PREDICTIVE OPTIMIZATION OF SAG MILL WEAR USING ROCKY

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INTRODUCTION

No one in industry is happy with downtime losses incurred due to a machine that won't operate. In the mining sector, these losses can be particularly large. For example, a trained professional crew requires between 40 and 120 hours to replace the worn liner of a Semi-Autogenous Grinding (SAG) mill with each hour costing between 30,000 to 200,000 USD and such maintenance can occur every six to nine months [1]. SAG mills are the technology of choice for reducing primary hard-rock ore to feed size for use in a secondary crusher. In these mills, cascading ore undergoes impact breakage against grinding balls in a rotating cylindrical shell. Continuous operation of these mills is disrupted when the mill liner, comprising lifter bars plates intended to protect the parent shell and provide necessary lift for the grinding action, wears out after months of processing abrasive material.

Mining companies can realize significant cost savings only by slowing peak wear rate without compromising throughput, an outcome that calls for optimizing both the liner design and operating process parameters. Conventional approaches to achieve these goals are based on a combination of practical experience and hit-or-miss trial studies that modulate design features and/or operating conditions [2].

However, it is not feasible to perform a comprehensive experimental design, especially when the mill is in constant operation. Discrete element method (DEM) simulations, which are based on first-principle physics, have proven very helpful in such cases by enabling increased process insight and evaluation of a large number of possible solutions. Using a commercial DEM software like Rocky, an engineering team can easily evaluate changing process variables, such as speed and fill level [3], or a new lifter design that incorporates changed face angle and height [4, 5] with a high degree of accuracy, exemplified by excellent matching between experimental observations and computational predictions [6]. This article highlights how Rocky DEM software can help in predicting liner wear and fine-tuning optimum conditions for SAG mill operation.

CASE SCENARIO

Consider a large SAG mill with a diameter of 10.97 m, as shown in Figure 1a. The mill has a *hi–lo* liner design with alternating rows of high and low lifters (Figure 1b).The mill processes rocks of 200 mm to 300 mm, using 350 mm steel balls as the grinding media. It operates at these conditions: speed 10 rpm (80% of critical speed), volumetric fill- 14.5%, ratio of balls to rocks- 4:1 by mass. Based on practical experience, mill throughput decreases substantially after the lo lifters have worn out by 60% or more. The mining company decided to replace the mill liner at this 60% target. Under typical operating conditions, the mill liner wears out in five months, inflicting frequent and huge downtime losses.

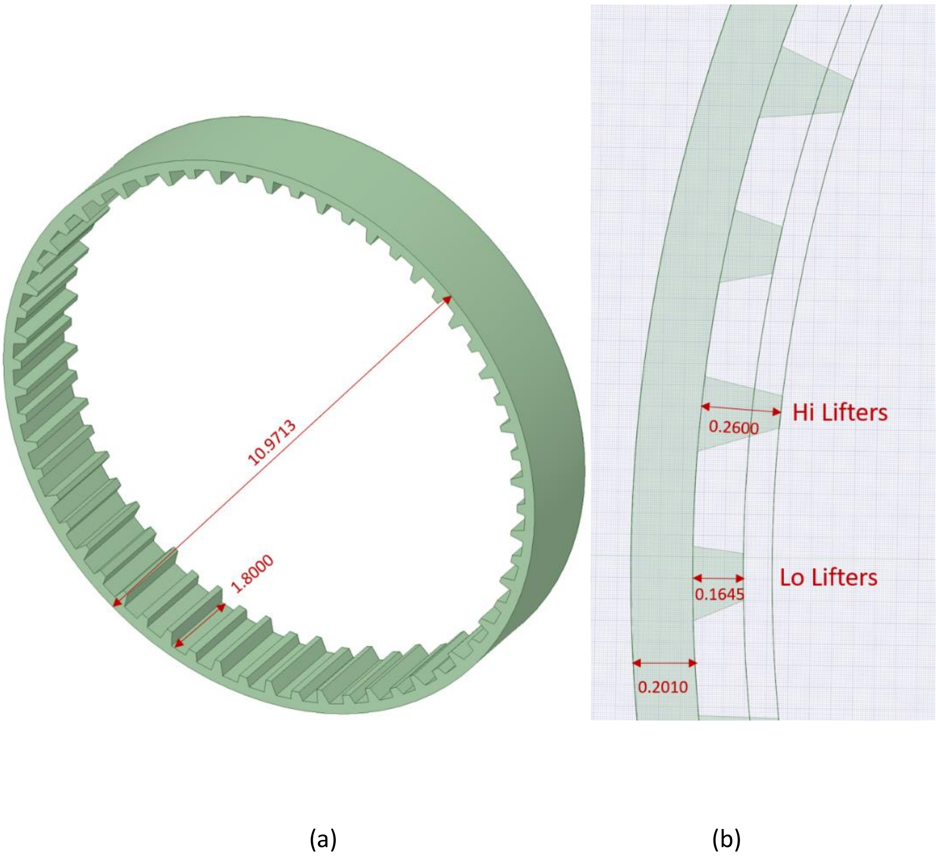


Figure 1: Mill slice used for DEM calculations. *All dimensions are in meters.*

The company wants to analyze if the mill is operating under optimum conditions — and subsequently, if a modified lifter design is needed. Given the operating schedule and costs involved, conventional approaches seem unfeasible. Streamlining optimization using DEM appears to be a viable option to help the company to reach its goals.

When choosing a DEM software, attention must be paid to a number of factors:

- Accuracy of physics: scientific rigor and validation of models used, accurate representation of process and boundary conditions
- Costs: license, hardware, external software and trained personnel
- Return on investment: enhanced process understanding and time taken to evaluate multiple solutions [7]

Rocky software provides physically robust, tried-and-tested models with state-of-the-art hardware capabilities along with post-processing tools to quantify boundary wear and evaluate milling performance.

CUSTOM ROCKY FEATURES FOR MILL DESIGN

Predicting Geometry Wear

Quantification of boundary wear in Rocky is done using the validated Archard's wear model [8]. The governing equation is $A\ dh = C_{model}\ dw$, where A is the surface area of a boundary element and dh is the incremental loss in depth when subject to shear work dw. While specification of the wear parameter C_{model} should achieve accelerated wear, care must be taken to avoid very fast and abrupt changes. Often, determination of C_{model} is done after calibration against known experimental data, such as loss in height or mass of the lifters with time. Once a robust wear parameter is obtained, potential process and design changes can be evaluated with a high degree of confidence.

Evaluating Mill Performance Using Energy Spectra

Rocky provides comprehensive breakage models to predict performance, but these are computationally very intensive. The software's energy spectra tool enables reliable predictions of breakage and attrition rates for continuous processes without running breakage calculations. This tool collects energy for normal and tangential collisions gathered between user-specified (experimental or literature-based) minimum and maximum energy (a) per particle type per time step, and (b) per collision type, which accounts for all combinations of particle–particle and particle–boundary collisions. These calculations are used to predict power draw, process throughput and milling efficiency. Further details can be found in Rocky literature [9, 10].

CASE SET-UP

In theory, the SAG mill system can be modeled as is with its millions of moving parts as well as arbitrary rock shapes and sizes. But the calculations won't finish in real time! Practical solution to enable real-time decision-making requires simplifying the problem with reasonable assumptions that capture only essential parts.

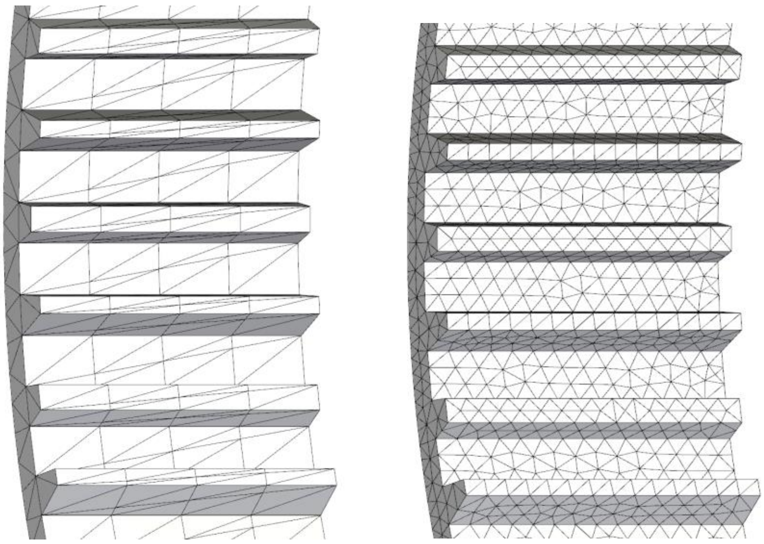
For example, there's no need to model every moving part — not even the whole geometry! A representative slice (Figure 1a) at the feed end with periodic boundaries to mimic continuous processing will suffice. Bulk flow within a SAG mill is inertial in nature: as long as the mass and size are representative, rock shape will not impact much, so frictional spherical particles with some rolling resistance can be used. It is critical to achieve good discretization of the mill liner for implementation of the wear model.

Preparing Geometry

Even though Archard's wear model allows mesh size to be independent of particle size, element size is important, since it influences total element count and wear parameter value used. If a fine mesh with high element count is used, a low wear parameter needed to be used- both effects would lead to a longer run time. If the mesh is too coarse, there is a risk of abrupt and unphysical changes due to removal of large chunks of material. Thus, it is important to balance boundary element sizes. A good starting point is to have five to ten elements across the width. For a mill slice with a width of 1.8 m (as in this case), a boundary element size of 0.195 m is specified within Rocky. Mesh quality for this case was determined using visual inspection to ensure that there are no highly skewed elements nor elements that span an entire face. Figures 2(a) and (b) provide examples of bad and good meshes for the mill.

Input Parameters

Rocky software requires a number of user inputs (Table 1) to accurately capture process dynamics using established and validated contact physics models, which are detailed in Rocky's technical manual. Most of the inputs are trivially obtained. Some of the material interaction parameters may not be known; these may be determined from literature or simple calibration experiments, like angle of repose measurements. For this case study, material properties and interaction parameters are based on typical experiential values and listed in Tables 2 and 3, respectively.



(a) (b)

Figure 2: Representation of (a) bad and (b) good mesh. The bad mesh size is 500 mm. In contrast, the good mesh uses 195 mm elements.

Physics	Contact Model
	Gravity Direction
Geometry	Import Meshed Geometry
	Inlet surface
	Wear Parameter
Motion Frame	Motion Type
	Duration
	Velocity and Acceleration
Material (Rock, Balls, Boundary)	Density
	Young's Modulus
Material Interaction(Rock–Rock, Rock–Ball, Ball–Ball, Rock–Boundary, Ball–Boundary)	Friction
	Restitution
	Adhesion
Particles	Shape
	Size
	Rolling Resistance
CFD Coupling	None, One Way, or Two-Way
Input (Rock, Ball)	Mass Flow Rate
Domain Settings	Periodic Boundary Direction
Solver Settings	Simulation Time
	Hardware (CPU, GPU, Multi-CPU)
	Energy Spectra (Min. and Max. Energy)
	Time to collect wear statistics

Table 1: Rocky user inputs for SAG mill simulation

Property		Rock	Ball		Boundary
Density (kg/m^3)		2,800	7,800		1,400
Rolling Resistance		0.35	0		N/A
Young's Modulus (Pa)		1.00E+08	1.00E+08		1.00E+11
Size	300 mm	100%	350 mm	100%	Slice Width: 1.8 m
	250 mm	70%			
	200 mm	20%			

Table 2. Material properties used for simulation

Interaction Parameters	*Rock–Rock*	*Rock–Ball*	*Rock–Boundary*	*Ball–Boundary*
Friction	0.8	0.5	0.3	0.3
Restitution	0.5	0.5	0.3	0.3
Adhesive Force	0	0	0	0

Table 3. Material interaction parameters used for simulation

Parameter	*Value*	*Wear on Lo Lifters (%)*
Speed (rpm)	8	42.90
	10	60.00
	12	66.51
Fill (%v/v)	10	60.58
	14.5	59.27
	20	61.49
Balls/Rocks (%w/wt.)	2	65.20
	4	60.00
	8	54.96

Table 4. Effect of process changes on lo lifter wear

A rectangular inlet is created with specification of coordinates and time duration for depositing the particles at a mass flow rate specified as in the Input section. The simulation run time should be long enough to see an accelerated but uniform wear progression of the lifters and collect enough statistics for robust Energy Spectra calculations, in this case the run time was set to 500 seconds. Collection of the wear statistics is initialized after 20 seconds when the simulation is expected to reach steady state.

In terms of hardware, Rocky's hallmark differentiation is that it provides users with CPU, GPU and proprietary multi-GPU technology. Guidelines for choice of hardware are available on the Rocky website [11].

RUNNING THE FIRST CASE

This case serves to evaluate the feasibility of both the mesh and the wear parameter. Figures 3a and 3b demonstrate the progression of wear after 200 seconds of simulation using the default initial wear parameter of 1e-06 J/m3, using “bad” and “good” meshes, respectively. The coarser, “bad” mesh develops unrealistic overlaps at 200 seconds and worsens thereafter. In contrast, the mill slice run with the finer, “good” mesh wears uniformly, completely wearing out by 500 seconds. This result suggests that the initial wear rate is too high and needs to be decreased to match the target wear.

(a) (b)

Figure 3. Predicted wear using a wear parameter of 1e-06 J/m^3 after 200 seconds using (a) bad mesh and (b) good mesh

CALIBRATION OF WEAR PARAMETER

For the initial case running with the “good” mesh, the worn geometry is simply exported and the lifter height is measured, as shown in Figures 1b and 4, the latter being a comparison between the worn and the reference mill slice. From height measurements, the average wear on the lo lifters was quantified to be 78.3 %. The target of 60 % wear on the lo lifters can be adjusted in either of the following three ways:

(a) Changing the simulation time and keeping the initial wear parameter if the initial results look stable, in this case it would need to run for 154 seconds. This is the most common option.
(b) For the same run time, changing the wear parameter if the simulation looks unstable. This would lead us to using a value of 7.06 e-07 J/m^3 for a run of 200 seconds.
(c) Changing both the wear parameter and the run time in order to match multiple time points from experimental data or collect more wear statistics. If the target wear on the lo lifters is to be reached at 500 seconds for this case, the simulation can be run with a wear parameter of 3.07e-07 J/m3 to give a wear of 68.4%. 60% wear is obtained at 438.6 seconds in this case. Subsequent runs can use this wear parameter and duration. As an alternative, the wear parameter is iterated once more to a value of 2.69e-07 J/m3 to match the target at 500 seconds. This result affirms that the wear parameter follows the proportionality constraint, as required by the model.

After three simulations running six hours each on one GPU, the value of the wear parameter is obtained. These results are leveraged to obtain qualitative and quantitative information of process dynamics, as well as to investigate a number of solutions.

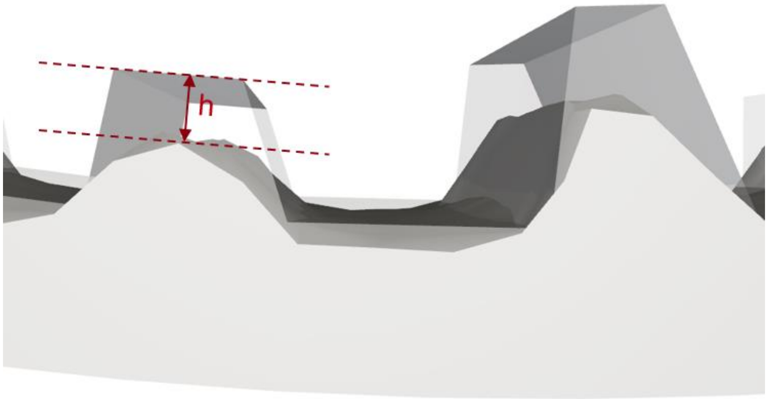


Figure 4: Lifter wear after 500 seconds as demonstrated by comparison of actual and reference mill slices

POST-PROCESSING AND VISUALIZATION

Preliminary simulation post-processing was done to visualize and confirm process behavior to conventional understanding. Rocky software makes this simple with click-and-play features inside the UI — there is no need to export and process data externally. Users can see instantaneous or average values of a number of particle and boundary variables as well as visualization of particle path lines, Eulerian visualization of parameters like velocity and volume fraction, and more.
The mean impact on the walls and particle translational velocity at different time points are shown in Figure 5. The relative power distributions of normal collisions for different types of collisions across a range of collision energies was obtained using the energy spectra tool (Figure 6). Rock–rock and rock–liner collisions are associated with maximum power draw, followed by rock–ball collisions. Energy corresponding to maximum power and collision frequency follows the order Rock–Liner < Rock–Rock < Rock–Ball. The probability of breaking hard rocks is expected to parallel this rank order. Under default operating conditions, steel ball collisions with the mill liner and other balls are relatively low, which is very desired.

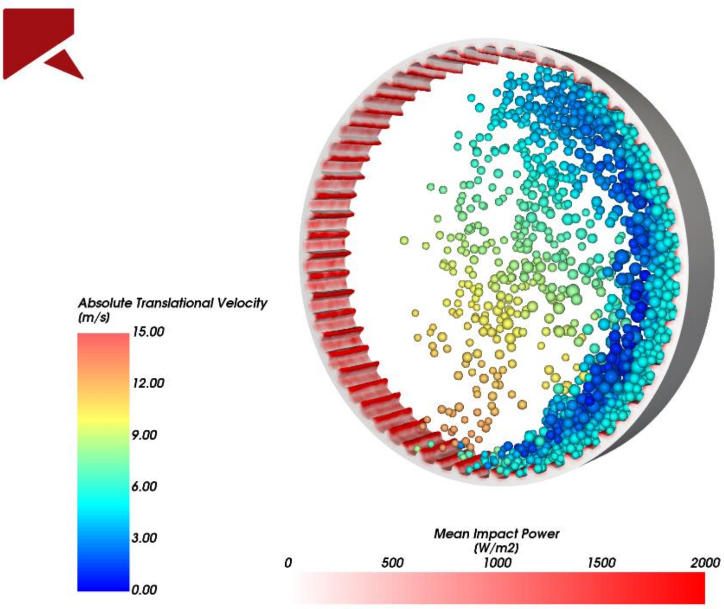


Figure 5: Mean impact power of walls and instantaneous particle velocity at 200 seconds for default case

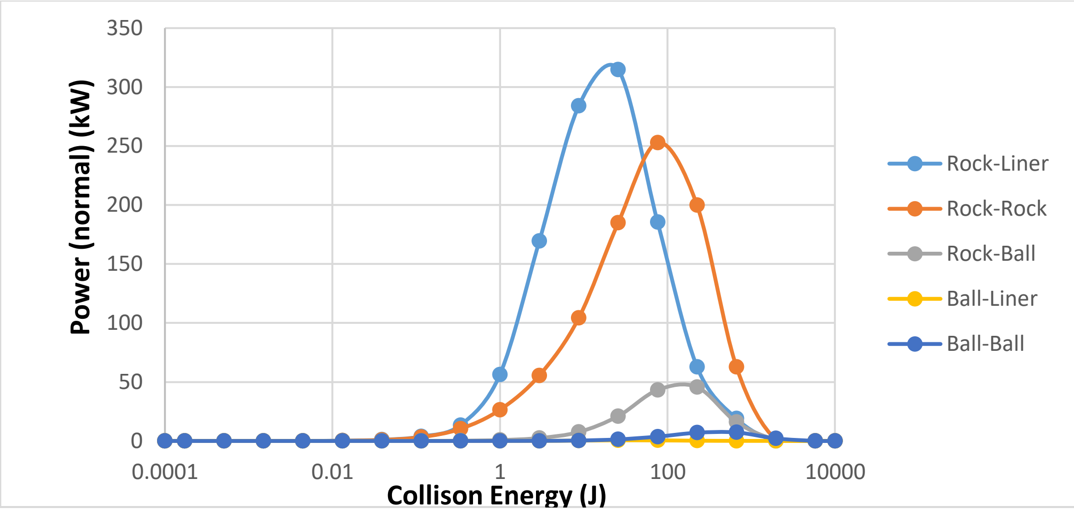


Figure 6: Power distribution of normal collisions for different types of collision as a function of collision energy with operating speed of 10 rpm

DESIGN OF SIMULATION EXPERIMENTS (DOSE)

A three-factorial, three-level analysis studied the effect of rotational speed, volumetric fill, and the ratio of rock to balls on liner wear. Table 4 summarizes the results. It is clear that, from all the variables considered in this study, rotational speed has the most impact on wear, with 8 rpm and 12 rpm showing the least and most wear, respectively. Using DEM enabled ruling out two variables, saving on some experiments. In terms of mill performance, for collisions above a threshold-specific energy of breakage for a given particle, specific power directly relates to breakage probability. For a feed with minimum specific energy of 50J/kg typical of hard rocks, Figure 7 shows that 8 rpm can hardly break any of them!

The Rocky process can further include investigation of speeds between 8 rpm and 10 rpm and other process variables; it can assist with modifying the liner design, as illustrated in these studies [4, 5].

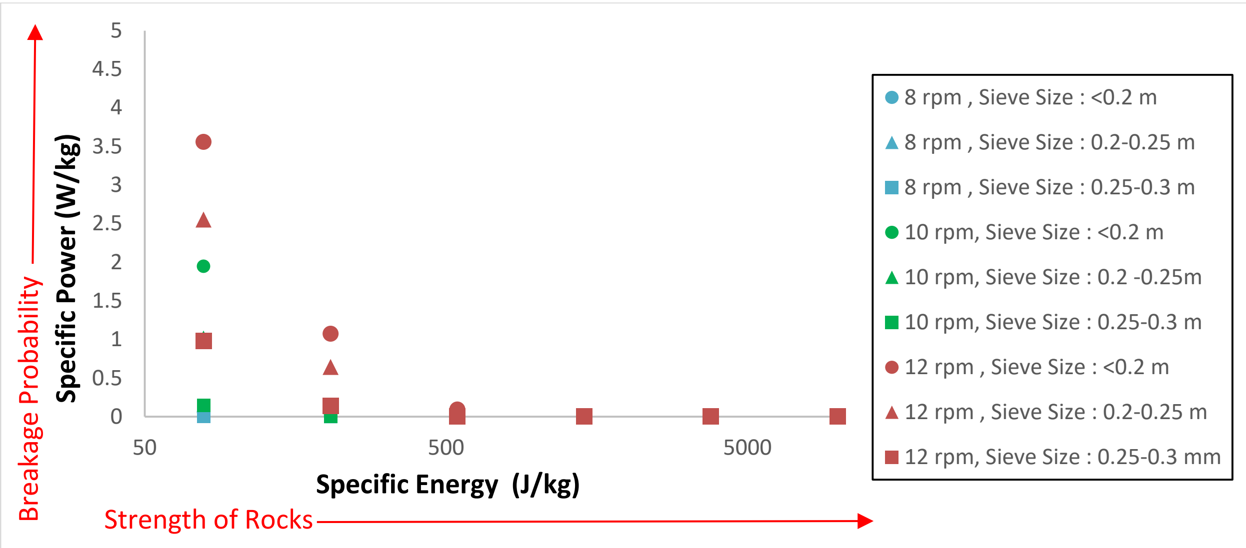


Figure 7: Variation of specific power consumption as a function of specific energy for different size fractions and operating speed

PROVIDING VALUE

The case study described shows how Rocky software is valuable to users:

Enhanced Process Understanding

Accurate and validated physical models yield results matching experiments, and state-of-the-art post-processing tools aid in internal mill dynamics. A number of software features have helped the mining company reach its goals: visualization and quantification of wear, power draw and break-up into different collision types, and collision and breakage statistics.

Quick Investigation of Multiple Solutions

This study ran 10 simulations in approximately 60 hours to evaluate the effect of changing three process variables. While an illustrative study is limited in its scope to evaluate other parameters and operating conditions as well as alternate designs, engineering teams can perform detailed analysis with Rocky to provide accurate and fast answers to mining processing problems.

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