and an ongoing commitment to performance analysis, has resulted in a performance-based dataset defining 15 individual comminution circuits. The database further provides a useful basis for comparing the available techniques to define circuit efficiency.

In this paper, the authors will review various methods for assessing comminution circuit efficiency in the context of the Newmont database, including the Bond, Morrell, and size specific energy (SSE) methodologies. The authors will show that SSE method generates a relative efficient measure that allows equipment performance to be assessed in isolation, and is in that sense comparable to the Morrell approach, whereas the published Bond approach is better suited to overall circuit analysis. The combination of these three methods allows a comprehensive understanding of the effectiveness of each comminution circuit, highlighting improvement opportunities, and providing a baseline from which the potential of new technologies can be measured.

The results of this analysis were also plotted on the comminution energy curves, a free platform provided by the Coalition for Eco Efficient Comminution (CEEC) and the Julius Kruttschnitt Mineral Research Centre (JKMRC). The energy intensity of each Newmont site was assessed using four individual energy indices.

In this paper, the authors will discuss the insights generated from each analysis method and demonstrate their relative merits as observed for the operations studied in this assessment.

Keywords

Energy efficiency, SAG milling, Ball milling, Bond, Morrell

Introduction

Newmont GoldCorp is the world's leading gold company with active operations in North America, South America, Australia, and Africa. The scope of this paper is limited to the Newmont operations held prior to the recently completed acquisition of GoldCorp. Newmont GoldCorp's commitment to environmentally responsible mining is reflected in its status as the mining industry leader in overall sustainability as noted by the Dow Jones Sustainability World Index from 2015-2018, and requires continued assessment of comminution efficiency in all operations and projects.

From 2009 to 2011 Newmont engaged in a global collaboration with Metso's Process Technology and Innovation Group to conduct mine-to-mill optimisation studies at its operations in Nevada, Peru, Ghana, and Australia. The mine-to-mill baseline assessment process required full comminution circuit surveys to define the magnitude of performance improvement opportunities, and in several cases involved the campaigning of future ore sources that were considerably more competent than the typical mill feed stock. As a result, the survey database is somewhat skewed towards grinding circuits not operating in their most optimised, or even normal, operating condition.

Bond (1952) proposed the use of the P_{80} size to characterise the fineness of mineral powders. It proved to be an extremely useful measure as it typically captured the top end of the linear (in log-log space) section of the size distribution before it started to roll over, as per the Rosin-Rammler (1933) distribution. However, as Bond (1961) acknowledged, using P_{80} to assess the comminution energy consumption only works when the size distributions are parallel in log-log space. For instance, it is widely acknowledged that the size reduction achieved by SAG mills should not be assessed by measuring the P_{80} because the internal breakage mechanisms typically result in non-parallel feed and product size distributions (Amelunxen and Meadows, 2011; Napier-Munn et al., 1996). Bond developed three standardised characterisation tests (crushing, rod milling, and ball milling) that were compared to results from a pilot plant containing closed-circuit crushing, open circuit rod milling, and closed-circuit ball milling. From these comparisons, empirical constants were applied to the laboratory test results so that the pilot scale results could be predicted. The Global Mining Guidelines (GMG) produced a standardised methodology for calculating a Bond Standard Work index from the individual tests (GMG, 2015). This method will be followed in this paper.

Morrell (2004) recognised the limitations of the Bond method to benchmark SAG milling circuits and proposed an alternative method that relied upon a large database of operating circuits and modified the exponent of the Bond equations to be size dependent. This database was compared to drop weight test and Bond ball milling test results to obtain benchmarks of typical comminution circuit designs. The total circuit specific energy is calculated using an approach that was also standardised by the GMG (2016). However, the SAG mill specific energy is calculated using proprietary models and the specific ball milling specific energy is the differential between the SAG mill and total specific energy requirements. This method acknowledges the limitations of using the P_{80} of the transfer size between the SAG mill and the ball mill. The Ausgrind approach (Lane et al., 2013) provides a similar result to the Morrell approach by modifying the characterisation results; however, this method will not be covered in this paper.

An alternative technique is explored in this paper that avoids the limitations of using P_{80} by benchmarking the equipment based on the energy consumed in the generation of fines: the SSE methodology. A similar method was first used by Davis (1919) and has subsequently been used by numerous authors; however, the methodology was never formalised. The method relies on the Rittinger (1867) theory that comminution energy consumption is proportional to surface area production. However, due to the fractal nature of particle size distributions, the surface area is actually infinite and can only be measured on a relative basis. Therefore, since the fines contain the vast majority of the surface area, fines production is a good indicator of surface area production. Typically, 75 µm has been used in SAG and ball milling circuits as the marker size to define what is considered 'fines' (Ballantyne et al., 2015c; Musa and Morrison, 2009). However, alternative marker sizes may be considered when this is ineffective, for operations targeting significantly coarser or finer size reduction.

In its drive to promote continuous improvement, Newmont has published a summary of the performance of 13 of its sites in 2015 (Giblett and Hart, 2016) and conducted 17 full comminution circuit surveys, accompanied by standard ore characterisation tests in recent years. The 2015 performance data will be used to benchmark the comminution energy intensity using the energy curves methodology to supplement Newmont's conventional assessment methods, which follow the approach developed by Morrell. Additionally, the circuit survey dataset will be used to evaluate the performance of these circuits using the Bond, Morrell, and SSE efficiency methodologies.

Benchmarking using the Comminution Energy Curves

The energy curve methodology was developed to present the variability in comminution energy intensity of different operations. A significant database was collected, and the curves were developed to be similar to cost curves allowing easy adoption for the industry. Since comminution energy intensity is dependant on many factors, a standard suite of four energy curves were initially adopted.

Newmont's drive for continual improvement led to the publication of benchmarking results from 13 grinding circuits (see Table 1). This data was then submitted for benchmarking on the comminution energy curves. These sites were comparable on four of the foundational curves: Bond work index (BWi), operating work index, specific energy, and copper equivalent specific energy (production figures were sourced from publicly reported values from the 2015 annual report).

Table 1 – Newmont operations 2015 performance summary (Giblett and Hart, 2016)

					2015 performance summary			
Operation	**Configuration**	**A*b**	**BWi**	**Mt/a**	**Mill utilisation**	**Steel kg/t**	**Grind size**	**kWh/t**
Ahafo	SABC/A	25–35	15–20	6.6	89.3	1.0	106	23.6
Akyem	SABC/A	30–45	10–15	7.2	80.7	1.0	75	19.0
Batu Hijau	SABC/B	30–70	10–15	42.0	89.6	0.5	260	10.1
Boddington	High pressure grinding roll/ball	22–33	12–17	37.2	88.3	0.6	160	14.7
Carlin Mill 5	SABC	30–40	20–25	4.5	91.4	1.2	140	17.3
Carlin Mill 6	Twin chamber ball mill	40	15	3.2	85.0	0.4	79	19.3
Kalgoorlie Consolidated Gold Mines (KCGM)								
Fimiston	SABC	31–42	13–16	9.1	85.8	0.8	170	15.3
Mt Charlotte	Crush/SAB			2.5	89.0	0.6	150	17.4
Phoenix	Crush/SABC	27–74	10–20	10.0	90.8	1.6	106	18.1
Tanami	SS ball	22-33	15–20	2.2	91.3	0.5	155	17.0
Twin Creeks								
Sage	SAB	65–75	15–20	1.1	90.3	1.5	25	34.8
Juniper	SABC	70–80	10	3.6	93.8	0.5	55	9.7
Yanacocha	SS SAG	45–100	14–19	6.1	96.1	2.1	164	17.5

BWi – Bond ball mill work index; SAB – semi-autogenous grinding ball; SS – single-stage; SAG – semi-autogenous grinding.

Figure 1 shows the position of the mines on the BWi energy curve. BWi is a measure of the hardness of an ore. The standard Bond method to define specific energy requirements requires crushing, rod, and ball work indices to be determined. Whereas, this dataset contained only the Bond ball milling work index as Newmont favours the Morrell approach that uses the SMC Test® to define coarse comminution energy requirements. However, it should be noted that in the Bond standard approach, the ball milling work index has the largest influence. For a P_{80} of 100 µm, the ball milling work index accounts for approximately 70% of the weighting in the Bond standard calculation (GMG, 2015), with the rod mill taking 25% and the crushing work index 5%.

Newmont's operations cover the full range of the BWi energy curve, with Mine 7 the most competent ore and Mine 10 the least. However, all of these ores showed a much higher drop weight index (DWi) than would be expected from their Bond ball milling work indices. In fact, the average ratio of DWi to Bond ball mill work index was at the 90th percentile of a much larger database. This result indicates that the SAG milling power requirements for these ores is likely to be much greater than what would be expected from the Bond ball mill work index. For instance, Mine 12 sits close to the 50th percent in BWi but has a design A*b of 27, which is in the top 8% of drop weight test results. As such Bond ball mill work index alone is not an effective basis to estimate the comminution energy requirements for many of Newmonts operations.

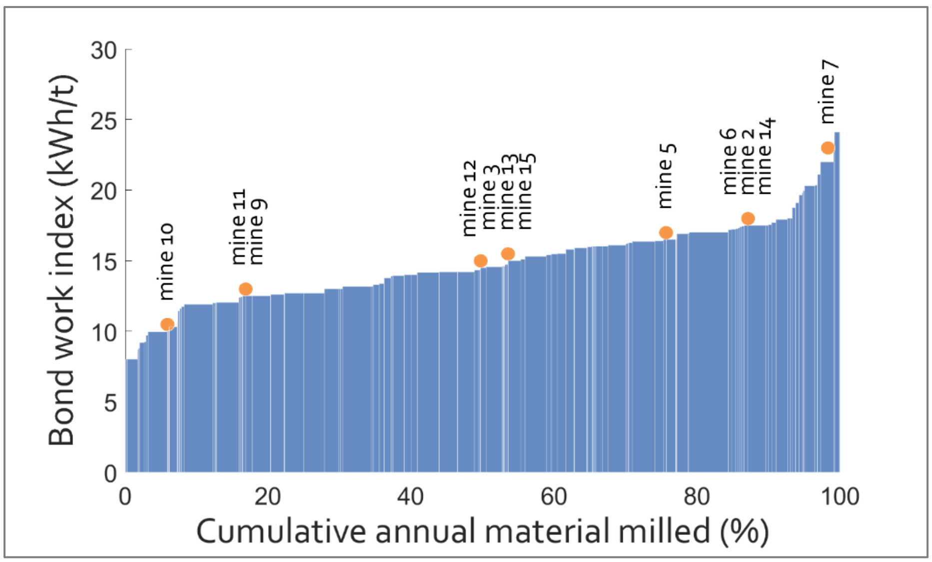

Figure 1 – Newmont sites on the Bond intensity energy curve, comparing the BWi

The position of the sites on the Bond operating work index (OWi) energy curve is presented in Figure 2. What is interesting to note is that the relative position of the mines has changed from the previous figure. This indicates that these mines were not all operating at the same efficiency relative to the ore competence. The circuit type and operating conditions both play a role in determining the ratio of OWi to BWi. All the mines occupied a lower (or similar) position on the OWi energy curve than they did on the BWi energy curve. This indicates that they all operated at a higher energy efficiency than the majority of the mines in the energy curve database. The comminution efficiency evaluation of these circuits will be explored in more detail later in the paper.

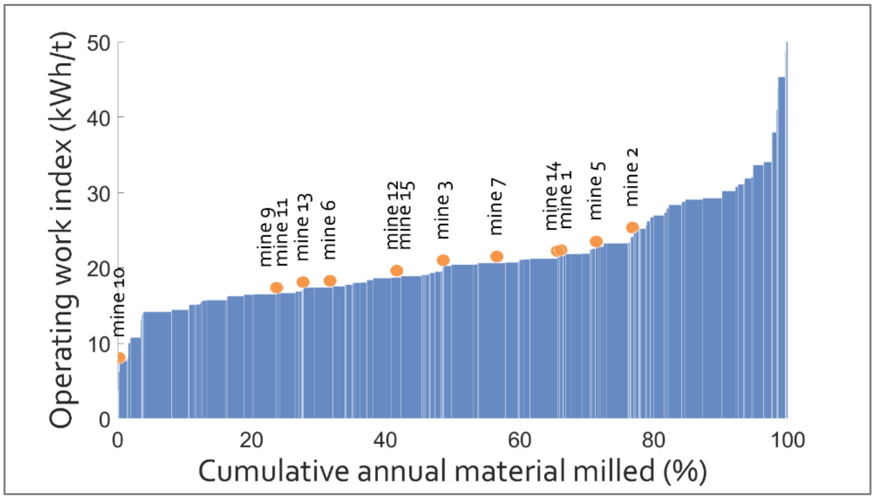

Figure 2 – Newmont sites on the Bond intensity energy curve, comparing the OWi

The tonne intensity energy curve ranks milling circuits based on the specific energy requirements (kWh/t). This is the most commonly used energy intensity metric and it is influenced by the ore hardness (generalised by BWi), circuit efficiency, and the grind size required to achieve sufficient liberation and recovery. Figure 3 shows the position of the Newmont sites on this energy curve; once again, the position of the mines has changed in comparison to the OWi curve and they cover the full breadth of the distribution. The most significant changes in relative position on the energy curve from the Bond intensity curve to the tonne intensity curve relate to Mine 9 and Mine 6. Mine 9 dropped from the 24th percentile in terms of OWi to the 4th percentile in terms of specific energy. This was due to the coarse liberation and high throughput at Mine 9, which allowed a target P_{80} of 260 µm. Grinding to this coarse size requires significantly lower specific energy requirements. On the other hand, the very fine grind (25 µm) targeted at Mine 6 required high specific energy, moving this operation from the 30th percentile (OWi) to the 97th percentile (specific energy), as would be expected at such a fine final product size.

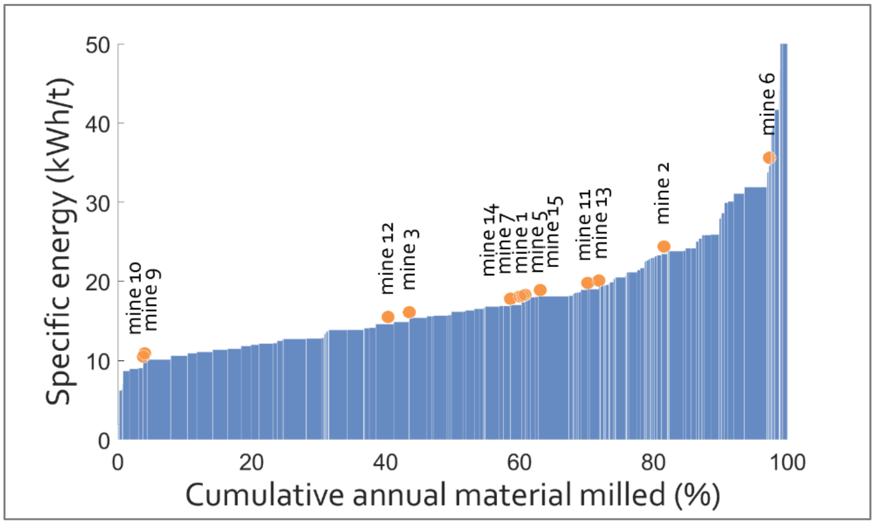

Figure 3 – Newmont sites on the tonne intensity energy curve

Finally, the grade intensity energy curve represents the energy required to generate a tonne of metal product. The copper specific production is used to compare the results from different commodities (Figure 4). In addition to ore hardness, circuit efficiency, and grind size, ore feed grade and recovery efficiency plays a significant role in the position of a mine on this curve. Mines 5 and 14 display the most significant change in position from the tonne intensity curve. These mines move from close to the 60th percentile in terms of specific energy to below the 10th percentile of copper equivalent specific energy. This change in relative position indicates that these two sites have significantly larger annual production of gold relative to their milling rate (i.e. higher ore grade and recovery) than other mines in the database. The position of the mines does not change significantly if compared solely to operations where gold is the primary product.

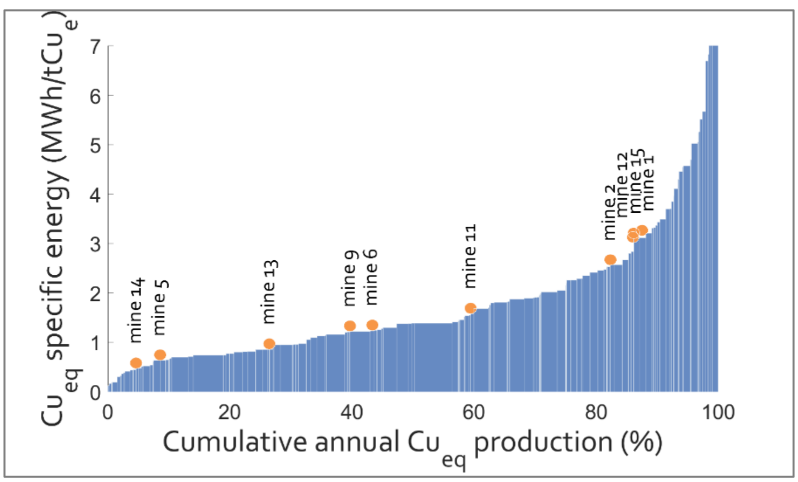

Figure 4 – Newmont sites on the grade intensity energy curve

The most significant outcome from this energy curve analysis was that the relative position of the mines was different for each of the energy curves. This shows the benefit of the energy curve approach to benchmarking, as it considers the multiple factors that influence energy intensity. Investigations are currently underway to incorporate the coarse competence in the methodology. Figure 5 shows the relative position of four chosen sites across the four energy curves. The change in position across these four curves give an indication of the energy signature of the comminution circuit.

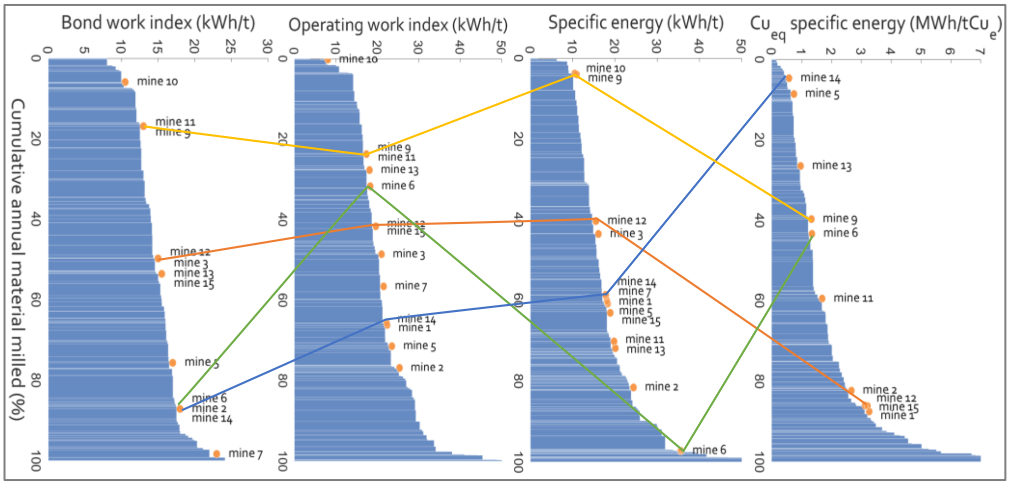

Figure 5 – Relative position of mines 2, 6, 12, and 14 highlighted sites across the four energy curves

Benchmarking Energy Efficiency

The energy curves methodology is effective for benchmarking sites on their comminution energy intensity using four typical measurements. However, to assess the efficiency with which they are utilising the energy in breakage, different approaches are required. There are two major approaches that are widely used: Bond and Morrell. The Global Mining Standards Group formalised the Bond and Morrell approaches and published them on their website (GMG, 2015, 2016). Both approaches use standardised laboratory characterisation tests to evaluate the response of the rock sample to breakage. Empirical relationships between the laboratory results and pilot or full-scale machines are then used to convert the test results into parameters that indicate the energy required to generate a specific product size from a given feed. As explained in the introduction, because these techniques use the P_{80} to describe a size distribution, the calculations are only valid for determining the total specific energy requirement from a primary crusher to a cyclone overflow (in SAG and HPGR-based circuits). The Morell and Ausgrind methods calculate the SAG specific energy from the coarse competence and find the Ball milling energy from the difference. However, this does not account for the degree of size reduction achieved by the SAG or ball mill individually.

Once the specific energy requirement to achieve the size reduction is predicted, a survey of the milling circuit provides a measurement of the specific energy achieved by the operating circuit. The comparison of these two figures gives an indication of the comminution energy efficiency achieved by the operating circuit.

STANDARD BOND METHOD

The 17 comminution circuit surveys conducted by Newmont were evaluated using the standard Bond methodology. One limitation of this dataset was that the Bond crushing and rod work index tests were not regularly conducted. Therefore, the predicted specific energy of the circuits is evaluated predominately using the ball milling work index alone. As already highlighted, the standard work index calculation is heavily weighted towards the ball milling test results, so the impact of this missing data on the total circuit specific energy calculation is likely to be insubstantial.

The specific energy predicted using the standard Bond technique was mapped against the specific energy measured in the survey (Figure 6). The difference between observed and predicted specific energy is the same as the difference between OWi and BWi. The degree to which the site falls below the parity line is an indicator of the efficiency of the circuit in comparison to Bond's standard circuit. As can be seen the majority of the surveys indicate that the measured specific energy was significantly greater than what is predicted using the standard Bond approach. This inefficiency indicated by the Bond technique is not unusual for modern circuits and has lead to a range of efficiency factors to be invented to describe circuits that deviate from the standard circuit (Rowland and Kjos, 1980).

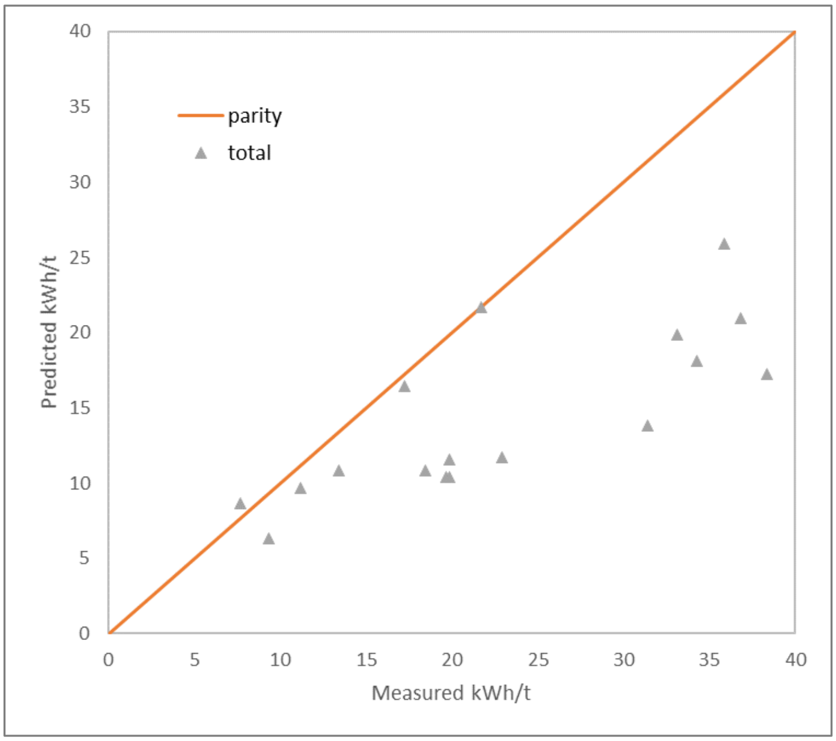

Figure 6 – Measured versus predicted specific energy consumption of the comminution circuit using the standard Bond method

STANDARD MORRELL METHOD

Unlike the Bond approach, the Morrell technique was not developed from controlled pilot-plant operation on a standard circuit. Instead, Morrell utilised an extensive database of operating circuit surveys to calibrate the characterisation tests and the equations used to predict the specific energy. Therefore, Morrell typically predicts a more achievable specific energy in comparison to Bond.

Figure 7 shows the predicted versus measured specific energy figures for the Morrell approach. In comparison to the Bond technique, the Morrell approach also predicts the energy split between the SAG mill and ball mill. Therefore, the Morrell approach allows the benchmarking of both the SAG and the ball mill efficiency individually as well as the total circuit. However, it should be noted that this energy split prediction is dependent on the DWi results, not the transfer particle size distribution. The Newmont survey dataset agrees well with Morrell's predicted specific energy requirements for the total circuit as well as the SAG and ball mill individual splits.

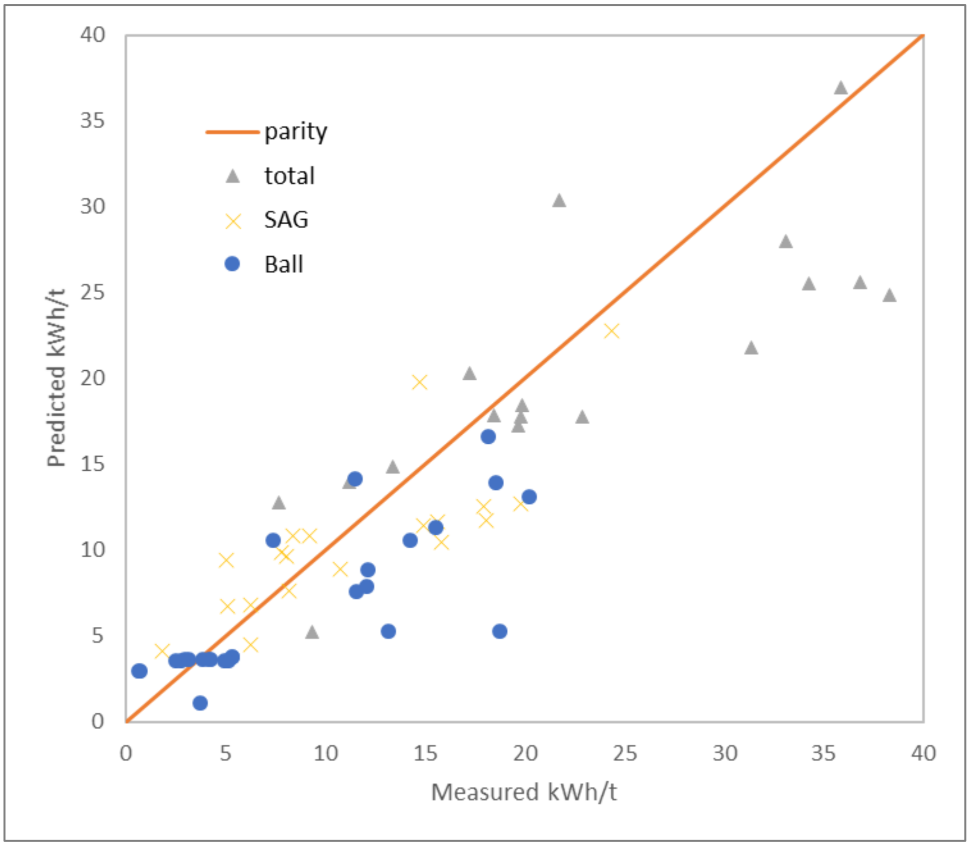

Figure 7 – Measured versus predicted specific energy consumption using the standard Morrell method

SIZE SPECIFIC ENERGY MODIFICATIONS TO THE STANDARD METHODS

The SSE approach has been proven effective at comparatively benchmarking equipment when operating on the same ore (Ballantyne et al., 2015a). However, the development of a characterisation test for the SSE in the laboratory has remained elusive (Ballantyne et al., 2015b). Therefore, combining the ability for SSE energy to assess the energy split between equipment based on the production of fines with established characterisation techniques, like Bond and Morrell, to assess the total circuit specific energy represents a significant advancement in comminution efficiency assessment (Figure 8).

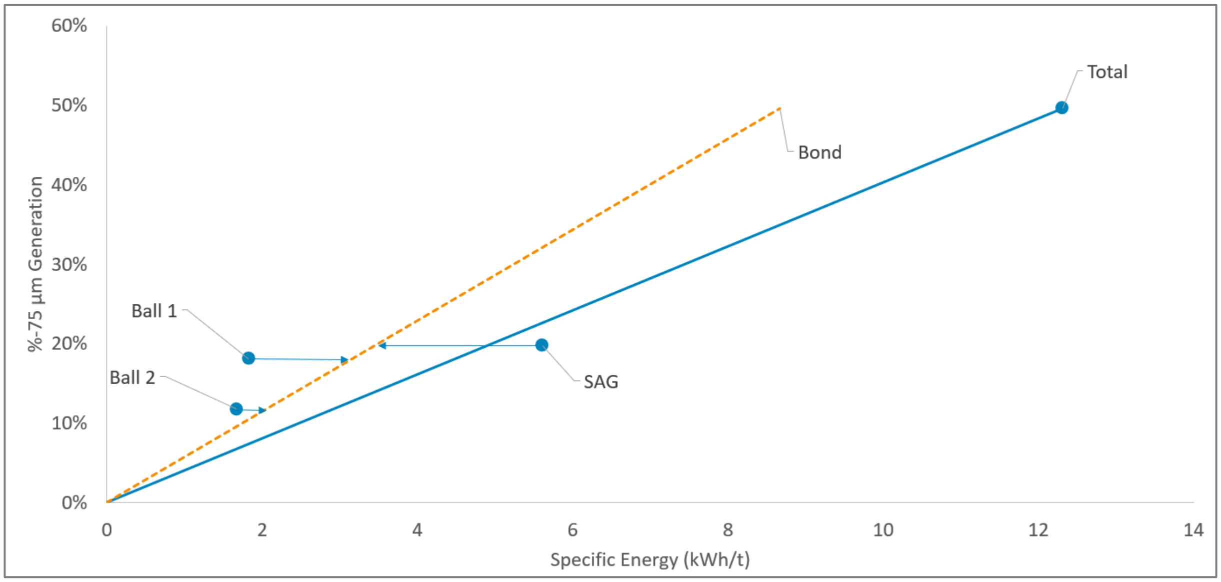

Figure 8 – SSE benchmarking using Bond as the total circuit energy basis

Figure 9 shows the results from combining the SSE with the Bond approach in predicting the specific energy requirements of the SAG and ball mills in the survey database. Because the Bond approach underestimates the power requirements of these modern circuits, the majority of the circuits and equipment sit below the parity line. However, this discrepancy is consistent, and if an overall efficiency factor of 60% is applied, a consistent scatter around the parity line is produced.

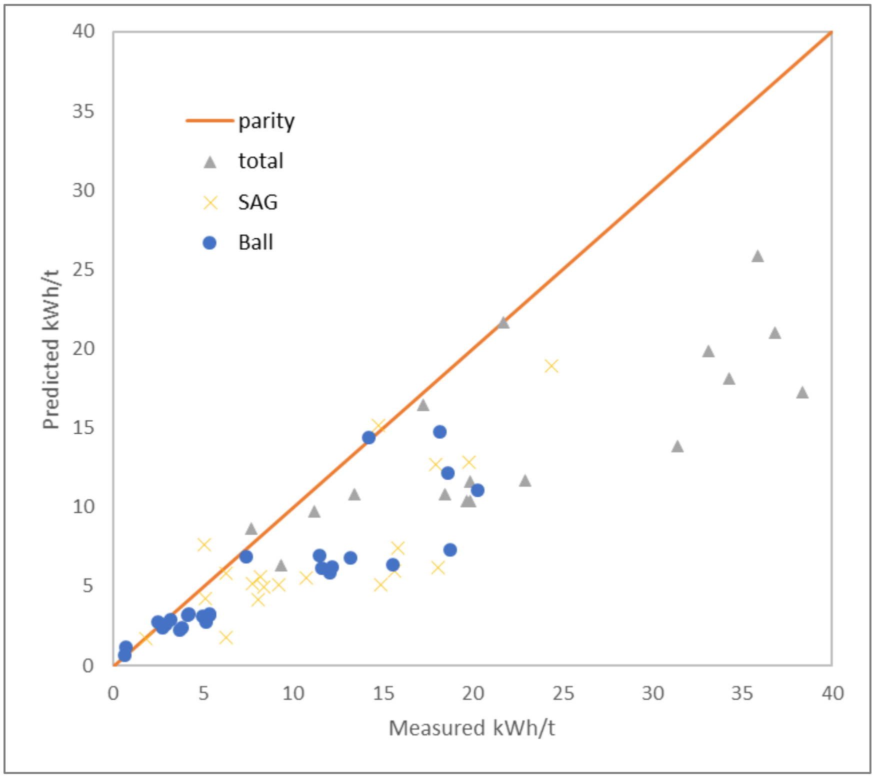

Figure 9 – Measured versus predicted specific energy consumption using the SSE modified Bond method

The combination of SSE and Morrell's total circuit methodology is shown in Figure 10. This method removes the need to estimate the SAG mill specific energy using a proprietary method, and simply splits the energy based on the generation of new fines by each mill. Using SSE to predict the specific energy of the SAG and ball mills individually gives a similar result to the standard Morrell method for this data. This is surprising because the SSE approach does not consider the difference in coarse and fine competence, but simply assumes that the energy to produce new fine material is the same for both the SAG and ball mill. As expected, there are indications that the SSE of the SAG mill increases relative to the ball mill when the drop weight results indicate an increase in coarse competence without the corresponding increase in Bond ball mill work index. Therefore, the current simplistic application of SSE may provide more accurate predictions when combined with some of the known relationships between coarse and fine competence characteristics.

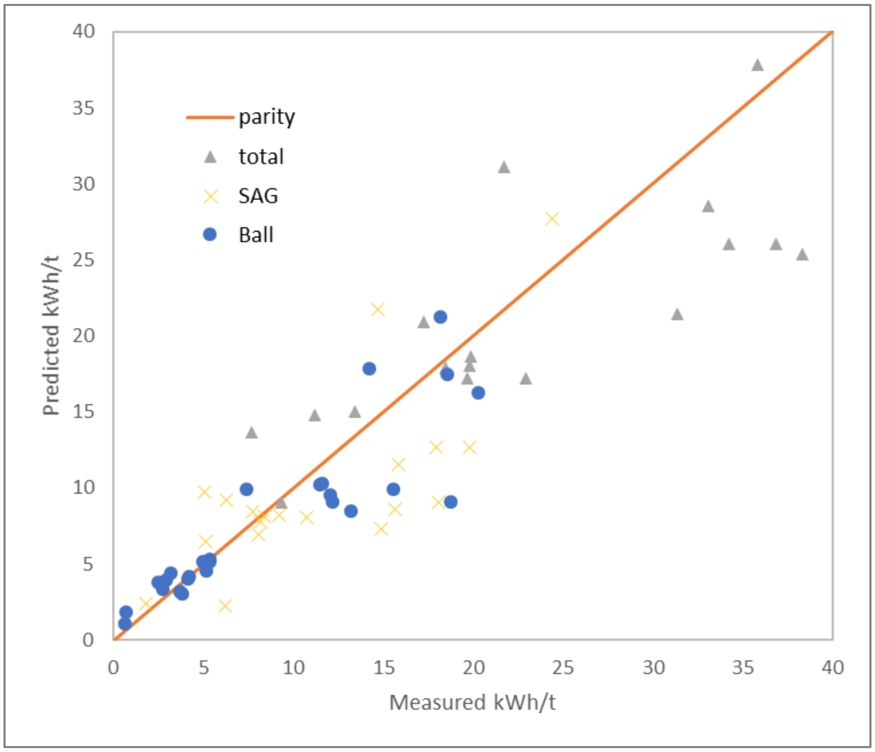

Figure 10 – Measured versus predicted specific energy consumption using the SSE modified Morrell method

Size Specific Energy for Different Marker Sizes

Unlike previous work on SSE, the marker size of 75 µm could not be applied across all surveys in this dataset. In some cases, the P_{80} of the final grind size was much finer than 75 µm and a finer marker size was required. Recent analysis on the relationship between marker size and SSE has shown that there is a consistent relationship that is related to the slope of the particle size distribution in log/log space (Ballantyne and Powell, 2016). And the slope of the particle size distribution in log/log space is also the exponent in a power law relationship, which is related to the fractal dimension of the breakage (fractal dimension = 3 - particle size distribution gradient) (Turcotte, 1986). The fractal dimension of breakage also has the benefit of having a physical significance; low fractal dimensions relate to a breakage mechanism associated with bulk splitting, whereas high fractal dimensions relate to pulverisation. More recently, this was investigated in greater depth and it was found that when the fractal dimension of breakage equalled 2.5, the results from SSE analysis was mathematically equivalent to Bond's approach (Ballantyne, 2019). Similarly, the SSE was proportional to the Morrell approach when the fractal dimension of breakage equalled Morrell's exponent parameter (3 - 0.295 + P_{80}/1000000) (Morrell, 2009). Therefore, in addition to providing accurate predictions when the slope of the feed and product sizes were not similar, SSE may be applicable over a wider range of cases than Bond and Morrell individually.

The relationship between SSE and marker size for each piece of equipment surveyed by Newmont is presented in Figure 11. A consistent relationship is seen across all the equipment and ore-types surveyed. Analysis of the gradient of these relationships was conducted and there was no significant difference identified for the different mill types (SAG and ball). The distribution of the fractal dimensions (3 + gradient of the SSE relationship) of breakage measured in all the surveys is presented in Figure 12. This shows that the majority of the survey results indicated that larger fractal dimensions were measured than Bond would predict (2.5). This may be the reason that Newmont has found the Morrell approach to provide good prediction of its performance.

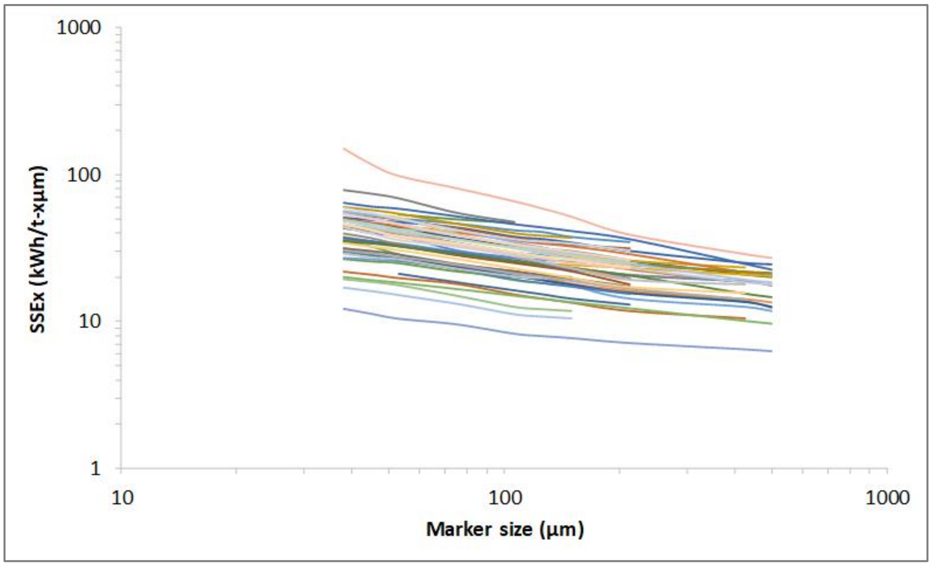

Figure 11 – Size specific energy at different marker sizes for the mills in the surveys

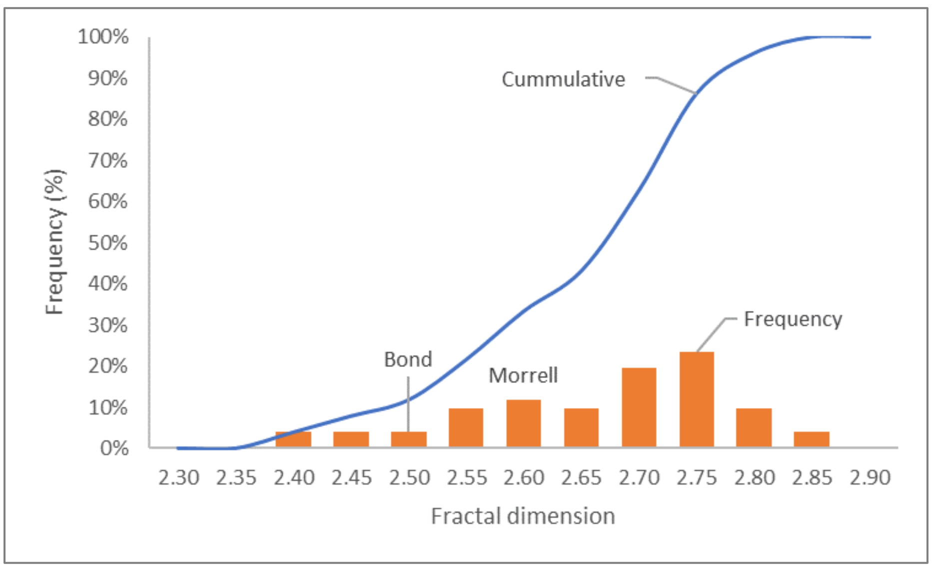

Figure 12 – Distribution of fractal dimensions for the breakage of the Newmont ores in the surveys

Interestingly, there were consistently different fractal dimensions observed for different ores (Figure 13). For instance, ore 1 produced fractal dimensions between 2.7 and 2.8 for both SAG and ball milling, whereas similar milling environments with ore-type 8 produced fractal dimensions between 2.4 and 2.55 (similar to Bond). There was even a difference between ore types at the same mine. For instance, ore 1 shows the results from the surveys conducted on the underground ore, which had a larger fractal dimension than ore 2, which was conducted on the open pit ore. This shows that there is potentially an ore type dependence that is independent of the milling environment that needs to be characterised to fully understand this relationship.

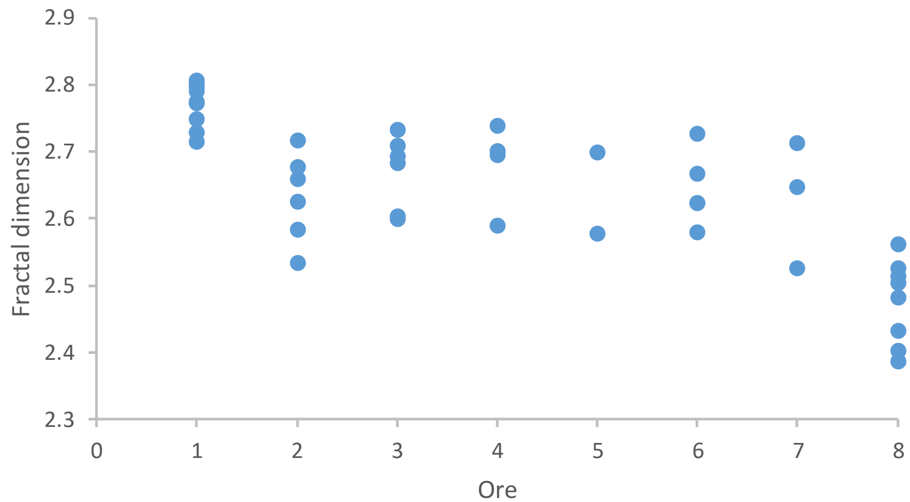

Figure 13 – Fractal dimension of breakage for the different ores

Conclusions

This paper displays the merits of many different analysis techniques in assessing comminution energy efficiency using data from Newmont operations. Newmont strives for continuous improvement at its mines and the methods described in this paper are being used by Newmont to identify improvement opportunities.

The comminution energy curves approach was used to benchmark the energy intensity of Newmont mines from 2015 performance summary. The performance of the 13 grinding circuits was assessed using four of the energy curves: BWi, OWi, specific energy, and copper equivalent specific energy. The position of these operations was not consistent across the four curves. The relative position of the mines was dependent on the ore hardness, circuit efficiency, grind size target, ore grade, and recovery. This approach shows that benchmarking comminution energy intensity using a single figure is an inappropriate approach that will unfairly handicap some operations based on their in-built ore characteristics. Instead, the signature of a mine across multiple benchmarks should be used to obtain a full representation of the comminution energy consumption. Newmont's drive for efficiency improvements is also highlighted through this approach as all the operations were at a similar or lower position on the OWi energy curve relative to their positions on the BWi curve.

The Morrell and Bond approaches to energy efficiency evaluation were applied to 17 circuit surveys conducted by Newmont. The Bond approach consistently underpredicted the total circuit specific energy and was unable to split the power draw of the SAG and ball mills due to the non-parallel size distributions. The Morrell approach resulted in a much more achievable predicted specific energy figure. The proprietary Morrell SAG mill specific energy calculation provided an appropriate energy split between the SAG and ball milling specific energy. This may have been due to the higher than average fractal dimension that was observed for the majority of Newmonts operations.

The focus of this paper was the application of the SSE methodology in combination with the Bond and Morrell approaches. Previous publications have explored the ability for SSE to indicate the relative efficiency of different equipment in a circuit. However, combining the SSE calculation with the total circuit specific energy predictions of the Bond and Morrell approaches allowed the SSE to be benchmarked against industry standard characterisation tests.

Further exploration of the SSE methodology was conducted and showed that there is potential to describe the SSE across a range of marker sizes, thus allowing the fractal dimension of breakage to be assessed. The fractal dimension of breakage was found to be an ore-dependent characteristic, independent of the comminution device.

References

Amelunxen, P., & Meadows, D. (2011). Not another HPGR trade-off study! *Minerals & Metallurgical Processing*, 28(1), 1-7.

Ballantyne, G. (2019). Assessing comminution energy efficiency with the Size Specific Energy (SSE) approach. In *European Symposium on Comminution & Classification (submitted)*, Leeds, UK.

Ballantyne, G. R., Mainza, A., & Powell, M. S. (2015a). Using comminution energy intensity curves to assess efficiency of gold processing circuits. In *World Gold 2015*, Johannesburg, South Africa.

Ballantyne, G. R., Peukert, W., & Powell, M. S. (2015b). Size specific energy (SSE)—Energy required to generate minus 75 micron material. *International Journal of Mineral Processing*, 139, 2-6.

Ballantyne, G. R., & Powell, M. S. (2016). Using the comminution energy curves to assess equipment performance, In *Comminution*, ed. International, M.E., Capetown, South Africa.

Ballantyne, G. R., Powell, M. S., Bonfils, B., & Yahyaei, M. (2015c). Simple energy measures for assessing total circuit efficiency, In *SAG conference*, Vancouver, Canada.

Bond, F. C. (1952). The third theory of comminution. *Transactions AIME*, 484-494.

Bond, F. C. (1961). Crushing and Grinding Calculations Parts 1 and 2. *British Chemical Engineering*, 6(6, 8), 378-385, 543-548.

Davis, E. W. (1919). Fine crushing in ball-mills. *Transactions of the American Institute of Mining Engineers*, 1919, 61, 250-296.

Giblett, A., & Hart, S. (2016). Grinding Circuit Practices at Newmont. In *Mill Operators' Conference*. AusIMM, Perth.

Global Mining Guidelines (2015). Determining the Bond Efficiency of industrial grinding circuits, In *Industrial Comminution Efficiency (ICE)*. Retrieved from http://www.globalminingstandards.org/.

Global Mining Guidelines (2016). Morrell method for determining comminution circuit specific energy and assessing energy utilization efficiency of existing circuits, In *Industrial Comminution Efficiency (ICE)*. Retrieved from http://www.globalminingstandards.org/.

Lane, G., Foggiatto, B., & Bueno, M. P. (2013). Power-based Comminution calculations using Ausgrind. In *International Mineral Processing Conference – Procemin*, Santiago, Chile.

Morrell, S. (2004). An alternative energy–size relationship to that proposed by Bond for the design and optimisation of grinding circuits. *International Journal of Mineral Processing*, 2004, 74(1-4), 133-141.

Morrell, S. (2009). Predicting the overall specific energy requirement of crushing, high pressure grinding roll and tumbling mill circuits. *Minerals Engineering*, 2009, 22(6), 544-549.

Musa, F., & Morrison, R. (2009). A more sustainable approach to assessing comminution efficiency. *Minerals Engineering*, 22, 593-601.

Napier-Munn, T. J., Morrell, S., Morrison, R. D., & Kojovic, T. (1996). *Mineral comminution circuits: Their operation and optimisation*. Julius Kruttschnitt Mineral Research Centre, Indooroopilly, Australia.

Rittinger, P. R. (1867). *Lehrbuch der Aufbereitungskunde*. Ernst and Korn, Berlin.

Rowland, C. A., & Kjos, D. M. (1980). Rod and ball mills. In *Mineral Processing Plant Design, AIME*, eds. Mular, A. L., Bhuppa, R. B., pp. 239-278.

Turcotte, D. L. (1986). Fractals and Fragmentation. *Journal of Geophysical Research*, 1986, 91(B2), 1921-1926.