



Diamond plant statistics, process efficiencies, liberation modelling, and simulation: The art of the possible

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Synopsis

The paper brings together the language of diamond numbers and the underlying principles for calculation of diamond liberation, followed by estimation of process efficiency at circuit and complete plant levels. In this way it provides a reference point, albeit a mixture of the theoretical and empirical, to assess the effectiveness of diamond plant accounting systems in the field. Having established today's baseline, the wider aim is ongoing education, peer technical debate, and progression to a more exact science.

Keywords

diamonds, liberation, recovery, modelling.

Introduction

Quantification of stream content in a diamond processing plant as part of daily mass balance statistics is unlike similar exercises for other commodities. This is due to the particulate distribution of diamonds, relatively low grades, wide range of particle sizes, the indeterminate state of diamond liberation, and the absence of an assay office, among other factors. It is best described as 'the art of the possible', given the combination of difficult data acquisition, wide use of proxy measurements, and the uniqueness of diamond extraction.

All business entities are obliged by law to produce auditable annual financial statements. The same applies to mining businesses, and it is not just confined to the financial statements. There are equally onerous legal requirements applicable to Mineral Resource and Reserve estimates in terms of tonnages, grades, and even economic values. Does the same requirement apply to the 'metallurgical accounting statements?' The answer is a definite 'maybe'. The vast majority of commodities are easy to measure, be it by means of mass flows or metal/mineral content, but diamonds are very different.

The key objective of the paper is a general revision of the current status quo in terms of diamond numbers, a description of a typical process flow sheet, estimation of diamond liberation using the preferential liberation factor (PLF) deportment model, and leveraging the use of plant statistics for modelling and simulation purposes. It concludes by emphasising the need for industry-wide accepted diamond simulation guidelines and plant accounting practices.

Diamond numeracy terminology

By means of a general introduction, a number of quantitative descriptors are presented, specific to diamond processing, highlighting the uniqueness of diamond numeracy. This will include diamond particle sizing, diamond sizing frequency distributions (DSFDs), ore grades, liberated and locked diamond distributions, and the prevalence of matrix calculations when using the deportment model. Corresponding descriptors are also included for the carrier ore phase.

Diamond sieve classes

Diamonds are sized according to circular aperture sieve sizes commonly referred to as diamond sieve (DS) classes, mathematically nonstandard, but generally accepted in the industry. The standard DS classes are shown in Table I; with equivalent top, bottom, and geometric mean values when mapped across to conventional square mesh sizing sieves. The last column is an indication of average diamond weight in carats per DS class, where one carat is equivalent to 0.20 g.

Above +23DS, diamonds are measured individually (carats per stone) and summarized as total carats and numbers in the size fractions +15 ct, +20 ct, +30 ct, +45 ct, +60 ct, and +100 ct. These are classified as the special large sales ranges.

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Table I

Standard DS classes

Tag	Top size (mm)	Bottom size (mm)	Mean size (mm)	Average mass per diamond (carats)
+23DS	11.64	9.28	10.39	8.036
+21DS	9.28	7.09	8.11	4.850
+19DS	7.09	5.56	6.28	2.480
+17DS	5.56	4.93	5.24	1.570
+15DS	4.93	4.62	4.77	1.260
+13DS	4.62	3.85	4.22	0.860
+12DS	3.85	3.42	3.63	0.561
+11DS	3.42	2.86	3.13	0.371
+9DS	2.86	2.35	2.59	0.211
+7DS	2.35	2.00	2.17	0.123
+6DS	2.00	1.72	1.85	0.089
+5DS	1.72	1.47	1.59	0.072
+3DS	1.47	1.15	1.30	0.035
+2DS	1.15	1.03	1.09	0.021
+1DS	1.03	0.82	0.92	0.014
-1DS	0.82	0.00	0.58	0.001

By means of example, Table II shows a series of sizing screens used for determination of the ore particle size distribution (PSD). Selection of screen sizes is an operator decision aligned to plant operational parameters and laboratory practices. The selection below is applicable to coarse incoming run-of-mine (ROM) ore and will change in a reducing manner deeper into the flow sheet. The location tag *i* refers to row position with reference to matrix calculation examples.

Ore grade

The grade of a kimberlitic orebody is generally expressed as carats per hundred tons, abbreviated to cpht. In the case of marine deposits the grade is expressed as carats per square metre (ct/m²), and in the case of alluvial deposits carats per cubic metre (ct/m³) is also used. For the purpose of simplicity, a grade of 100 cpht for a hypothetical sample of 100 t has been used in the calculation examples that follow.

Diamond size frequency distribution

Conversion of the scalar grade value into vector format

provides insight as to the distribution of diamonds within the orebody. This is particularly useful given the highly particulate distributions, skewness effects, and generally low grades. Table III provides such information incorporating components of Table I, the data used being purely for demonstration purposes and not referenced to any particular mining operation. The location tag *j* refers to column position with reference to matrix calculation examples.

The third column is an indication of average commercial value per DS class, again for illustrative purposes only, as such information is generally considered confidential and will vary across the industry. The exponential increase in value as a function of size is duly noted.

From Table III, the following deductions and observations are noted

- Diminishing returns if one pursues total recovery efficiency, ensuring no losses at the upper end but accepting some losses at the lower end.
- The average value per carat calculates to \$184.95, which does not correspond to any specific DS class, highlighting the limitation of averages.
- The average value per particle calculates to \$6.09, well below the value of the smallest DS class. Another trivial example on the limitation of averages.

Table II

Ore size classes

Location tag <i>i</i>	Tag	Top size (mm)	Bottom size (mm)	Mean size (mm)	PSD	Cumulative passing (%)
1	+150.0	200.00	150.00	173.21	5.00	95.00
2	+90.0	150.00	90.00	116.19	10.00	85.00
3	+45.0	90.00	45.00	63.64	25.00	60.00
4	+25.0	45.00	25.00	33.54	20.00	40.00
5	+8.0	25.00	8.00	14.14	20.00	20.00
6	+4.0	8.00	4.00	5.66	10.00	10.00
7	+1.0	4.00	1.00	2.00	5.00	5.00
8	-1.0	1.00	0.00	0.71	5.00	0.00
Total		100.00				

Table III

DSFD information

Location tag <i>j</i>	Tag	Price (\$ per carat)	DSFD	Cumulative passing (%)	Particles	Particles (%)	Mass (ct)	Value (\$)	Value (%)
1	+23DS	2000	2	98	0.25	0.01	2	4 000	21.63
2	+21DS	1000	3	95	0.62	0.02	3	3 000	16.22
3	+19DS	600	4	91	1.61	0.05	4	2 400	12.98
4	+17DS	300	5	86	3.18	0.10	5	1 500	8.11
5	+15DS	250	6	80	4.76	0.16	6	1 500	8.11
6	+13DS	150	7	73	8.14	0.27	7	1 050	5.68
7	+12DS	100	8	65	14.26	0.47	8	\$800	4.33
8	+11DS	90	9	56	24.26	0.80	9	\$810	4.38
9	+9DS	75	10	46	47.39	1.56	10	\$750	4.06
10	+7DS	65	11	35	89.43	2.95	11	\$715	3.87
11	+6DS	65	10	25	112.36	3.70	10	\$650	3.51
12	+5DS	65	9	16	125.00	4.12	9	\$585	3.16
13	+3DS	60	7	9	200.00	6.59	7	\$420	2.27
14	+2DS	50	4	5	190.48	6.27	4	\$200	1.08
15	+1DS	35	3	2	214.29	7.06	3	\$105	0.57
16	-1DS	5	2	0	2000.00	65.88	2	\$10	0.05
Totals	100		3036.03	100.00	100	18 495	100.00		

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- Also note that improved efficiency in a diamond plant usually refers to improved fine diamond recovery. This will automatically reduce the average value per carat, but will improve the average dollar per ton revenue recovered. This is therefore the measure to be used for overall improved plant performance.

Matrix distribution of diamonds – ore size class by diamond size class

Given the broad particulate distribution of diamonds, mass balances and meaningful unit process efficiency information must be derived both at a global level and per DS class. Key to this approach is the use of matrix mathematics to distribute diamonds into discrete packages based on both PSD and DSFD information. Table IV is the integration of information displayed in Tables I, II, and III. It serves as the baseline for the PLF deportment liberation calculations that follow, using the following parameters:

- The number of ore size classes is 8, denoted by counter i in Table II
- The number of diamond size class is 16, denoted by counter j in Table III
- A position within the matrix is denoted by (i,j) in line with accepted notation (row, column)
- Sample mass 100 t
- Ore grade 100 cpht
- Total diamond content 100 ct.

Diamond packet allocation per OS|DS location is calculated as follows

$$D(i,j) = TD * M(OSi) * M(DSj) \quad [1]$$

where

$D(i,j)$ Diamond content in OS class i and DS class j

TD Total diamond content, the multiplication of ore grade and sample mass

$M(OSi)$ Fractional ore mass distribution (PSD)

$M(DSj)$ Fractional diamond mass distribution (DSFD).

Locked and liberated diamond grades

Unique to diamond processing is the important distinction between locked and liberated diamonds, which will be illustrated in the section dealing with deportment mathematics. A fully liberated diamond is free of any adhering gangue material as illustrated in Figure 1, while a partly liberated diamond shows residual adherence to the host rock as in Figure 2. By definition, a locked diamond is fully enclosed within the host ore and not

visible to the human eye.

Generic diamond flow sheet

Material flow within a typical diamond processing plant is shown in Figure 3, with emphasis on the key circuits of liberation, concentration, and final recovery.

Liberation circuit

The purpose of the liberation circuit is processing of incoming ROM ore, in order to economically release the majority of locked diamonds associated with the various ore types. This circuit employs unit operations such as comminution, fragmentation, grinding, crushing, scrubbing, and screening. Efficient liberation is a function of rock mechanical properties, fracture theory, geology, and choice of crushing and milling technology as the key variables.

Fineness of grind, as indicated by the PSD, is currently the best proxy measurement of liberation efficiency. The true quantifier of liberation efficiency by definition can only be free diamonds as a fraction of total diamonds. The latter can be determined by stage crushing of residual tailings until all the diamonds are released. In assay terms this would be equivalent to acid dissolution or fire assay, and is too costly and impractical



Figure 1—Fully liberated diamonds



Figure 2—Partially liberated diamond

Table IV

Diamond allocation per OS|DS class

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS	OS total
+150.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
+90.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	1.000	0.900	0.700	0.400	0.300	0.200	10.0
+45.0	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.250	2.500	2.750	2.500	2.250	1.750	1.000	0.750	0.500	25.0
+25.0	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	20.0
+8.0	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	20.0
+4.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	1.000	0.900	0.700	0.400	0.300	0.200	10.0
+1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
-1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
DS total	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	10.000	9.000	7.000	4.000	3.000	2.000	100.000

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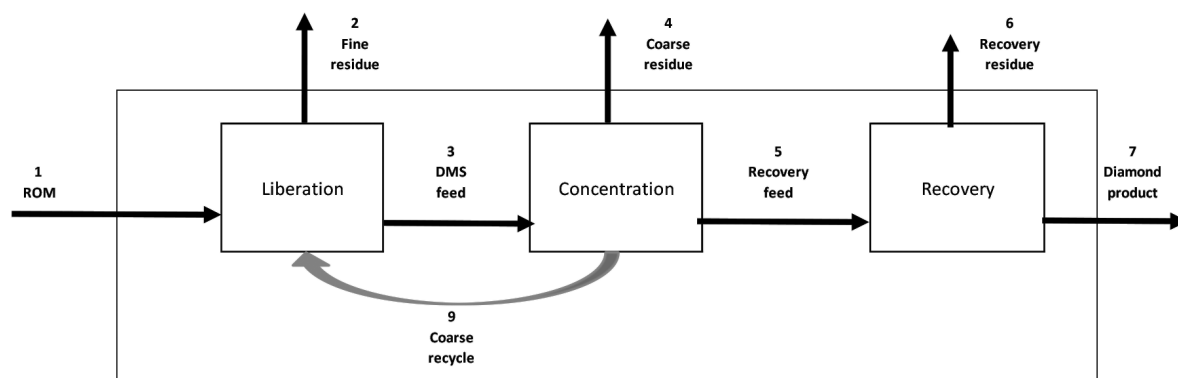


Figure 3—Diamond plant material flow

in the diamond industry. Nonetheless, fineness of grind remains the best measure in combination with secondary process measurements such as percentage reduction to fine and coarse residue streams and their associated PSDs.

Concentration circuit

The purpose of the concentration circuit is to separate out a diamond-rich stream which can be fed through to the final recovery circuit. Feed to the concentration circuit is from the front-end liberation circuit containing free liberated diamonds (along with residual locked diamonds), other free liberated mineral grains of variable density and mineralogical properties, waste rock particles, and residual clays and slimes depending on the quality of the upstream washing processes.

Given that concentration is currently dominated by dense medium separation (DMS), the key material property is the densimetric distribution of the incoming feed. DMS circuits can either be combined, treating the complete PSD, or split, consisting of separate fines and coarse circuits. In such cases the coarse tails above the mid cut-off size (MCO) are recirculated back to the liberation circuit for further processing. Given the advances in sensor-based sorting, coarse concentration using DMS is increasingly being replaced by X ray transmission (XRT) sorters.

Recovery circuit

The purpose of the recovery circuit is targeted identification and extraction of liberated diamonds emanating from the concentration circuit. The major unit processes found in a recovery plant include sizing screens, magnetic separators, electronic sorting machines, dryers, and glove boxes. There are many variations of recovery plant flow sheets focusing either on maximum diamond recovery efficiency or maximum product grade, or both.

Understanding of the material properties of the gangue as well as the fundamentals of the candidate sensor technologies is critical to successful recovery circuit design. Alignment of these two aspects is critical in order to maximize recovery efficiency at the lowest possible yield.

Determination of diamond liberation

While it is accepted that comminution promotes mineral liberation, with a positive correlation between fineness of grind and degree of liberation, modelling and quantification of mineral liberation is not always straightforward. In the case of diamond processing, reducing everything to 'bug dust' destroys the valuable species; therefore the objective becomes one of optimum

grind. This in turn requires understanding of diamond liberation and associated numerical modelling of the process. This is currently done by using the diamond deportment model, which combines PSD, PSFD, grade, and the PLF to predict liberated and locked diamond content distribution within the processing plant.

In times long past, the rule of thumb for estimating diamond lock-up was the '4:1 rule', indicating that the maximum nominal size of a diamond that could be locked within an ore particle was $\frac{1}{4}$ the nominal size of the particle; alternatively, the particle was four times the diamond size. This is the definition of PLF, represented as an inverse within 0 and 1. The typical range of PLF values is between 0.25 and 0.45, with 0.35 a good starting point. A low PLF value indicates reduced lock-up and easier liberation usually associated with larger diamonds, the converse applying to smaller diamonds. In applying the PLF as shown in Figure 4, a step function is used, meaning either fully liberated (1) or fully locked (0), which although simplistic has proved its robustness in industry.

This is an area in need of much research to improve from a step function to the more familiar S-curve associated with all mineral extraction processes, as shown in Figure 5. For the purposes of this narrative and associated examples the PLF will be used in its simplest step function form. As fundamental knowledge improves in the coming years, inclusive of new liberation concepts and ideas, scientific alternatives to the PLF deportment model will become possible.

The diamond deportment model and associated mathematics

Calculation of liberated and locked diamond content is a five-step process, the starting point being the allocation of total diamonds into their respective OSIDS classes, as described in the derivation of Table IV, reproduced below as Matrix A.

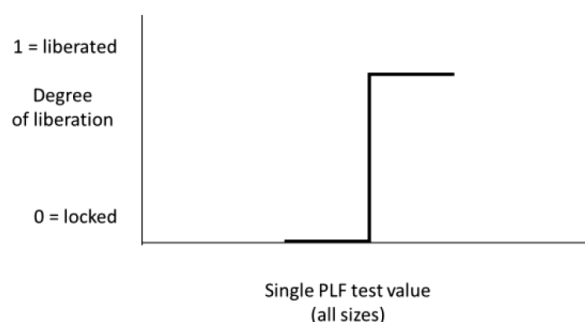


Figure 4—Current PLF application (size-independent)

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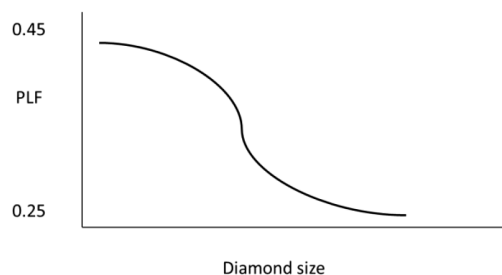


Figure 5—Future PLF application (size-dependent)

The second step is calculation of diamond to ore size ratio per OS/DS class as shown in Matrix B.

$$\text{Ratio}(i, j) = \text{Mean size DSj} / \text{Mean size OSi} \quad [2]$$

The third step is application of the PLF test (constant value of 0.35) to determine liberation status.

$$\text{if Ratio}(i, j) \geq \text{PLF then } L(i, j) = 1, \text{ else } L(i, j) = 0 \quad [3]$$

Matrix D is the multiplication result of Matrix A by Matrix C, with the last row in Matrix D providing an estimate of the liberated DSFD. This is a new distinct mineral stream separated out from the ore stream.

$$\text{Liberated Diamond}(i, j) = \text{Matrix A}(i, j) * \text{Matrix C}(i, j) \quad [4]$$

Subtracting Matrix D from Matrix A, shown as Matrix E, gives the estimate of locked diamonds which remain associated with the ore classes. This in effect is the locked DSFD.

$$\text{Locked Diamond}(i, j) = \text{Matrix A}(i, j) - \text{Matrix D}(i, j) \quad [5]$$

Matrix A. Diamond allocation per OS/DS class

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS	OS total
+150.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
+90.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	1.000	0.900	0.700	0.400	0.300	0.200	10.0
+45.0	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.250	2.500	2.750	2.500	2.250	1.750	1.000	0.750	0.500	25.0
+25.0	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	20.0
+8.0	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	20.0
+4.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	1.000	0.900	0.700	0.400	0.300	0.200	10.0
+1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
-1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.0
DS total	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	10.000	9.000	7.000	4.000	3.000	2.000	100.000

Matrix B. Diamond to ore size ratio per OS/DS class

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS
+150.0	0.060	0.047	0.036	0.030	0.028	0.024	0.021	0.018	0.015	0.013	0.011	0.009	0.008	0.006	0.005	0.003
+90.0	0.089	0.070	0.054	0.045	0.041	0.036	0.031	0.027	0.022	0.019	0.016	0.014	0.011	0.009	0.008	0.005
+45.0	0.163	0.127	0.099	0.082	0.075	0.066	0.057	0.049	0.041	0.034	0.029	0.025	0.020	0.017	0.014	0.009
+25.0	0.310	0.242	0.187	0.156	0.142	0.126	0.108	0.093	0.077	0.065	0.055	0.047	0.039	0.032	0.027	0.017
+8.0	0.735	0.574	0.444	0.370	0.337	0.298	0.257	0.221	0.183	0.153	0.131	0.112	0.092	0.077	0.065	0.041
+4.0	1.837	1.434	1.110	0.926	0.844	0.746	0.641	0.553	0.458	0.383	0.328	0.281	0.230	0.192	0.162	0.103
+1.0	5.197	4.056	3.139	2.618	2.386	2.109	1.814	1.564	1.296	1.084	0.927	0.795	0.650	0.544	0.460	0.290
-1.0	14.698	11.471	8.879	7.404	6.749	5.964	5.132	4.423	3.666	3.066	2.623	2.249	1.839	1.539	1.300	0.820

Matrix C. Liberation status (0 = locked, 1 = liberated)

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS
+150.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+90.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+45.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+8.0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
+4.0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
+1.0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

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Matrix D. Liberated diamond per OS/DS class

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS	OS total
+150.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+90.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+45.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+25.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
+8.0	0.400	0.600	0.800	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.800
+4.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	0.000	0.000	0.000	0.000	0.000	0.000	6.500
+1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.000	4.900
-1.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.000

Matrix E. Locked diamonds per OS/DS class

(i/j - O/D)	+23DS	+21DS	+19DS	+17DS	+15DS	+13DS	+12DS	+11DS	+9DS	+7DS	+6DS	+5DS	+3DS	+2DS	+1DS	-1DS	OS total
+150.0	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500	0.550	0.500	0.450	0.350	0.200	0.150	0.100	5.000
+90.0	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000	1.100	1.000	0.900	0.700	0.400	0.300	0.200	10.000
+45.0	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.250	2.500	2.750	2.500	2.250	1.750	1.000	0.750	0.500	25.000
+25.0	0.400	0.600	0.800	1.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	20.000
+8.0	0.000	0.000	0.000	0.000	1.200	1.400	1.600	1.800	2.000	2.200	2.000	1.800	1.400	0.800	0.600	0.400	17.200
+4.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.900	0.700	0.400	0.300	0.200	3.500
+1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.100
-1.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DS total	1.200	1.800	2.400	3.000	4.800	5.600	6.400	7.200	8.000	8.800	9.000	8.100	6.300	3.600	2.700	1.900	80.800

The information contained in the above matrices is useful in determination of diamond content across the flow sheet. Determination of value distribution is easily done by incorporating price data to generate a corresponding set of financial matrices. The combination of the two is critical in identifying the MCO for the concentration circuit, with concentration tailings above the MCO close-circuited back to the liberation circuit for additional processing. Figure 6 shows the DSFD for the example used above in terms of liberated, locked, and total distributions.

In concluding the discussion on the PLF deportment model it suffices to say that accurate knowledge of the grade in critical. Additional to this is the interplay between the DSFD and stream PSD, as the two key drivers, in the determination of optimum grind for a diamond processing plant.

Diamond lock-up model based on density differentials

Reference is made to earlier methods used to estimate diamond lock-up based on the difference in densities between diamonds and the host ore, with specific application to DMS. It is premised on the assumption that an ore particle containing a locked diamond having a composite density equal to the DMS cut point will be lost to the tailings stream. This is illustrated in Figure 7, showing a spherical diamond enclosed within a spherical kimberlite ore particle.

The maximum size of a diamond that can be locked within an ore particle, expressed volumetrically, is given by Equation [6].

$$V_d \leq V_p * \left(\frac{D_{dms} - D_k}{D_d - D_k} \right) \quad [6]$$

where
 V_d Volume of diamond
 V_p Volume of particle

D_d Density of diamond, typically 3.52
 D_{dms} Cut point density of DMS circuit, typically 3.10
 D_k Density of kimberlite rock, typically 2.60

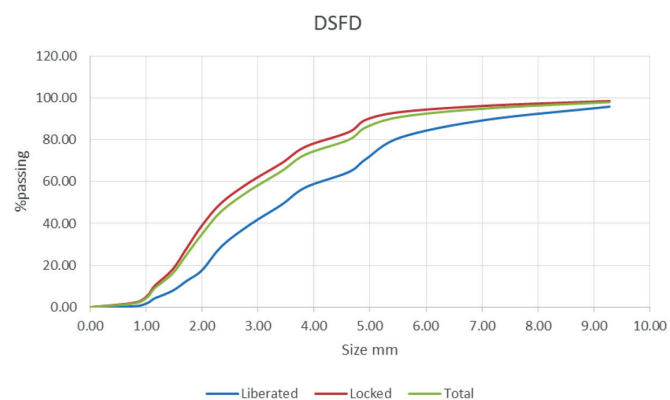


Figure 6—DSFD showing liberated and locked contributions

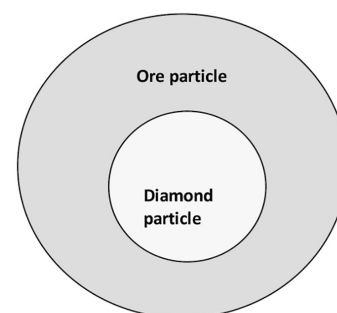


Figure 7—Composite spherical diamond and ore particle

Diamond plant statistics, process efficiencies, liberation modelling, and simulation

Expressed in terms of particle sizes, the Equation [7] applies at the point of equilibrium.

$$\left(\frac{S_d}{S_k}\right) = \sqrt[3]{((Ddms - Dk)/(Dd - Dk))} \quad [7]$$

where

S_d Size of diamond expressed as the diameter

S_p Size of the particle expressed as the diameter

Substituting the typical values above yields a diamond to ore size ratio of 0.82, indicating that such a situation cannot exist in terms of the PLF deportment model, which operates in the range 0.25 to 0.45 with 0.82 indicating complete liberation. It is not the purpose of this paper to critique the validity of the two approaches, other than to emphasise the need for continuous research and validation as to the fundamental mechanisms of diamond liberation, and conversely diamond lock-up. The industry remains open to new thinking.

Simulation package imperative

Calculation of the metallurgical flow sheet mass balance is a daunting task at the best of times, even for single-phase commodity operations. With the advent of computers and the wide availability of simulation packages it is much easier nowadays, and many commodity-specific packages have been developed over the years. Given the relative complexity of diamond mathematics as illustrated with the diamond deportment model, the need for diamond-specific simulation packages goes without saying.

Figure 8 is a very simplistic representation of such a simulation package using off-the-shelf software as the top block, to which is interfaced custom-developed diamond tracking subroutines represented in the bottom block. The interconnectors between the two are the ore and diamond data-sets for all the streams in the flow sheet.

Diamond flow sheet simulation packages do exist, although they are generally considered to be proprietary information. This applies to producer companies, engineering design houses, and industry consultants, among others. In the author's opinion, the critical challenge is the need for an industry-agreed package, open source and available to all participants. This will make for a single point of reference, simplified peer reviews, and improved industry technical assurance.

Plant statistics and circuit efficiencies

Plant statistics

With reference to Figure 3, imagine the ideal mass balance statistics depicted in Figure 9, where all major streams are fully quantified in terms of ore and diamond throughput, with all associated PSD and DSFD information. Diamond throughput is indicated as carats per hour (c/h), while % dbw (percentage diamond by weight) is a quality measure on the final export product. Some of the information will be derived from field instrumentation and production returns, with the balance estimated by means of simulation modelling software. To add reliability to the latter would require periodic auditing of these streams through an independent bulk sample plant (BSP). This is a discussion for another day, given the decline in such capability across the industry.

The reality is closer to Figure 10, with complete ore mass balance information on the majority of key process streams, while diamond content information is limited to the ROM and final

product streams. This should be a minimum requirement until such time that full diamond accounting systems and protocols are developed and adopted by industry.

Total plant recovery efficiency

Despite the scarcity of internal stream diamond information, calculation and evaluation of the overall recovery efficiency is possible by reconciliation of diamonds recovered in stream 7 against ROM diamonds sent to the plant in ROM stream 1. This is done both at the global level for an overall plant efficiency factor and per DS class, in the understanding that recovery efficiency decreases as a function of size. Such a hypothetical control chart is shown in Figure 11. Depending on the level of available geological and plant data, coupled to the technical sophistication of associated information systems, useful insights are possible, namely:

- Constant under- or over-recovery across the DS spectrum, indicating inaccuracy on incoming grade
- Reduced recoveries in certain DS classes, indicative of process losses about those size fractions
- Reduced recoveries in the larger DS classes, possible evidence of diamond damage or security issues
- Recovery efficiencies in excess of ROM, indicative of breakage from larger DS classes into smaller DS classes or grade inaccuracies.

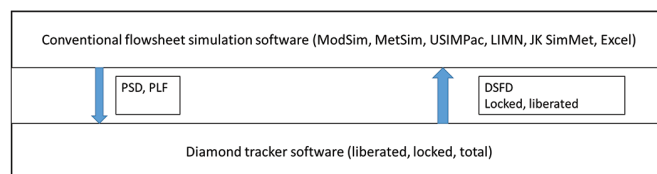


Figure 8—Simplified representation for a generic diamond flow sheet simulation package

Stream	1	2	3	4	5	6	7	9
Description	ROM feed	Fines residue	DMS feed	Coarse residue	Recovery feed	Recovery residue	Diamond product	Internal recycle
Mass flow	t/h	t/h	t/h	t/h	t/h	t/h	c/h	t/h
Size distribution	PSD	PSD	PSD	PSD	PSD	PSD	DSFD	PSD
Grade	cpht	cpht	cpht	cpht	cpht	cpht	% dbw	cpht
Liberated diamonds	c/h	c/h	c/h	c/h	c/h	c/h	c/h	c/h
Locked diamonds	c/h	c/h	c/h	c/h	c/h	c/h	N/A	c/h
DSFD	Locked Liberated Total	Locked Liberated Total	Locked Liberated Total	Locked Liberated Total	Locked Liberated Total	Locked Liberated Total	Liberated	Locked Liberated Total

Figure 9—Plant mass balance statistics in an ideal world

Stream	1	2	3	4	5	6	7	9
Description	ROM feed	Fines residue	DMS feed	Coarse residue	Recovery feed	Recovery residue	Diamond product	Internal recycle
Mass flow	t/h	t/h	t/h	t/h	t/h	t/h	c/h	t/h
Size distribution	PSD	PSD	PSD	PSD	PSD	PSD	DSFD	PSD
Grade	cpht						% dbw	
Liberated diamonds							c/h	
Locked diamonds								
DSFD	Total						Total	

Figure 10—Current plant mass balance statistics

Diamond plant statistics, process efficiencies, liberation modelling, and simulation

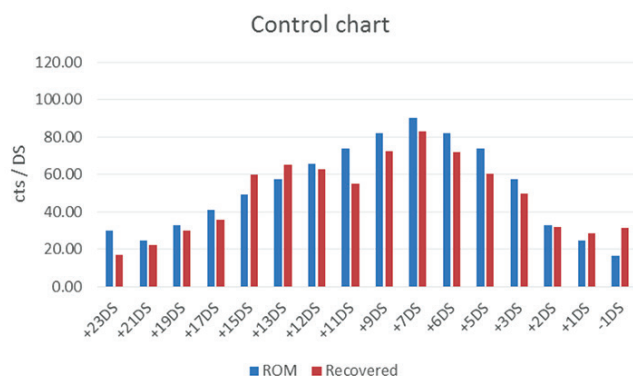


Figure 11—Control chart example

The use of control charts is widely practiced across the industry, providing high-level assurance as to plant performance and linking back to mineral resource estimates. Such charts can be compiled per ore type, defined production periods, and also over cumulative timelines.

Plant liberation efficiency

Reconstitution of the outgoing stream PSD data (streams 2, 4, and 6) to calculate an *in-situ* plant PSD can serve as a useful proxy measurement to estimate liberation efficiency for the complete plant. This internal PSD, in combination with ROM grade and the PLF deportment algorithm, also provides a total liberated diamond profile for the plant, which in combination with control chart information can guide the plant metallurgists to identify areas of process inefficiencies.

Concentration circuit efficiency

In the case of plants using DMS as the method of concentration, the circuit efficiency is determined by the use of density tracer testing, in combination with periodic washability curves of the cyclone product streams. The latter is standard practice across all commodities using DMS. In the case of diamonds, particular emphasis is placed on recovery efficiency to sinks at density point 3.52 g/cm³ specific to diamond.

Given the increasing use of electronic sorting as a way of concentration, estimation of process efficiency is done by use of proxy tracers. In operations where independent audit plants are available, tailings and concentrate samples can be taken for separate processing, to determine process efficiency.

Recovery plant circuit efficiency

Figure 12 is a generic representation of material flow within

a final recovery plant. The incoming feed is separated into a number of distinct size fractions, shown as fines, middles, and coarse. These are treated through a primary recovery circuit to produce an initial rougher concentrate which is upgraded in a secondary re-concentration circuit to produce a final product suitable for hand sorting. In comparison to the upstream circuits, recovery plants are high-security, low-throughput operations targeting liberated diamonds. Modern-day designs include sampling points, making it possible to take audit samples in order to determine process efficiencies at unit process level, and also per size stream and for the whole recovery plant. This is supplemented by the use of proxy tracers for machine set-up purposes.

Conclusions

In line with the key objective of the paper, a general revision of existing information, operational practices, industry *status quo*, and empirical process models into a single narrative is required. This is for the purposes of continuous learning, ongoing debate, and development into a more exact science. Some pointers into the future:

- Adaptation of an industry-accepted diamond flow sheet simulation package, accessible to all stakeholders, thus enhancing the assurance process
- Ongoing research into the fundamentals of diamond liberation as a possible alternative to the PLF deportment model currently in use
- Uniformity in plant statistics reporting and adaptation of minimum requirements
- Continuous education in the industry.

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References

- MACHOWSKI, R. 2007. Technique for estimation of diamond lockup in a diamond processing plant. *Proceedings of Diamonds Source to Use Conference 2007*. Southern African Institute of Mining and Metallurgy, Johannesburg.
- SASMAN, F., DEETLEFS, B., and VAN DER WESTHUYZEN, P. 2018. Application of diamond size frequency distribution and XRT technology at a large diamond producer. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 1. pp. 1–6. ◆

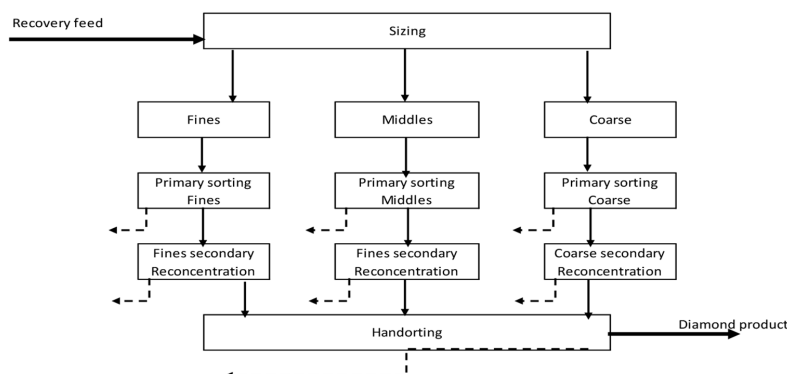


Figure 12—Recovery plant material flow