On the use of common statistical techniques to long standing issues in mining operations

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ABSTRACT

Modern day data historians provide an abundance of plant operational data. The 'mining' of that data, using statistical methods, may unearth valuable information about the process. Traditionally, instrument data has been thought to be too compromised by missing values, bad data or unreliable instrument response to the true underlying physical quantity to make this possible. Instruments, however, have become more reliable particularly so when the instrument itself no longer contains moving or wetted parts. Moreover, statistical methods enable graphical exploration of data, trends and interrelations, followed by detailed robust analysis even when faced with numerous missing data points. Two well-known methods are applied to three long standing issues in mining operations, first in isolation then, on the third issue, in combination.

Regression analysis is a common statistical technique well suited to determining representative pump efficiency of slurry pumps in operation over a wide range of load and wear states. Representative efficiency at the Best Efficiency Point (BEP) is calculated even if the pump never operated near its BEP. Factor analysis is applied to find the distribution of combinations of cyclones operating on a 14 cyclone battery. This distribution turns out to be strikingly skewed as opposed to the average number of cyclones open or closed which is flat. A variance-covariance analysis of such distributions brought to light a long forgotten feature of the cyclone gate valve control algorithm. The combination of regression analysis and factor analysis was found useful in deriving state and location dependent pipeline characteristics of a long concentrate pipeline.

INTRODUCTION

There are a number of long standing issues in mining operations that can potentially be resolved using the abundance of data archived in modern data historians coupled with common statistical techniques. The degradation of slurry pump performance by wear is such an issue. The real time pump efficiency as the ratio of electric pump power and hydraulic pump power is not a good indicator of pump condition. Since the pump is not always operating at the same point on its pump curve, the efficiency varies independent of pump condition or wear state. In this case the statistical technique of linear modelling can be applied to derive the shape of pump and efficiency curve from which the pump's Best Efficiency Point (BEP) can be found by interpolation, even if the pump has not actually operated at the BEP. The trend of BEP with time is a good indicator of pump condition. Trend analysis can thus be applied to effectuate preventive maintenance.

The distribution of slurry flow inside a cyclone battery's manifold is heavily influenced by the ordering of cyclones open and closed to flow. In a 10 cyclone battery operating with, on average, 6 open cyclones, the number of possible combinations of 6 out of 10 equals 210. Whereas cyclone gate valve control algorithms attempt to average out the hours of operation of each cyclone they do not usually take into account the ordering of cyclones open and closed. It is thus possible that some cyclones are presented with slurry of higher or lower density as the slurry starts to settle in the distribution manifold as a result of lower flow velocities. In this case the statistical technique of factor analysis can be applied to derive the relative frequencies of cyclones open and closed by their order on the manifold. Surprisingly, some combinations of cyclones open occur much more frequently and such observed combinations correlate to a high degree with the cyclone gate valve control algorithm. An improved control algorithm may thus be devised to more evenly distribute flow by different cyclone gate valve sequencing.

The hydraulic operating characteristic of a pipeline i.e. the relation of the hydraulic head and the flow rate (HQ curve) is dependent on the fluid density, pipeline length and trajectory through undulating land. In a case where the pipeline is long enough to hold batches of product of different density, it is no longer generally true that hydrostatic head loss is recovered. In mining operations with pipelines descending from mountainous areas to shore, it is common practice to reduce pipeline pressure by a varying number of flow chokes. Thus, the pipeline's characteristic HQ curve will be different for each choke valve combination. The pipeline may also be operated in gravity feed mode or pump assisted mode introducing a further dependency of the HQ curve on external factors. In such cases a combination of factor analysis and linear modelling can be applied to derive the pipeline's characteristic HQ curve for each possible combination of choke and pump settings. Knowledge of the HQ curve allows for more efficient pipeline planning and helps to maintain operation of the pipeline within safe limits.

METHODOLOGY

Although the concepts of statistical techniques are well known, the power of analysis of such techniques is unlocked only when an equally powerful software system is used. In this work the R system (R Development Core Team, 2012) is used. R provides:

- Effective handling and storage of data including missing data.
- Intuitive visualization, graphical facilities for data analysis and display.
- A coherent set of tools for data analysis.

- A simple and effective programming language.

This paper describes, from the wide array of statistical techniques available in R, the use of linear regression analysis, the use of factor and variance analysis and the combination of these two.

Representative pump efficiency by linear modelling

Slurry pumps wear, which results in degraded efficiency. Tracking the efficiency of a pump is complicated by the fact that a common baseline needs to be established. Hypothetically, if the pump were running at its Best Efficiency Point (BEP), tracking a representative pump efficiency is easy. In practice a pump seldom runs at its BEP. Because of varying load it may operate far off the BEP. Application of regression analysis results in the ability to infer the efficiency at BEP even when the pump has not been operated at BEP.

Pump curves by number of cyclones operating

For cyclone feed pumps the problem is exacerbated by the fact that the pump serves a battery of cyclones where the number of cyclones operating may vary over time. Thus not only the flow rate of the pump varies, also the system curve describing the loss of pressure with increasing flow varies. This is illustrated in Figure 1, where the battery pressure in psi is plotted versus the battery feed flow rate in gpm.

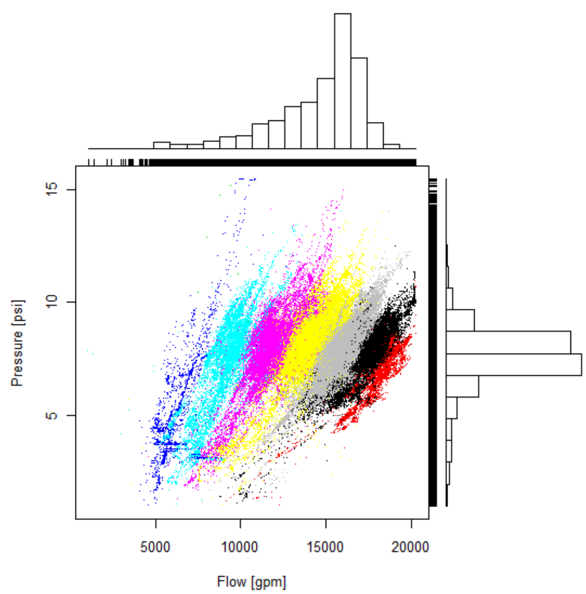

Figure 1 Pump curves by number of cyclones operating

Clearly the curves, when highlighted by colours to indicate the number of cyclones open on the battery, are similar but different. Since cyclones are operated in parallel, the flow resistance that the pump has to overcome drops when more cyclones are open. This is clearly visible, with 10 cyclones open (red) the flattest curve, 9 (black), 8 (grey), 7 (yellow), 6 (magenta), 5 (cyan) and 4 (blue) being the steepest with the highest resistance.

Dimensionless pump characteristics

Dimensionless numbers to characterize centrifugal pumps independent of size or type can easily be derived (Walshaw & Jobson, 1967). The interrelation between these dimensionless numbers is also well established (Van der Spek et al., 2009). By using the same pump data as shown in Figure 1, it is then easy to derive the four main characteristic curves of a pump. Figure 2 shows an example.

- The pump head curve, head coefficient C_H versus flow coefficient C_Q. This curve is either a straight line sloping down indicating loss of head with increasing rate of flow, or, with inclusion of pump frictional losses, part of an inverted parabola.
- The pump efficiency curve, pump efficiency η versus flow coefficient C_Q. The shape of this curve is dependent on the shape of the head curve but typically shows a maximum, which is identified as the pump's BEP.
- The pump power curve, pump power coefficient C_P versus pump speed coefficient C_S. This curve is always a straight line.
- The specific speed N_S versus pump speed C_S. By theory the specific speed varies inversely with the fourth power of the speed coefficient.

By regression analysis of the pump data from a period of 2 days, a best fit head curve (solid orange line, with the 95% confidence interval as dotted lines) is found. Likewise, the peak shaped efficiency graph can be fitted to a theoretical model, which immediately yields the BEP. Plotting this BEP point on the head curve shows it falls exactly on top of the head curve. Note that for any individual set of data at a certain number of operating cyclones (as indicated by colours) the pump was operating far off the BEP.

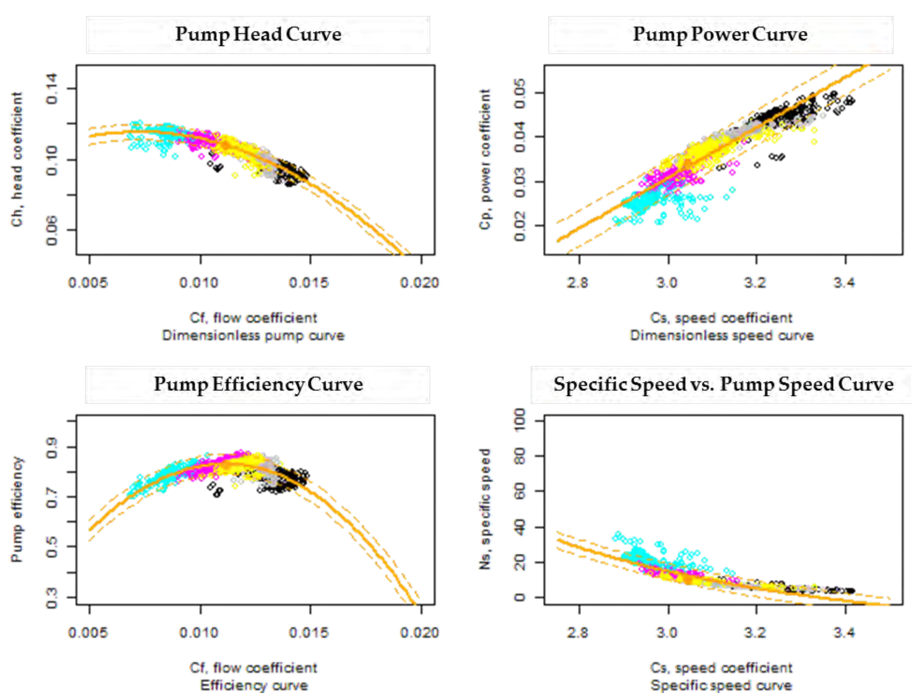

Figure 2 Four plots of pump performance

The last two plots on the right hand side provide a convenient check upon the regression analysis, which is applied only to the first two. The BEP is determined as the maximum of the efficiency curve and marked as such with an orange dot. The BEP can then be plotted on the head curve, the power curve and the specific speed curve, and it should fall within the dotted lines.

Ordering of operating cyclones by factor analysis

Cyclone battery gate valve control is usually set up to maintain constant battery pressure whilst distributing the utilisation of cyclones as evenly as possible in order to not wear out any particular one cyclone excessively. The particular combination of cyclones open is not a factor in the design of the control algorithm. The cyclone manifold, which distributes the feed flow over the cyclones open to flow, is necessarily of much larger diameter than the feed line. As a result, the flow slows down inside the manifold before it enters the individual cyclone's feed lines. The manifold is not usually equipped with baffles, strainers, vortex breakers or any other mechanism to influence the distribution of flow. Thus, the particular combination of cyclones open determines the flow pattern inside the manifold, which may lead to one or more cyclones being confronted with denser or less dense or coarser of finer material, depending upon the local fluid velocity inside the manifold. Whereas the average flow rate to each cyclone may well be constant, there is no guarantee that, on average, each cyclone is served the same density and coarseness of feed.

Counting combinations

By treating cyclone gate valve position as factors, it is possible to gain insight into the combinations of cyclones open during a, say, 2 day operating period. For a battery with 14 cyclones, with 10 cyclones open, there are 1001 different ways to distribute the flow inside the manifold.

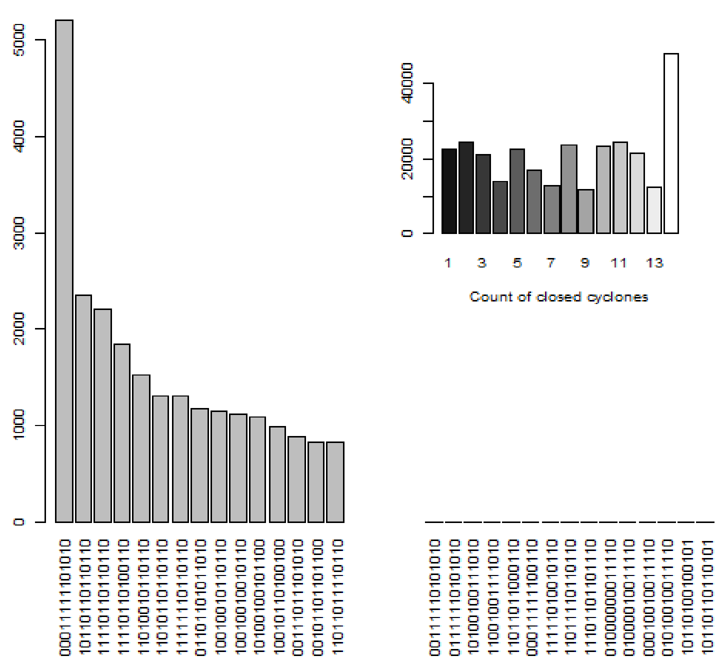

Figure 3 Cyclone combination counts

With varying number of open cyclones, the number of different combinations grows rapidly. It is therefore strange that some combinations of cyclones are much more likely to occur than others. Yet this is exactly what the factor counting shows in Figure 3. The inset graph shows that, on average, the gate valve control manages to evenly distribute the load over the 14 cyclones, each being as often closed as any other with the possible exception of cyclone #14. The distribution over certain combinations is, however highly skewed. The combination indicated by 0001111101010 occurs well over 5000 times in this 2 day period, more than two times more often than the next probable combination. Each digit position indicates a cyclone counting from 1 to 14, a '0' indicates a closed cyclone and a '1' an open cyclone. Because of the large number of possible combinations only the head (the left hand side) and the tail (the right hand side) are graphed. Note that the counted number of times that a combination occurs equates to the time that combination was in service as the data is taken from a historian, which exported the valve settings every minute.

Covariance analysis

The factor analysis can be taken one step further than simple counting of occurrences. Since for each combination of cyclones operating, battery pressure and battery feed flow are also at hand the variance in the relation between pressure and flow can be broken down by cyclone combination operating.

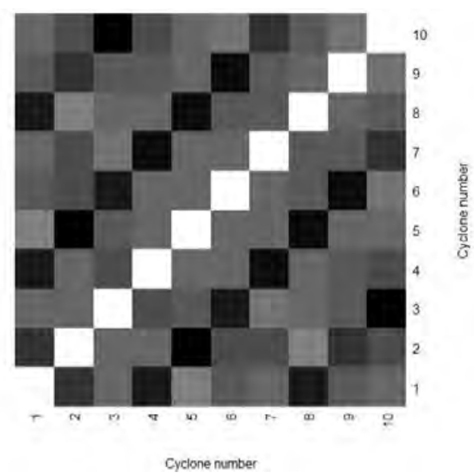

Figure 4 Covariances of cyclone combinations.

For a 10 cyclone battery the above 'checkerboard' plot (Figure 4) shows the variance scaled covariance i.e. the correlation coefficient of cyclone combinations graphically as a matrix of grey levels. Correlation coefficients range from +1 (white) to -1 (black). The appearance of side diagonals is a striking feature explained in this case by the gate valve control algorithm, which tries to open the next available cyclone skipping 3. Apart from lending belief to the factor analysis method the variance covariance analysis may be applied constructively as in to either randomize the distribution of cyclone open combinations or to enforce a certain pattern thought to promote a flow pattern in the manifold distribution box that equalizes density and coarseness of the individual cyclone feeds.

Pipeline characteristics

The hydraulic characteristic of a pipeline is of prime importance in operating the pipeline efficiently. Whereas for a water pipeline this characteristic is a plot of head (H) versus volumetric flow (Q), therefore named a HQ plot, for pipelines carrying concentrate or tailings the varying density in such pipes precludes the use of head. Instead pressure (P) and flow (Q) are used.

Correlating pressure and flow per station

A scatter plot matrix of pipeline flow rates and pressure at the start and end and all pressures at 9 Pressure Measurement Stations (PMS) is shown below in Figure 5.

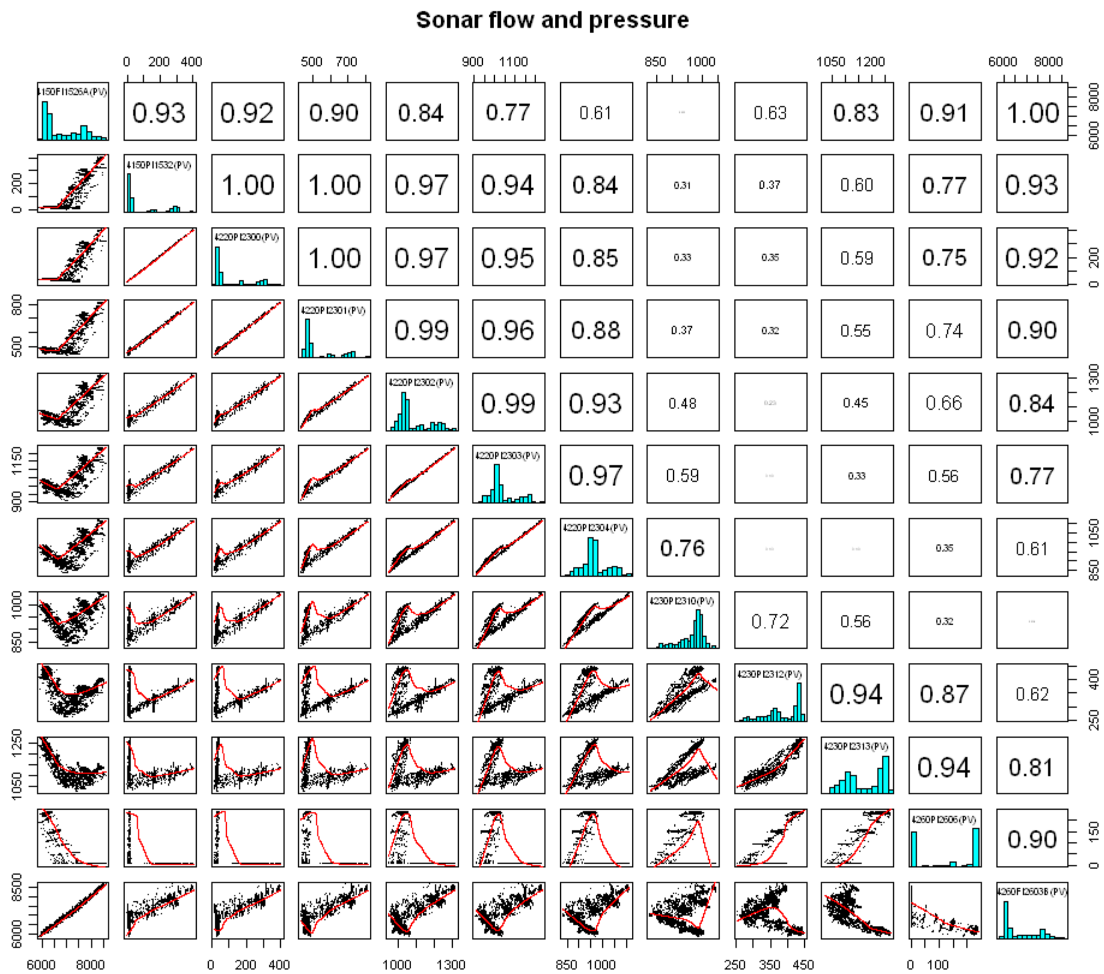

Figure 5 Pipeline flow and pressure scatter plot matrix

The scatter plot matrix lower triangle cross plots each measurement against every other. The main diagonal is a distribution histogram of values of that variable and the upper triangle prints the absolute value of the correlation coefficient between each. The first and last columns of the scatter plot matrix are the flow rate at the start and at the end of the line. All others are pressures at different PMS. The ordering is in the same sequence as on the real pipeline. At first glance this is a highly confusing plot because of all the V type correlation plots of pressures. Clearly, each distinct line indicates a different mode of operation of the pipeline, e.g. gravity fed, pump assisted, choke station fully open or one or more chokes operating. Splitting the data set by operating mode, much like the cyclone data, it is now possible to derive the pressure versus flow relationship for sections of the pipeline between PMS.

Derivation of the pipeline characteristic line per station

The pipeline's characteristic can be broken down by PMS and by pipeline operating mode. In Figure 6 below, the characteristic for each section between the PMS stations is given with colours of individual data points indicating the same operating mode. Overall the characteristic of the line is very similar, but in subgroups at PMS7 and PMS9 important details are being revealed.

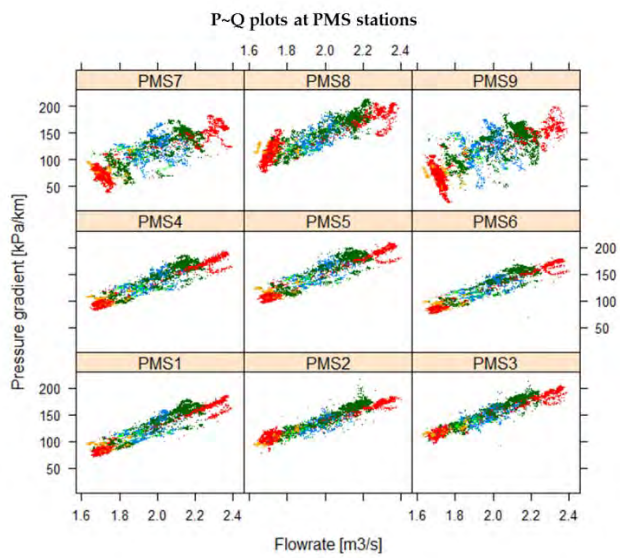

Figure 6 Pipeline characteristics by PMS

For PMS7 and PMS9 the red group at the low flow rate end rotates out of plane with the general trend of the characteristic. These are the uphill pipeline sections where in gravity fed operation the head dominates the characteristic line, leading to completely different but operating mode dependent local behaviour.

RESULTS AND DISCUSSION

A number of seemingly "impossible" results were obtained by applying well know statistical techniques to the abundance of data provided by modern day data historians.

- Representative BEP efficiency of slurry pumps can be tracked even if the pump never operated at BEP.

- The uneven distribution of operating cyclone combinations as opposed to individual cyclones requires flattening to help control the flow pattern in the battery's distribution manifold.
- A long concentrate pipeline's characteristic was found to be dependent on both location and operating mode.

Such insight into operations is extremely valuable and may lead to better product quality, lower maintenance cost and fewer process upsets. It is our belief that presently the data available in modern day historians is underutilized. With the advance in visualization techniques of statistical methods and with the availability of reliable instruments to populate the data historian, such as the non-invasive, array-based sonar flow meter with excellent long term stability, much can be learned and put to good practice in order to improve operations.

CONCLUSION

The combination of advancing statistical methods and the visualization thereof, the increasing reliability of measured data through the use of advanced instruments not subject to wear and tear, and the use of the abundance of data in present day data historians enables an unparalleled insight into mining operations.

ACKNOWLEDGEMENTS

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NOMENCLATURE

BEP	Best Efficiency Point
PMS	Pressure Measurement Station
CH	Head coefficient
CQ	Flow coefficient
CS	Speed coefficient
CP	Power coefficient
NS	Specific speed
η	Efficiency

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