Millstat – A Software Package for Statistical Analysis of Mill Databases

*Ming Song *, Xiangjun Qiu, Alexander Potapov and Lawrence Nordell*
Conveyor Dynamics, Inc.
Email: song@conveyor-dynamics.com

September, 2001

ABSTRACT

Mill operators use databases to collect operating data that allow off-line and/or on-line correlation of mill variables with performance. There are many measures of performance that may be overlooked. MILLSTAT is a statistical computer code that analyzes the databases. It is able to establish relationships between mill variables, observe effects of recorded and defined variables, identify performance changes due to liner and grate modifications or wear, detect abnormal phenomenon, compare mill performance between different periods of a mill and/or between different mills, determine optimal conditions of milling, and eventually make suggestions to improve milling efficiency.

MILLSTAT has been combined with the Population Balance Model (PBM) and mill simulation codes (Discrete Element Method (DEM), MILLSIM) to accurately predict equipment mass flow and transfer size distributions including product size P80. Together they can determine, in advance, throughput required to achieve the highest grinding rate, mineral recovery, or financial return while maximizing use of database information.

INTRODUCTION

Many variables affect mill performance such as SAG and ball mill power, rotation speed, water addition (reflecting flow ability; slurry rheology), mill holdup, primary and recycle crushers, liner and grate shape changes with life, trommel and screen efficiency, pan cavity geometry, number of cyclones, splitter condition, rock strength and size distribution, grind media and so on.

The MILLSTAT package is based on a proprietary set of statistical tools including multiple linear and non-linear regression, variance and covariance analysis for dependent and independent variables. The comprehensive package can be used to track process variables and their effects on mill circuit performance, and report the status at which the mill is working. It allows the user to recognize the optimal range for mill performance, detect abnormal phenomenon that may worsen milling efficiency, explain possible causes in detected abnormal phenomenon, and make suggestions on how to improve milling efficiency.

Linear and non-linear correction techniques, built into the software, make it possible to fairly compare mill performance between different stages of a line life, different liner lives of a mill and/or between different mills. Through the phase shift analysis, we can observe time delays between recorded streams, providing information for mill control processes.

MILLSTAT can be used on-line, to estimate PBM model parameters, which will improve accuracy in predicting transfer and product size distributions. This will determine, in advance, throughput to achieve required value of flotation P80 (e.g. mineral recovery target).

ESTABLISH RELATIONSHIPS

There exist certain relationships between variables. Data analysis makes it possible to identify relationships we can off-line and/or on-line observe. We can then correlate how the process variables (e.g. feed size distribution, mill load, power, rotation speed, water addition, liner life etc.) affect target variables (throughput, product size, mineral recovery etc.). Two examples of established relationships are given below.

Figure 1 shows the relationship of throughput (TPH) vs. bearing pressure (PRE), and the frequency histogram for a liner life period in a mill. The figure shows the strategy in controlling mill load by changing throughput. The increasing part on the curve is associated with finer and/or softer feed, and the decreasing part with coarser and/or harder feed.

Figure 2 illustrates the relationship between throughput and F80, 80% passing size in feed in another period. This figure describes how throughput changes with feed size.

IDENTIFY CURRENT OPERATING MODE

Figure 3 shows the relationship of throughput vs. SAG power (PWR) for a liner life in a mill. The figure shows that the range of SAG power from 14.5MW to 17.0MW is associated with higher throughput, and that higher power is associated with lower throughput, which may be caused by hard ore and/or coarse feed.

Similarly, Fig.4 illustrates the relationship of throughput vs. rotation speed in percent of critical speed (PCS) for the same period. From the figure, it is observed that the optimal range of rotation speed for the mill to work is from 72% to 76%. The frequency histogram shows that the dominant rotation speed is 79%, which is out of the suggested optimal range, and is associated with lower throughput than at the peak.

DETERMINE BEST OPERATING CONDITIONS

There is an optimal range for some mill variables to maximize mill performance. Controlling these variables, within the optimal range, may lead to higher throughput, or other benefits. MILLSTAT is able to detect this range and spot the optimal point. Fig. 5 describes the non-linear fitting of throughput vs. rotation speed for two liner life periods. It is observed that the peak throughput is at 73.5% of critical speed.

DETECT ABNORMAL PHENOMENON

One expects certain relationships hold between some variables according to his knowledge, experience, and intuition. Sometimes the real mill doesn't perform as he expects, or the expected patterns are hidden by some other factors. Detecting these phenomena, which may worsen milling efficiency, and discovering possible causes help in understanding the milling process and in improving milling efficiency.

For example, one may expect an increase in throughput as fines percentage in feed increases. Analyzing recorded data of two client mills, MILLSTAT demonstrates that throughput increases first (fines percentage below a certain value) and then decreases (fines percentage over that value) as fines percentage in feed goes up.

Figure 6 illustrates the first-up-then-down curve of throughput (TPH) vs. fines percentage (FPC) with the peak at around 50% fines in feed.

The usual explanation for this behavior is that in a similar manner to ball milling, a finer feed permits a higher throughput while maintaining a specified P80 (left branch) but in contrast to ball milling as all the large rock media pieces disappear out of the feed (right branch) the throughput drops.

An alternative explanation derived from experiences in two client mill circuits appears to be related to a mechanical factor identified as variable A in Fig. 7. This figure shows that Variable A is almost constant when fines percentage is less then 50%, but drops when it is over 50%. The decreased value of Variable A is associated with, and may be the cause of the lower throughput.

With MILSTAT the authors discover a controllable variable, which may cause the lower value for Variable A. The controllable variable is marked Variable B in Fig. 8. Variable A is constant when Variable B is larger than 1.0, and plummets when it is less than 1.0.

In a second example, one may expect that product size P80 (cyclone oversize) increases with feed size F80, that is, a coarser feed leads to a coarser product, and vice versa. However, Fig. 9 shows that a mill behaves in a very different way. The P80 goes down as the F80 increases. The authors suggest the possible reason as follows. The mill control system allows an increase (or decrease) in throughput when it finds a finer (coarser) feed. However, the increased (or decreased) amount in throughput seems to be too much so that the product becomes unexpectedly coarser (finer).

DEFINE NEW VARIABLES

MILLSTAT accepts a definition of new variables in terms of recorded variables. One example is given below to show that appropriately defining new variables provides better understanding in the milling process. Fig. 10 illustrates the relationship of a defined variable, Recycle Ratio of Solids in Ball Mill Circuits, vs. fines percentage in feed. The two pan-shaped curves suggest that the possible optimal range for fines percentage in feed is from 42 to 52.

COMPARE MILL PERFORMANCES

A question like the following often appears. Does a newly designed liner (or other condition's change, e.g., adoption of a new technique) improve milling efficiency?

A client mill ran two periods with different liner designs. The authors tag the two periods with Period 1 and Period 2. Direct comparison between two periods is given in Table 1, which lists throughput, SAG power, and SAG efficiency for the two periods. SAG efficiency is defined by throughput divided by SAG power.

From Table 1, 3.55% increase in throughput and 6.29% increase in SAG efficiency can be observed. However, these percentage numbers don't reflect the real performance improvement because other milling conditions are different in the two periods.

Table 1: Mill Performance Without Any Corrections

Periods	*Throughput*	*SAG Power*	*SAG Efficiency*
First	1966.9	18.79	104.9
Second	2036.8	18.31	111.5
Difference (%)	**+3.55**	-2.55	**+6.29**

To accurately examine the influences of one variable on the milling process we decouple the linear and non-linear effects of other significant variables. That is, we examine one variable by considering the other significant variables that are unchanged in the two periods. For this example, the authors detected three significant recorded variables: 80%

passing size in feed (F80), recycle crusher power (RCP), and ratio of water to ore (RWO). The mean values for these variables in the two periods are listed in Table 2.

Table 2: Milling Conditions in Two Periods

Periods	*F80*	*RCP*	*RWO*
First	87.39	813.2	0.570
Second	91.57	853.0	0.508

After the corrections for these three significant variables, the mill performance is listed in Table 3.

Table 3: Mill Performance After Corrections for F80, RCP and RWO

Periods	*Throughput*	*SAG Power*	*SAG Efficiency*
First	1898.0	18.79	101.0
Second	2106.2	18.31	115.0
Difference (%)	**+11.0**	-2.55	**+13.9**

An 11.0% increase in throughput and 13.9% gain in SAG efficiency can be seen. However, the comparison is still not precise. The two periods produce very different products. The 80% passing size in product, P80, is 166.2 microns and 208.9 microns respectively for the two periods. Comparison should be conducted considering that the two periods have the same milling conditions, and produce the same product as well.

By correcting for F80, RCP, RWO, and P80, Table 4 is given. Less improvement can be seen from the first period to the second. These results are obtained by correcting for all recorded significant variables.

Table 4: Mill Performance After Corrections for F80, RCP, RWO and P80

Periods	*Throughput*	*SAG Power*	*SAG Efficiency*
First	1952.6	18.79	103.9
Second	2014.1	18.31	110.0
Difference (%)	**+3.15**	-2.55	**+5.89**

However, these percentage numbers are still not convincingly accurate because one of the most significant factors hasn't been considered – ore hardness, which is not possible to record.

A variable is defined to reflect this factor, sometimes referred to as a "soft-sensor". For the client in the example, the authors have defined the ore hardness (ORE) and found that it has changed for the two periods. The second period milled harder ores. By correcting for F80, RCP, RWO, P80 and ORE we certify that the real increase is 7.93% in throughput, and 10.7% in SAG efficiency, shown in Table 5.

Table 5: Mill Performance After Corrections for F80, RCP, RWO, P80 and ORE

Periods	*Throughput*	*SAG Power*	*SAG Efficiency*
First	1893.7	18.79	100.8
Second	2043.9	18.31	111.6
Difference (%)	**+7.93**	-2.55	**+10.7**

All conditions before and after corrections are listed in Table 6.

Table 6: All Variables Before and After Corrections

Variables	*Before Corrections*		*After Corrections*	
	Period 1	*Period 2*	*Period 1*	*Period 2*
Throughput	1966.9	2036.8	1893.7	2043.9
SAG Efficiency	104.9	111.5	100.8	111.6
F80	87.39	91.57	90.0	90.0
RCP	813.2	853.0	900.0	900.0
RWO	0.570	0.508	0.540	0.540
P80	166.2	208.9	180.0	180.0
ORE	13.42	14.32	14.0	14.0

CORRECTION TECHNIQUES

Correction techniques are to decouple effects of other significant variables to examine influences of one variable on the milling process. The following gives examples on the importance of the correction techniques.

Figures 11 and 12 plot the relationship of throughput (TPH) vs. SAG power (PWR) before and after corrections for five significant variables, respectively for two periods in a mill. The corrections delete most noise on the curves, and show that throughput linearly increases with SAG power.

Too high or too low rotation speed worsens milling efficiency. This indicates that there exists an optimal value for rotation speed. Fig. 13 shows the relationship of throughput vs. rotation speed in percent of critical speed (PCS). Before corrections we hardly see where the optimal value is. After corrections for five factors it is observed that the optimal value for rotation speed is 75% of critical speed.

PHASE SHIFT ANALYSIS

The phase shift analysis technique enables us to observe time delays between various process streams.

As is well-known, if bearing pressure (SAG load) is detected too high (low) in a SAG mill, the operator will act to decrease (increase) throughput. Then bearing pressure will go down (up) because of decreased (increased) throughput. One may ask two questions: 1) When is throughput really decreased (increased) after a high (low) bearing pressure is detected? 2) When does bearing pressure really become low (high) after throughput is decreased (increased)?

Figure 14 is a typical result of the phase shift analysis, which plots the correlation number between bearing pressure and throughput vs. time shift. The lowest negative correlation value is at –6 min. shifting, and the highest positive correlation value is at +11.5 min. shifting. This answers the two questions. Throughput is really decreased (increased) 6 minutes after a high (low) bearing pressure is detected. And then bearing pressure really becomes low (high) in 11.5 minutes after throughput is decreased (increased).

The product will become coarser (finer) if throughput is increased (decreased). A natural question may be asked: When does the product really become coarser (finer) after throughput is increased (decreased)? Figure 15 shows the correlation number between product size and circuit feed rate vs. time shift. The positive highest correlation value is at +21 min. shifting. This indicates that the product really becomes coarser (finer) in 21 min. after throughput is increased (decreased).

PRODUCT SIZE PREDICTION

Combining with the Population Balance Model and mill circuit simulation code (MILLSIM) with MILLSTAT we can accurately predict the transfer and product size distributions.

Figure 16 demonstrates the comparison of product size P80 between prediction and measurement. Even though the milling process varies significantly over time, the historical average error of the prediction is 4.53%. The accomplishment is attributed to the linear and non-linear decoupling techniques of process variables.

Since the time delay from feed to product is more than 20 minutes, this prediction makes it possible to determine, in advance, the throughput required to optimize a target function in product.

CONCLUSIONS

Mining companies invest many tens of thousands of dollars to install instruments and collect operating data. However, how much of the collected data is appropriately interpreted, and to what extent the costly databases are used to help understand the milling process and optimize milling efficiency?

Data analysis will tell him much more than he expects when one is able to comprehensively analyze the data. MILLSTAT provides a powerful tool to interpret data and to maximize the use of database information, by establishing the relationships between process variables, both recorded and defined.

Many real examples presented in this paper show that with the software we are able to identify the status of the mill, determine the optimal range for operating variables, detect abnormal phenomenon that normally worsens milling efficiency, and give the possible reasons for the detected abnormal behavior.

Linear and non-linear correction techniques make it possible to fairly compare milling performance between different periods of a mill, and between different mills. It eliminates the wonder on the measure of improvement that is made when adopting new techniques.

Since MILLSTAT decouples linear and non-linear interactions among variables, it is used to determine PBM model parameters to predict the transfer and product size distributions. Average error of predicted P80, over a long period, is less than 5.0%. The accurate prediction is necessary in optimizing the production for the highest milling efficiency, mineral recovery and/or financial return (not only the highest throughput).

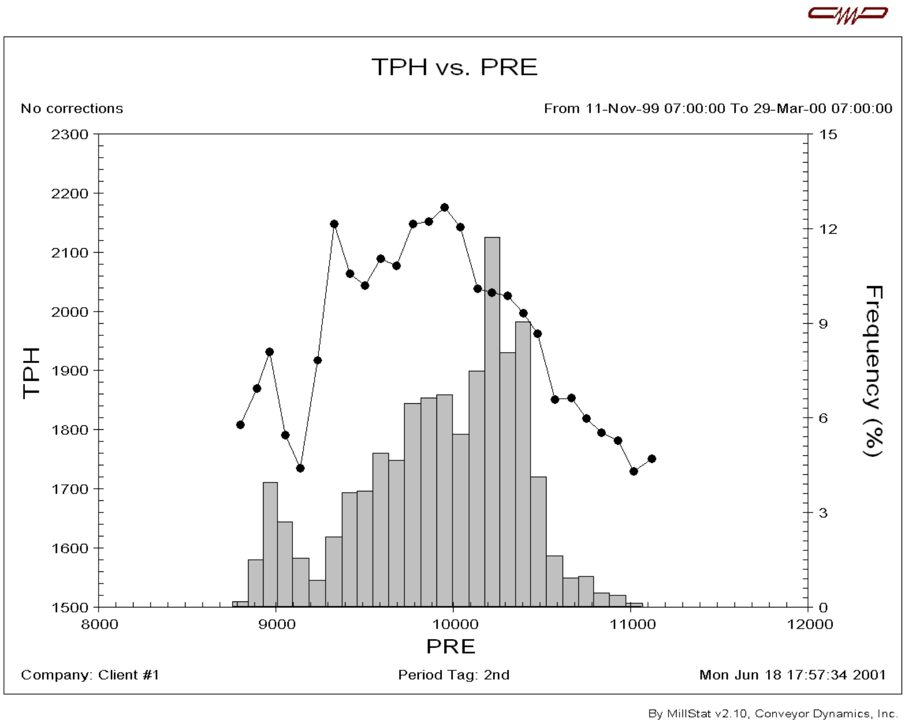

Figure 1. Throughput vs. Bearing Pressure

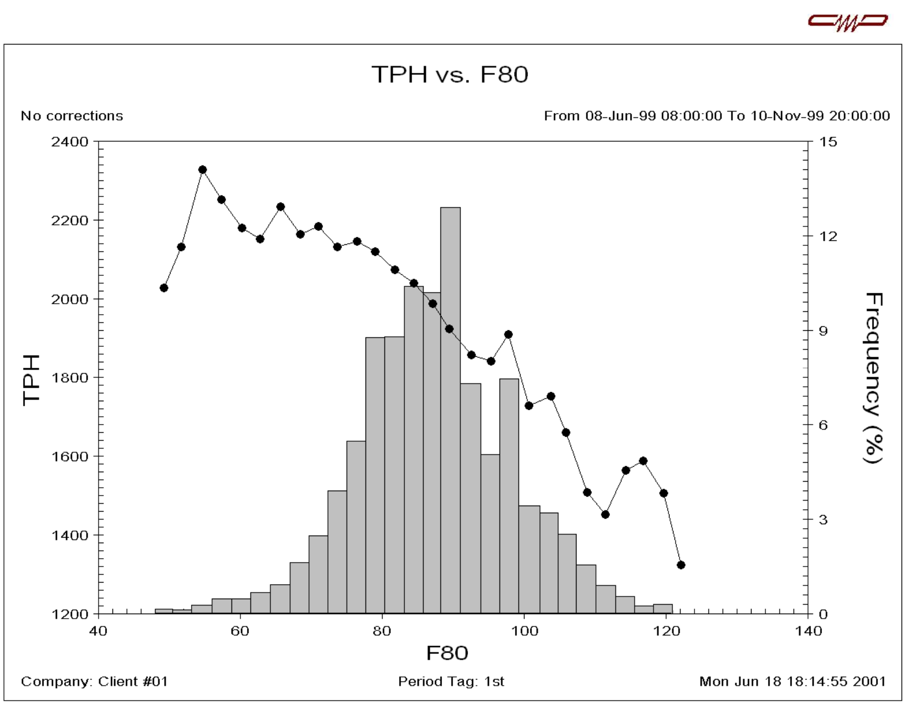

Figure 2. Throughput vs. F80

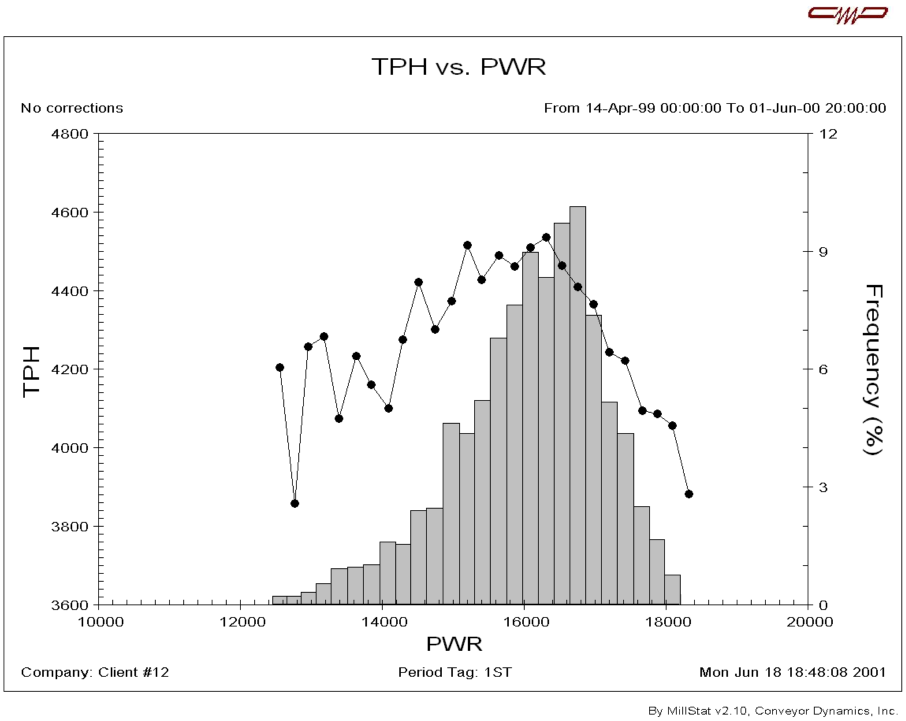

Figure 3. Throughput vs. SAG Power Draw

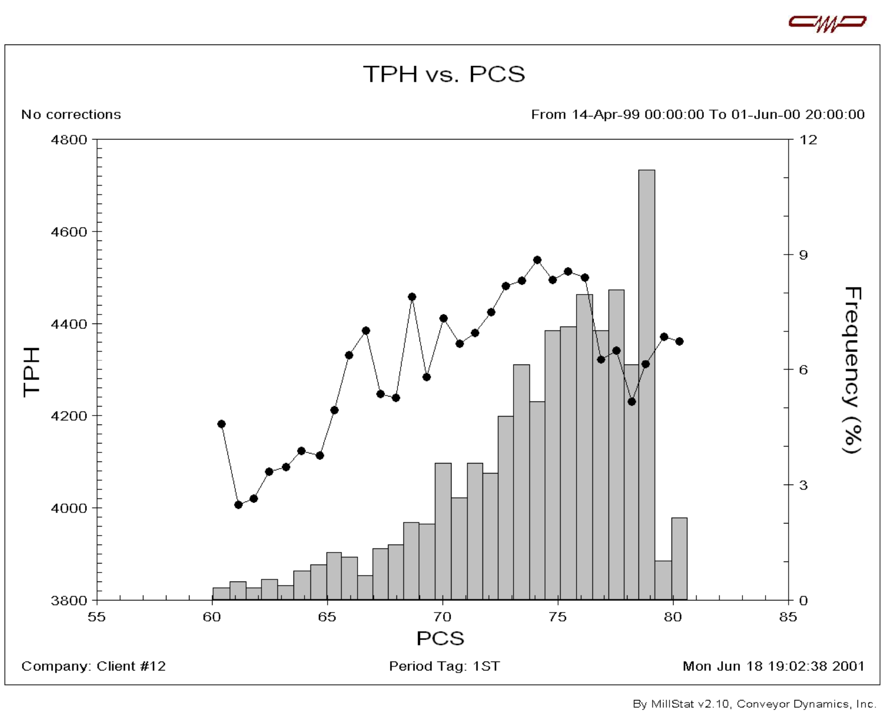

Figure 4. Throughput vs. Rotation Speed (% of Critical)

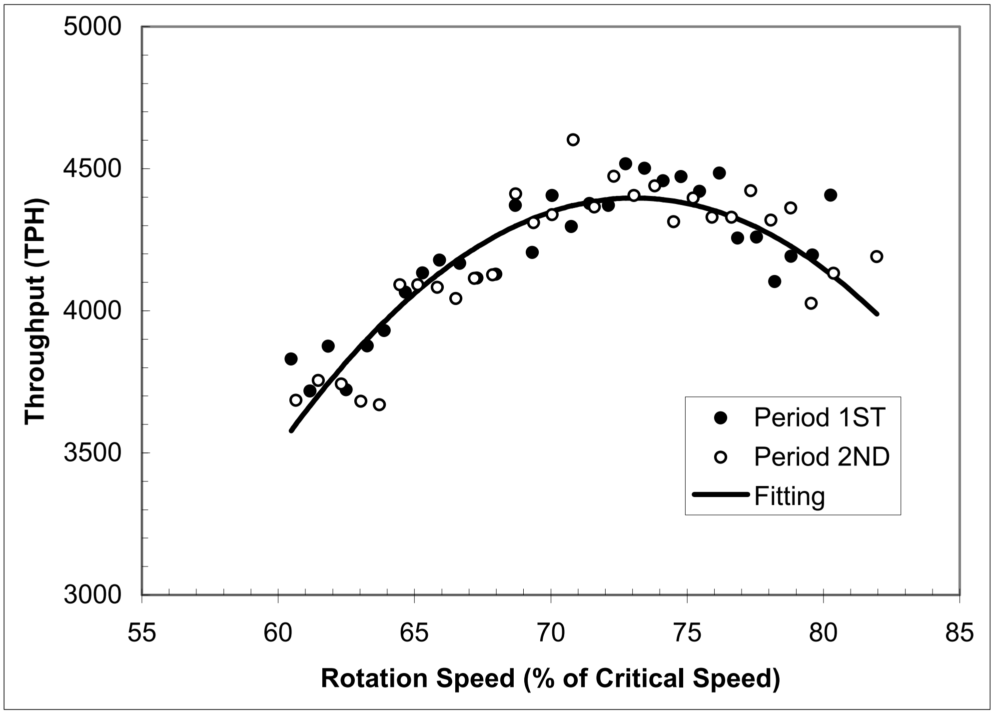

Figure 5. Maximizing Throughput for Rotation Speed

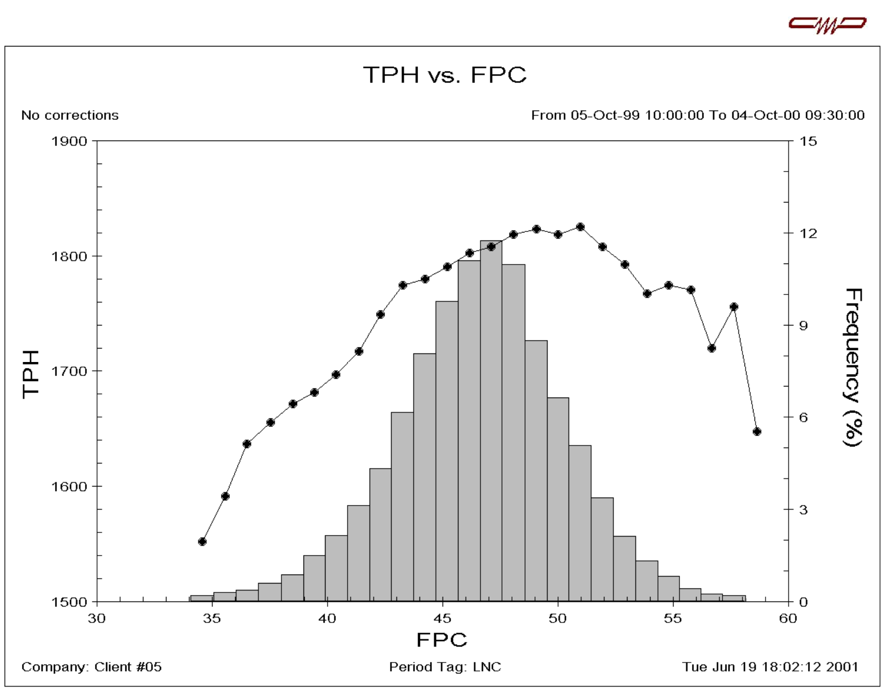

Figure 6. Throughput vs. Fines Percentage

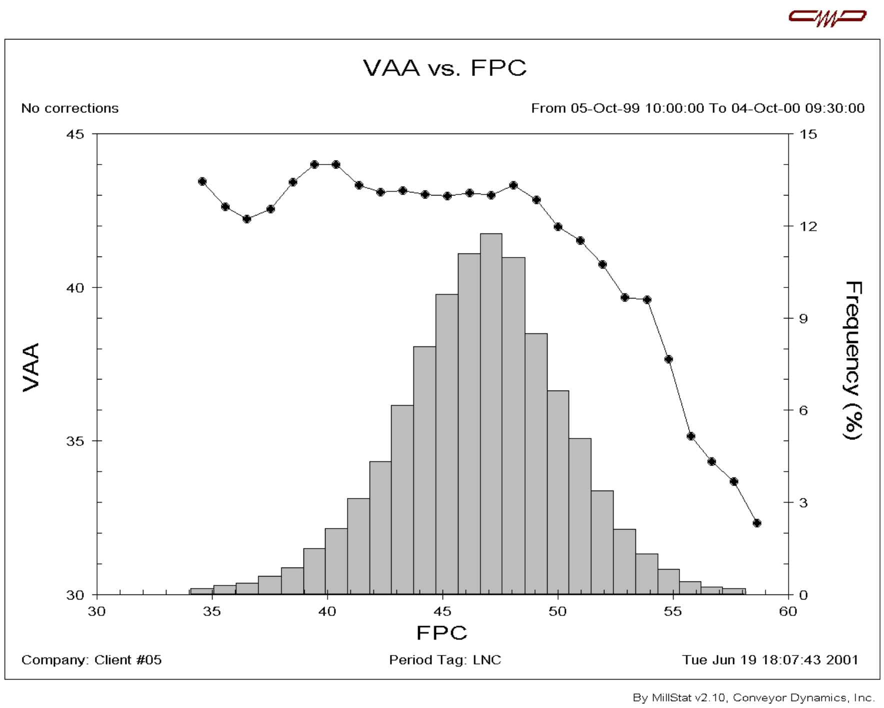

Figure 7. Variable A vs. Fines Percentage

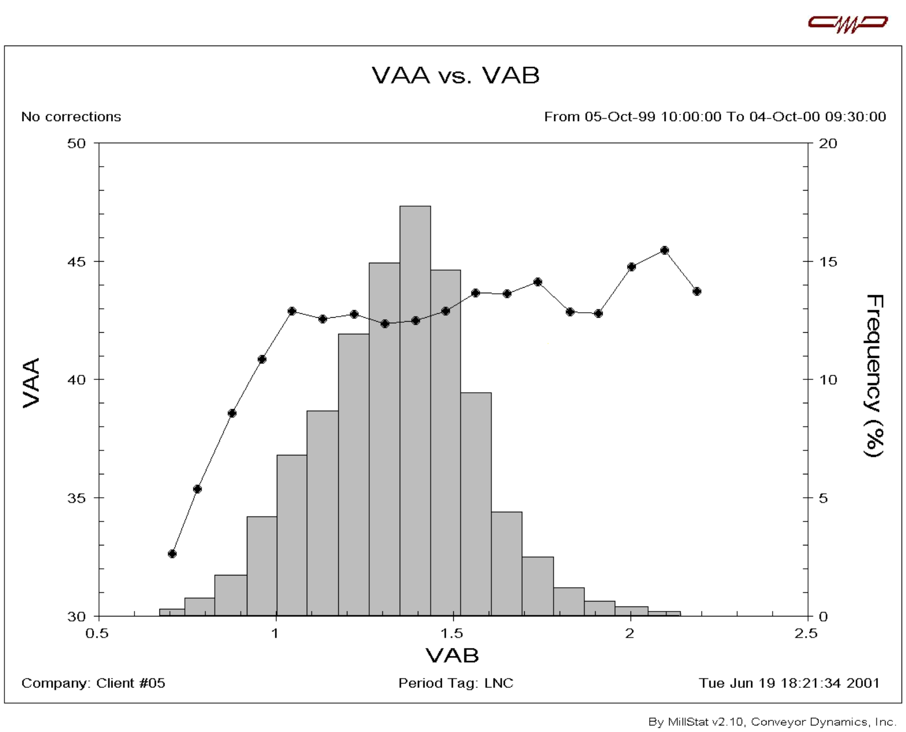

Figure 8. Variable A vs. Variable B

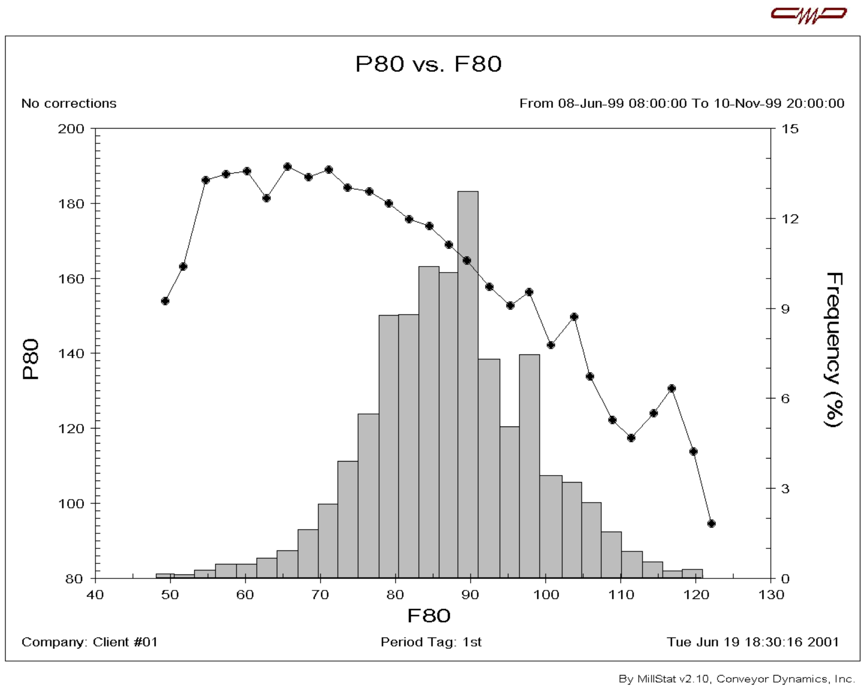

Figure 9. P80 vs. F80

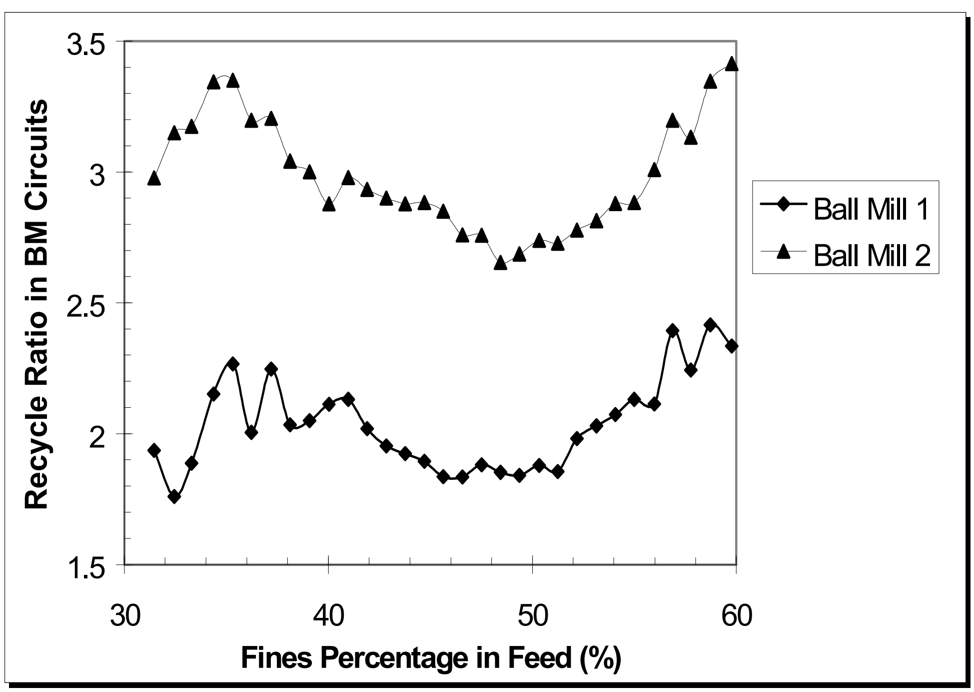

Figure 10. Recycle Ratio in BM Circuits vs. Fines Percentage in Feed

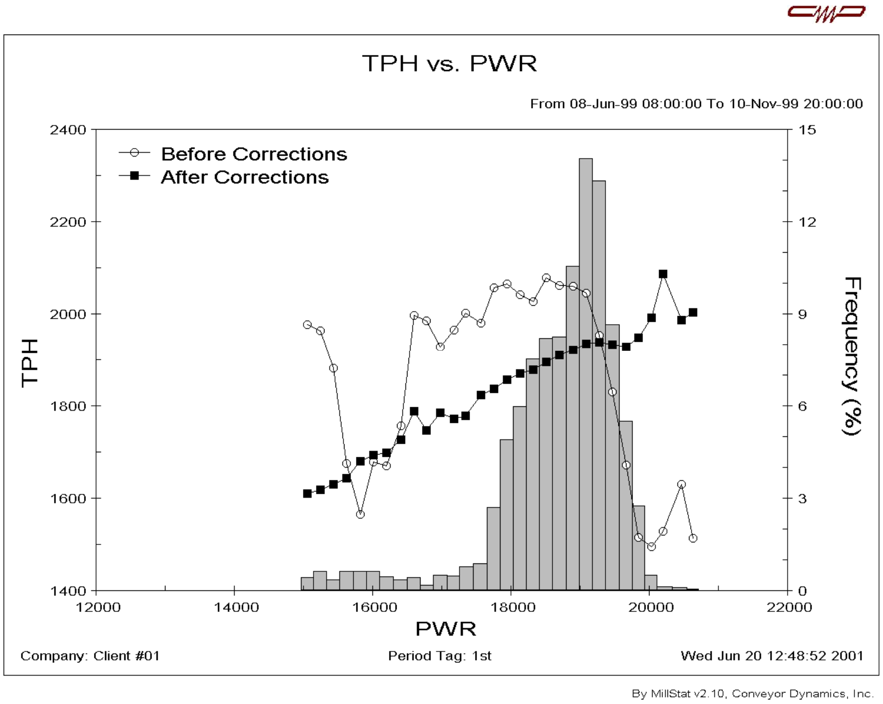

Figure 11. Throughput vs. SAG Power for 1st Period

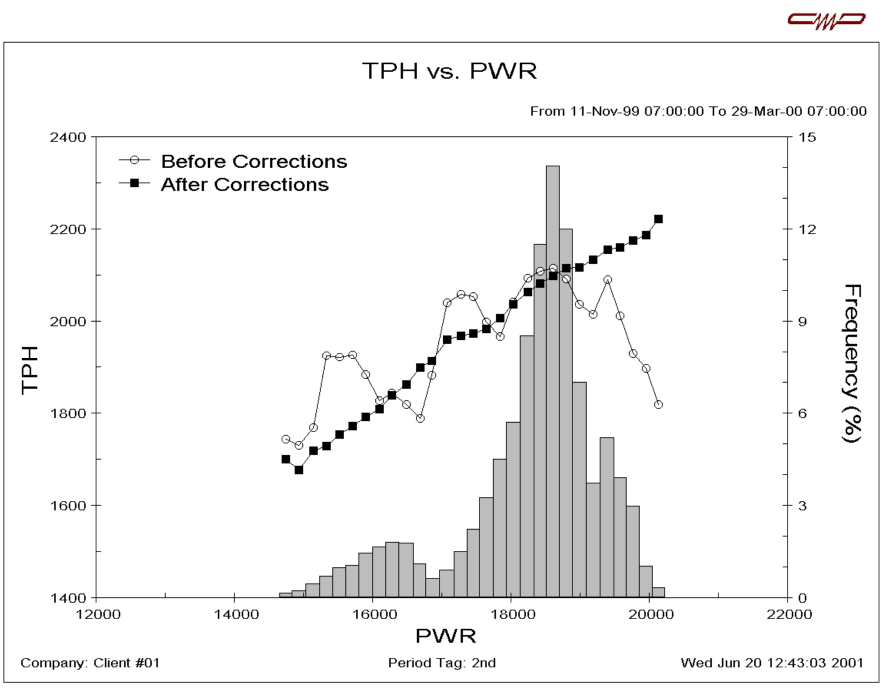

Figure 12. Throughput vs. SAG Power for 2nd Period

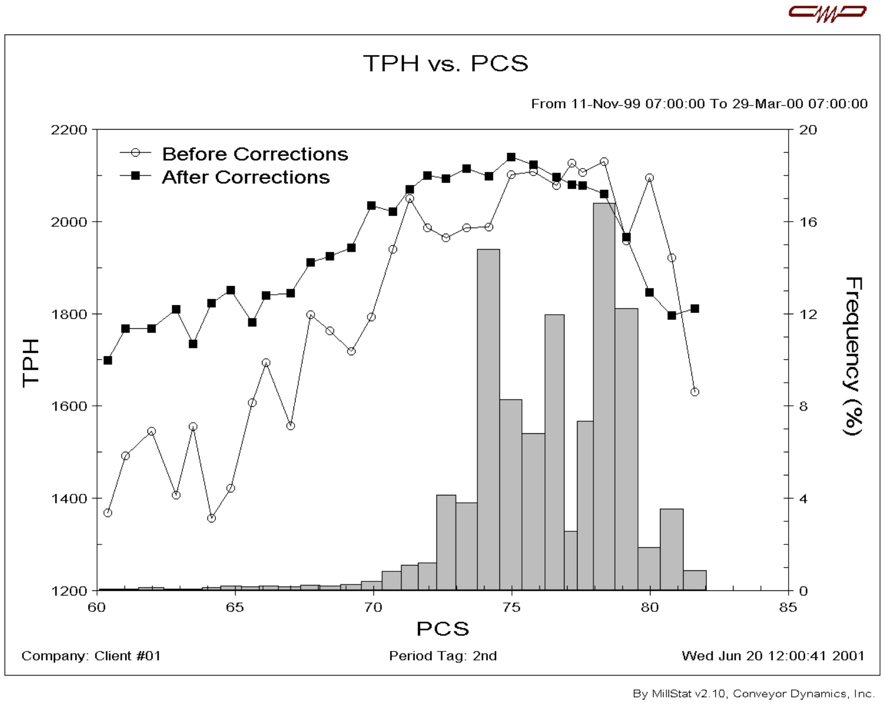

Figure 13. Throughput vs. Rotation Speed (% of Critical)

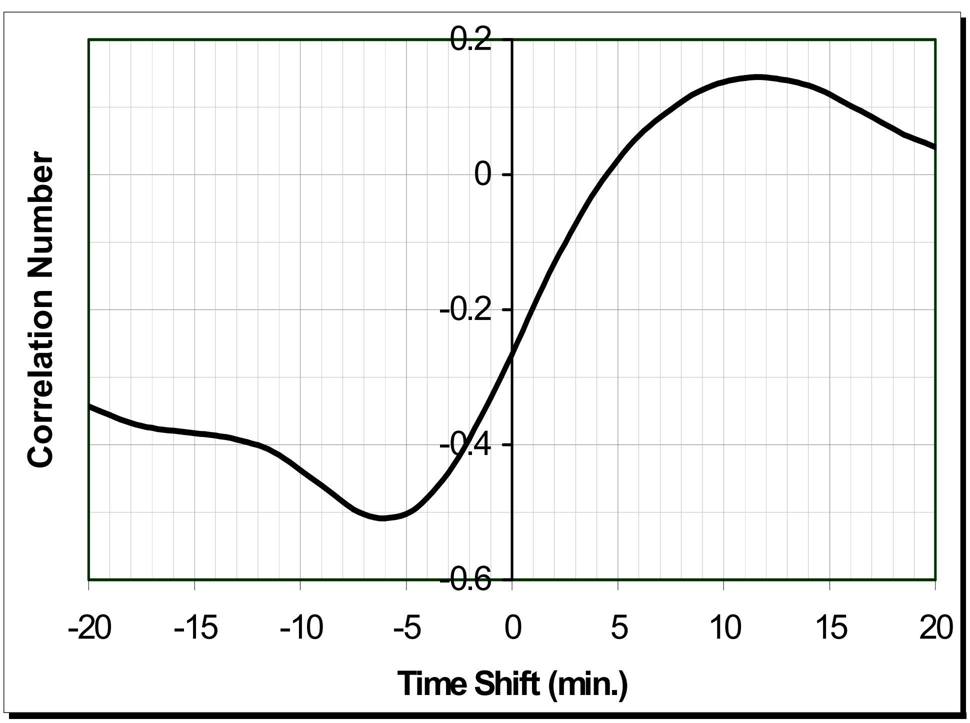

Figure 14. Phase Shift between Bearing Pressure and Throughput

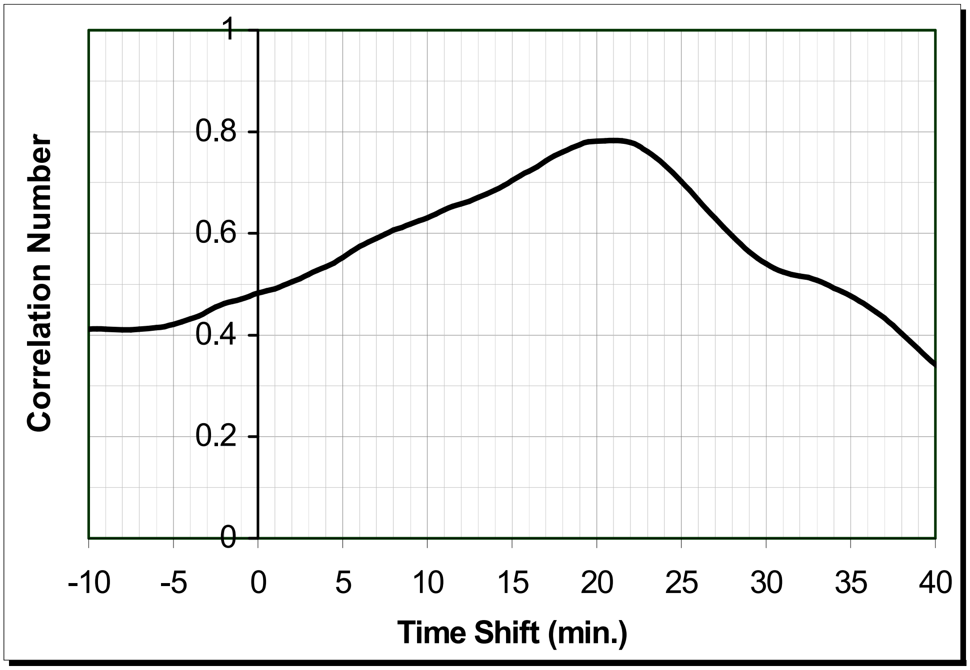

Fig. 15: Phase Shift between Circuit Feed Rate and Product Size

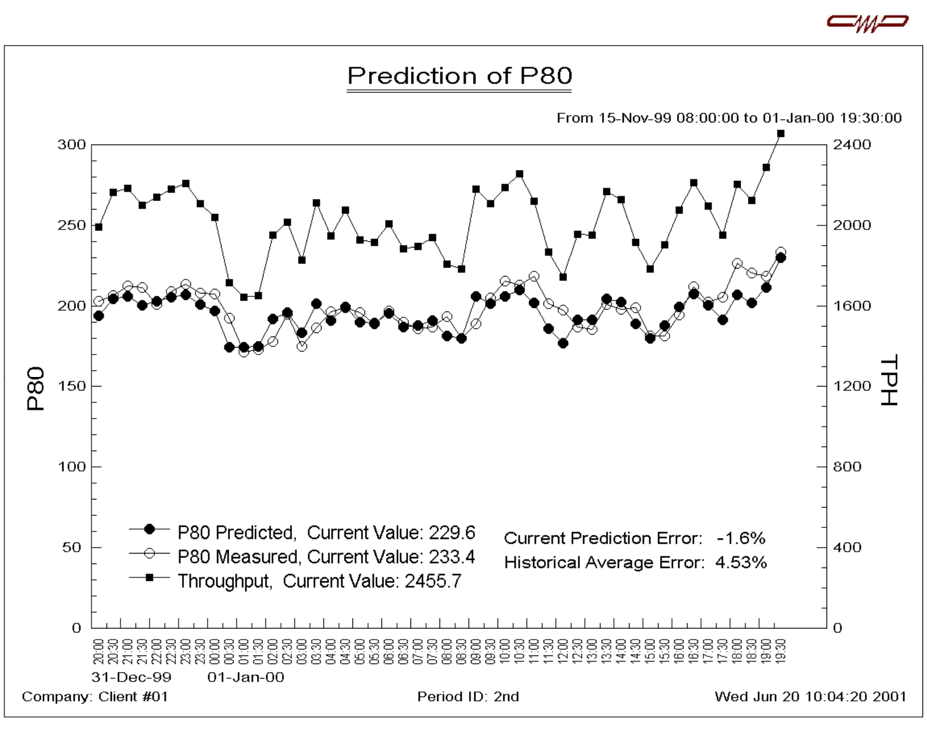

Figure 16. Prediction of P80