Process Reliability and Six-Sigma

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National Manufacturing Week Conference
Track For Manufacturing Process and Quality

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Manufacturing.net

March 13, 2000
McCormick Place Complex
Chicago, IL

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Abstract
Reliability of manufacturing processes can be obtained from daily production data when process failure criteria are established. Results of the analysis are displayed on Weibull probability plots. Losses are categorized and identified for corrective action based on a demonstrated production criterion, which gives a point estimate for the daily production value. Concepts from six-sigma methodology are used to establish the effective nameplate capacity rating for the process. The differences between the nameplate rating and the demonstrated production are labeled as efficiency and utilization losses.

What's the concept of process reliability?
Process reliability is a method for identifying problems, which have significant cost reduction opportunities for improvements. It started with the question: "Do I have a reliability problem or a production problem?" The author has reviewed hundreds of processes and found only one that did not need significant improvements—thus the chance for finding a process not requiring improvement is very small. Sometimes the problems are identified with a root for maintenance improvements. Very often the problems have roots in the operations area.

The Weibull process reliability technique is a look down method. It uses a Weibull probability plot. Weibull plots, from the field of reliability, are well-known tools. Details about Weibull analysis are explained in an authoritative engineering book. (Abernethy 1998) The Weibull technique presents important facts as an engineering graphic which is useful for people solving business problems. On one side of one sheet of paper, the Weibull plot tells the story. Often the patterns displayed on Weibull probability plots are helpful for understanding the problem and give insight in the solution.

One-page summaries are very important for busy people—particularly managers. Managers always look down on the process from a high altitude, and they see matters differently than the line personnel. Line personnel always look up the process from a low altitude where the view is overwhelming from a maze of problems. The considerable different viewpoints of management levels, stresses both the organization and the people.

The hardest part of any reliability analysis is getting the data. However, process reliability techniques use data available at any plant---daily output of prime quantities produced. Production quantities are precursors for money, and thus restriction in output is very important for every profit driven operation.

The Weibull technique aids in solving business problems as the cost of **un**reliability for processes are important. The importance requires quantification of process reliability. Reliability is about making businesses better. Definitions are listed at the end of the paper.

The Weibull process reliability techniques help define a strategic course of action for making improvements. The look down technique provides opportunities for developing a strategy to solve problems. The method tells the nature of problems and quantifying the losses. Supplying details for each problem involves the tactics at lower levels.

Figure 1 shows a Weibull plot using production data from a troubled process. The probability plot is constructed using a common tool in reliability known as WinSMITH™ Weibull software. (Fulton 2000)

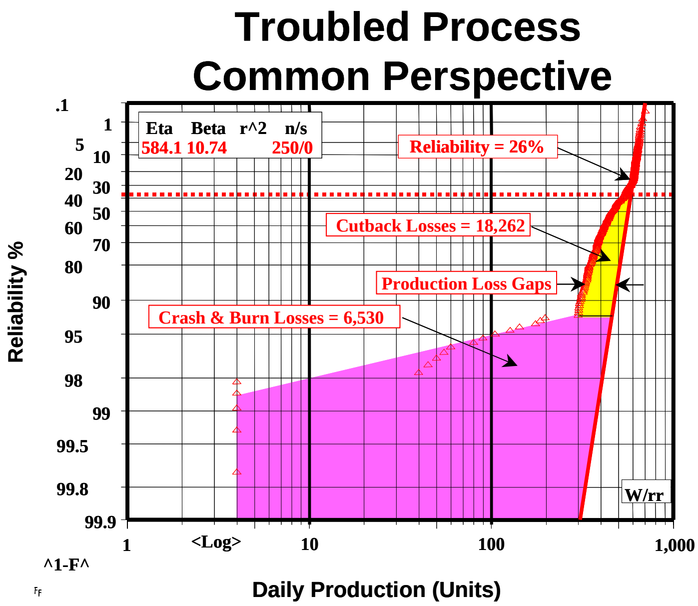

Figure 1: Example Of A Troubled Processes

The troubled process operates on a five-day per week schedule. During the one-year interval, the process could not operate for five days. Note the plot has 250 data points (5*52 – 10 = 250) as the plant had ten scheduled holidays—this is a view of convenience. The view in Figure 1 is based only on the data reported.

Notice the reliability of the process is defined at the point where the trend line, in the upper reaches of the production, began their losses at a cusp. A portion of the losses appear as cutbacks. Another portion of the losses appear as very severe problems characterized by a zone labeled crash and burn---both zones are associated with reliability problems. Figure 1 shows the process has a substantial reliability problem starting at ~26% reliability (finding this value involves both art and science and the answer is rarely the same exact value each time it is evaluated).

Figure 1, shows the cutback losses are 18,262 (for the zone between 26% and 92%), the crash and burn losses are 6,530 (for the zone between 63% and upward) for a total reliability problem of 24,792 units of production compared to the total output of 113,915 units. On a Pareto basis, the major reliability problem is cutbacks in output for Figure 1.

Also notice the five down days are plotted as a “small” number reflecting zero output---this ploy is used as zero values cannot be plotted on the Weibull probability plot’s logarithmic scale. Typically a value is selected 1/100 (two logs smaller) of the smallest actual production value recorded as representing zero--thus errors in the cumulative output are small. However, for presentation purposes here, the value is selected, as 4 so the extra decade of log values on the chart are not shown.

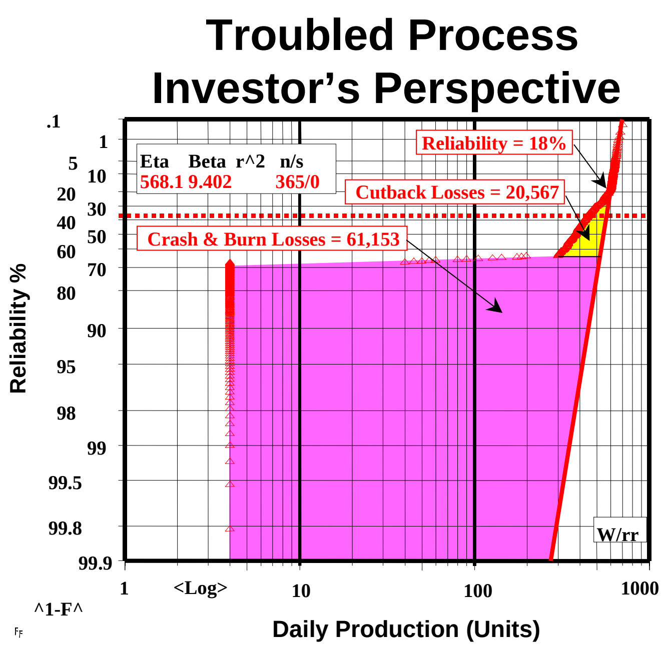

Figure 2: A Troubled Processes—2nd View

Figure 2 shows a production Weibull plot from the investor’s viewpoint, requiring accountability for 365 days of output.

From Figure 2, the cutback losses are 20,567 (for the zone between 18% to 62%), the crash and burn losses are 61,154 (for the zone between 62% and upward) for a total reliability problem of 81,721 units of production. compared to the total output of 114,415 units (remember the zero output is shown at 4 units and thus the slight increase in total output for Figure 2).

On a Pareto basis, the major reliability issue is a crash and burn problem from an idle plant only running on a 5-day per week schedule. This represents a substantial change in outlook compared to Figure 1.

The view from Figure 2 is preferred compared to Figure 1 because it avoids the provincial outlook of running a gentleman’s plant, and it incorporates the investor's viewpoint. However, a better datum (benchmark) is needed for judging the plant. Next, compare results of the troubled plant with a high performance facility without reliability problems.

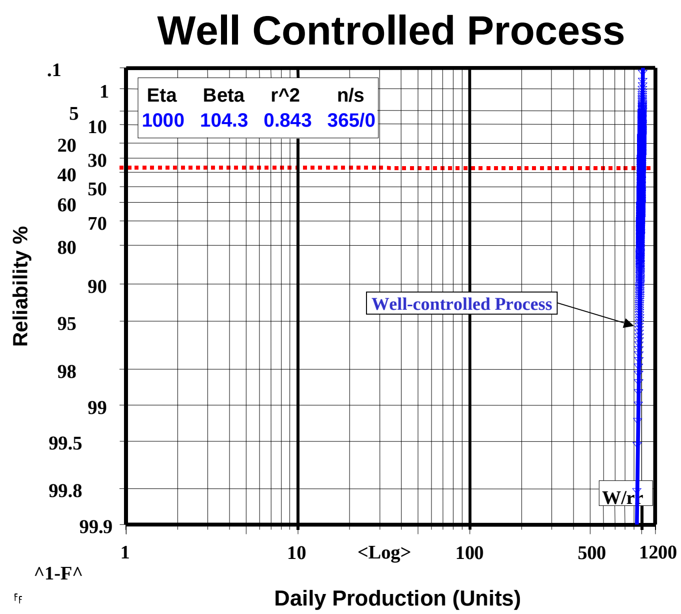

Figure 3: Examples Of Well Controlled Processes

Consider the results for two similar processes with essentially the same equipment and process capability as shown in Figure 3. The trend line shows a well-controlled production process (not best in class but very good), and it operates around the clock without problems.

In Figure 3, the well-controlled process does not have a reliability problem—i.e., no cusps on the trend line and the data closely fits the steep straight line on a Weibull plot. The well-controlled process has a demonstrated capacity of 1000 units per day as the single figure best representing a "stretch goal" for output, and this occurs at the demonstrated production value (eta) identified on the dotted line. For this case the well-controlled process has small output variation, which makes it very reliable and very predictable.

Also notice the difference in the patterns between a troubled data set of Figure 2 and a well-controlled data set shown in Figure 3—both are shown on a 365-day period. The patterns, cusps, and slopes of the trend lines provide some insight into the problems and how to resolve them. The well-controlled process has small variability in output, which is a desirable feature for six sigma considerations.

How were the probability plots made for Figures 1-3? Daily production data was used with a software package. (The data can be plotted by hand on Weibull graph paper although this is a slow and tedious process.)

The software sorts and ranks the data from low to high (time sequences are not maintained as the data is perceived to originate in a black box), and production quantity information is used for the abscissa, which is plotted on the log-scale. The method uses a statistical tool called median ranks plotting position for the Y-axis—specifically Benard's median rank method (which is described by Abernethy) to give the Y-axis position. Thus a X-Y point is found and plotted.

The Y-axis on a Weibull plot is the log of another log, which causes the unusual spacing of the percentage lines. Notice the Y-axis divisions are such that the data in the lower left hand zones are magnified—this is the troublesome area usually requiring improvements in manufacturing operations.

Please note that zero values for days when no production occurred cannot be plotted on a log scale, thus the ploy of using a "small" number such as two decades (two logs) less than the least real production values is used—this causes the stack of data at 4 units for the troubled process representing the 120 days of zero production. This is 32.76% of the total days available (based on Benard's median rank) or as shown on the Y-axis it is the compliment of 100%-32.76% = 67.33%.

Weibull lines (details for the equations are given in Abernethy's book) are defined by two statistics:

1) **Beta** is the slope of the line. For production data, steeper is better which means large values of beta are valued over small values for beta, and

2) **Eta** is the characteristic value at the reliability value of 36.8% or the complement for the cumulative distribution function (CDF) is 100%-36.8% = 63.2%. For production data, larger values of eta are valued over smaller eta values.

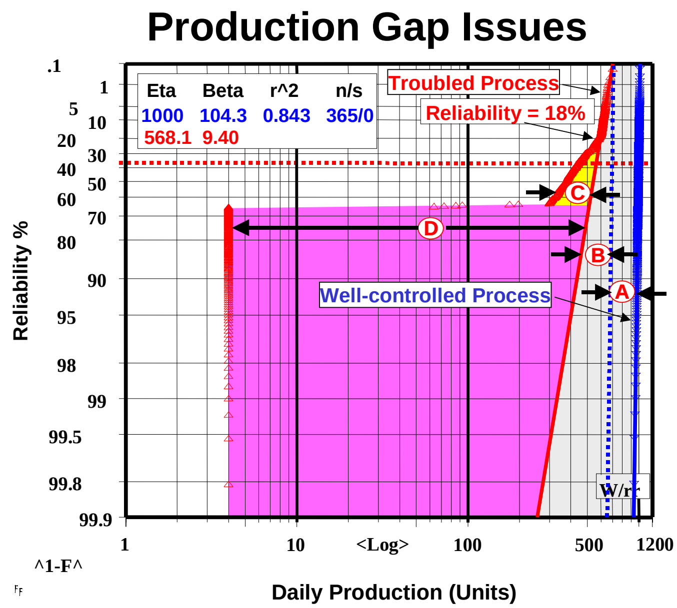

Figure 4: Production Gaps Between Two Processes

Data from Figure 2 and Figure 3 are plotted together on the same probability plot in Figure 4. The gaps between the lines and data points will quantify the type of losses as shown in Figure 4. Each gaps in production is an opportunity for improvement. Figure 2 shows the gaps in production between the two processes with typical identification of the zones.

Notice the difference in patterns between a troubled data set and the well controlled data set on the probability plot in Figure 4. The gaps between the lines and data points will quantify the type of losses.

Zone **A** identifies the utilization gap between the well controlled and a troubled process. The troubled process operates two out of three shifts each day. The gap between the actual production for the well-controlled process with beta = 104.3 and eta = 1000 and the trend line passing through the highest production point for the troubled process has a beta = 104.3 with and eta = 678.4. For 365 days, the losses are 116,732 units.

Zone **B** is an efficiency gap between the well-controlled process line drawn through the highest production point to give beta = 104.3 and eta = 678.4 and the troubled process trend line with beta = 9.40 and eta = 568.1. For 365 days, the efficiency losses compared to the well-controlled process are 49,520 units.

Zone **C** is a cutback gap from reliability problems. It extends from ~18% to ~62% and accounts for 20,567 units lost.

Zone **D** is the "crash and burn" problem associated with severe outages and decisions to operate on a five-day operation. The gap between the trend line for the troubled process, and the actual production (from ~68% to ~99.9%) accounts for 61,154 units lost.

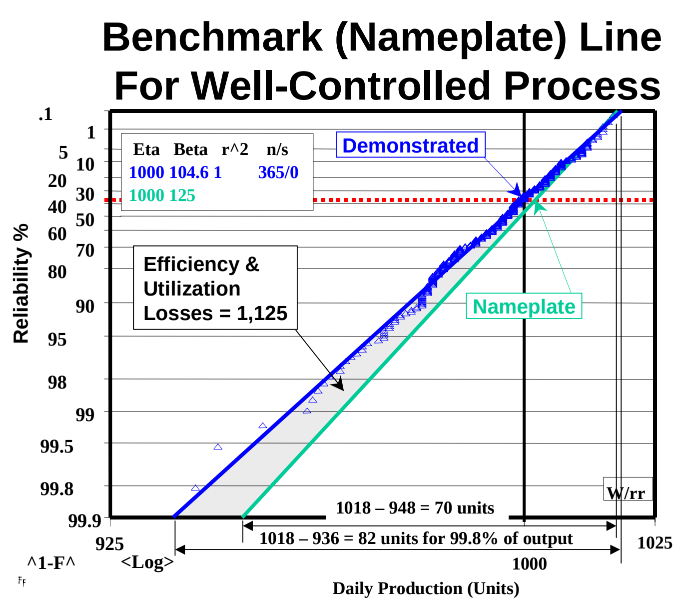

Figure 5: Benchmark With Losses Identified

The well-controlled process produced 363,015 units in 365 days compared to the troubled processes output of 114,415. This is an overall production gap of 248,600 units between the good and not so good process.

Even the well-controlled process needs a datum for benchmark purposes. The benchmark line is shown in Figure 5. The nameplate capacity line is drawn through the maximum output with a slope that is achievable by world-class plants of best in class. The nameplate trend line has a slope of beta = 125. The efficiency and utilization losses are labeled in Figure 5 as 1,125 units of production. The nameplate capacity line always lies to the left of the demonstrated production line. The same nameplate capacity line applies to the troubled process, which has the same installed capacity.

Demonstrated production and nameplate capacity points identified on Figure 5 are point estimates for the distribution. Point estimates are identified at 36.8% reliability because Weibull distributions have important mathematical properties at this point. These points are also stretch goals for production facilities whereby 63.2% of the production will be less than the demonstrated or nameplate point estimates.

Note the X-axis scale in Figure 5 has been expanded to illustrate the small losses for this process—using the X-axis scales from the previous plots would have only shown a hairline zone. Also note on Figure 5 the Y-axis represents almost the traditional six sigma range, i.e., 99.9% - 0.1% = 99.8% compared to the conventional six sigma representation of 99.73%. Furthermore the intercept of the demonstrated line and the nameplate line show the scatter expected in the output along the X-axis.

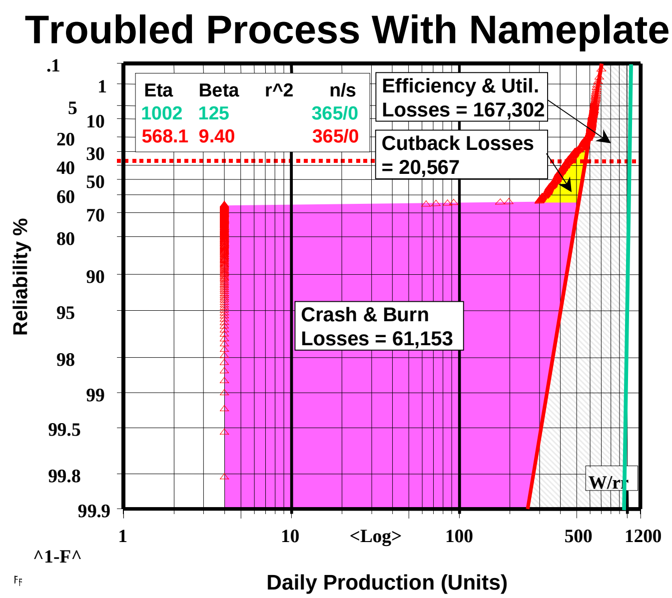

Figure 6: Troubled Process With All Losses Identified

Figure 6 shows the troubled process with the nameplate line. When the equations of the lines are defined by Weibull analysis, the production losses in each gap can be quantified with the amount of production lost. Notice how the problems have changed from Figure 1. The Pareto ranking of problems now shows:

1. Efficiency/utilization losses = 167, 302 units
2. Crash and burn losses = 61,153 units
3. Cutback losses = 20,567 units

Since production units are a precursor for money, the gaps from losses can be converted to currency values for deciding if proposed remedies are affordable. Why establish a Pareto distribution as shown from Figure 6? It is common for people to focus on trivial matters rather than on important issues. Yes, the troubled process does have a reliability problem as identified by a new technique, but it is small compared to the idle plant problem regarding utilization issues.

The reliability problem (associated with the cutback category) is not the first issue to resolve—the primary issue for resolution is low utilization of the process. Utilization is a management effectiveness issue. Effectiveness is the accomplishment of a desired objective (i.e., cut the losses so gross margins are improved and return on the investment is increased for stockholders).

The problems identified and ranked correctly in Figure 6 would not have been discovered without a datum for comparison, i.e., the nameplate capacity line. Consider how the problems of the troubled process vary depending upon the perspective shown in Table 1:

Table 1

Troubled Process's Perceived Problems Viewed On An Annual Basis				
Problem Category	Figure 1	Figure 2	Figure 4	Figure 6
Efficiency and utilization			166,252	167,377
Crash and burn	6,530	61,154	61,154	61,154
Cutback	18,262	20,567	20,567	20,567
Total losses (units)	24,792	81,721	247,973	249,098

Note the losses from Figure 6 exceed the annual production by 249,097/113,915 = 2.18. This is a large factor with great opportunity for improvement. It is important to convert lost units into money to generate action. For example, if the lost margin on each item is say $100, it is easy to convert nose counts of problems into actionable items to clearly explain which problem should be resolved first—fix the big money problems first!

Six-Sigma Issues And Weibull Process Analysis

Weibull process reliability analysis complements and extends the six-sigma techniques. Six-sigma techniques are concerned about time sequences of data. Weibull analysis looks at the output in a random manner where time sequence of data is not so important. The methods are different—but complementary.

The process reliability issue (in Deming fashion) is: Improve production output predictability by decreasing production output variations ⇨ Increase output by solving low output problems while decreasing costs ⇨ Make more profits ⇨ Take more orders as the low cost producer. The push for six-sigma considerations is a call for making six-sigma projects demonstrate meaningful changes at the top level where output can be measured and viewed in a meaningful way. This requires many details in the process must be carefully controlled to see tight control in output of the final product quantity.

The thrust of six-sigma is to control and reduce variations. This is also the thrust of Weibull process reliability analysis. The Weibull process reliability issue is to identify problems (and problem patterns), solve problems to reduce losses, and get processes under control. The major item identified above is to fractionate the problem into understandable categories so the problems are identified for important work priorities to reduce scatter-causing losses and to get the production process under control.

Shewhart, the father of six-sigma techniques, defined control as "…a phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future." (Shewhart 1931) Shewhart went on further to describe two patterns of variations, 1) "…unknown cause of a phenomenon will be termed a chance cause." these are difficult to find and eliminate, and 2) "…assignable causes of variation may be found and eliminated." these are easier to see and eliminate than variations because of chance events. Shewhart was not implying wide variation in control was acceptable.

Both conditions of chance variation (associated with slope of the lines on probability plots) and assignable cause variation (associated with translations of the lines on probability plots) are seen in the figures previously described. Steep data trend lines shows evidence of small chance events at work. Flatness of the data trends shows evidence of larger chance events at work. Cusps on the curves and trend line translations (to the left) show assignable causes at work.

Deming points out that without statistical control, the chaos of the system mask effects to make improvements and "With statistical control achieved, engineers and chemists became innovative, [and] creative. They now had an identifiable process." In the war against waste and hidden factories which butcher the output, Deming also says "We in America have worried about specifications: meet the specifications. In contrast, the Japanese have worried about uniformity, working for less and less variations about the nominal value…". (Deming 1986). Less variation shows steeper curves on Weibull probability plots. The substance of Weibull process reliability plots is to employ another tool to help identify and correct the problems and reduce losses not resolved by traditional tools. Traditional distribution curves for six-sigma process are usually bell-shaped and symmetrical. Weibull curves for production data are skewed.

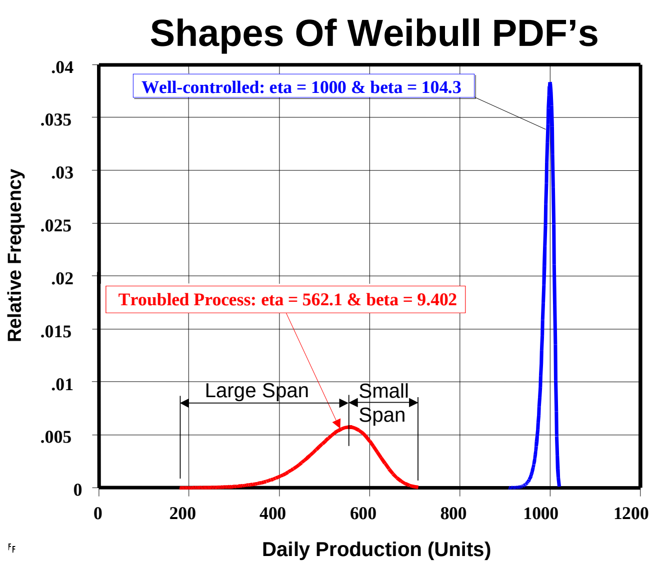

Figure 7: Shapes Of Weibull Curves

Weibull probability distribution curves, PDF, with steep betas show a relative distribution of production output, which is believable by production personnel. Weibull PDF curves, with their skew, show limits to higher levels of production but emphasizes greater chances for lower production—this is the case in most production facilities.

Look at Figure 7 to see the range of output either side of the peak. Also note the well-controlled data demonstrates Deming's idea about tight control of the outcome from production processes.

Non-symmetrical Weibull distributions are recognized as a universal law linking many scientific situations. The non-symmetrical concept appears useful in areas as diverse as turbulence, magnetic characteristics, mineral deposits, floods, land slides, species in ecosystems, self-similarity of vegetation, insurance losses, avalanches, earthquakes, and other issues associated with the edge of chaos which revolves around identifying patterns in apparently unpredictable sequences of events as described by Peel. (Peel 1999) These non-symmetrical, non-linear, concepts also fit the emerging science of complexity explaining many self-organizing events such as manufacturing processes, which can be explained with a few top down rules.

Processes with Weibull betas between 5 and 30 are very common and represent great opportunities for improvement. Processes with betas between 30 and 75 are less prevalent and have some opportunities for change.

Processes with Weibull betas more than 100 are important. They are models for six-sigma considerations. The author sees a few percent of processes exceeding 125. The current king-of-the-hill process proudly has a beta exceeding 250! The interesting thing about identifying process problems and making a concerted effort to improve process predictability: solving reliability problems results in a substantial personal and business growth event.

Action Items In Summary

Processes vary from the simpler systems of producing and delivering water to complex systems for producing and delivering complex chemicals and every thing in between. Process reliability is important for manufacturing processes to assess the health of the system and maximize gross profits. Seldom is process reliability quantified and controlled for maintaining the health of the money machine (i.e., the process). The very act of quantifying process reliability often uncovers other substantial problems as noted above.

Some processes are discrete, others are continuous—the Weibull process reliability technique works for both. For most manufacturing companies, the key process issues are how well are the production systems functioning and being utilized to generate cash, and what are the production quantities as precursors for gross profits—since more output is better.

Consider the process as viewed from a top down perspective from say 65,000 feet elevation and view the process as a black box. Look at the production output using Weibull techniques for analyzing both output and reliability from the black box. This top down view produces specific patterns on Weibull plots for understanding process reliability and other features important to manufacturing operations. Most production data will produce a straight line or series of straight-line segments on a Weibull plot. Abernethy suggest using the customary pragmatic concepts of Weibull analysis, if the data gives a straight-line plot on Weibull probability paper, it is a satisfactory fit to a Weibull distribution.

Cusps, on the Weibull straight line, identify reliability problems, which must be resolved. Likewise when the Weibull line is translated to the left toward smaller output and away from the nameplate capacity line and this identifies production problems. This is a refined method of gap analysis. The production gaps can be quantified first in terms of production quantities (a precursor for money) and second in terms of lost gross margin money. Also remember the data in Figures 1 and 6 involve a time frame of one year.

Do not lose the point that lost production must be converted into lost money! Money and time are understandable to everyone! Both money and time are actionable items outside of the range of technical talk. Money and time are the language of commerce, and if you want to sell your technical improvements you must be a salesperson and show the problem and solutions in terms of money and time. Frankly, the individuals with their hands on the moneybags are not interested in your intriguing technical explanations because they’re only concerned with money and time.

Of course the Weibull process reliability technique has identified the problem from a high altitude. Next is a requirement for a lower altitude search in asset utilization databanks to find where the localized problems are centered—do not focus on the nose count problems but focus on the financial results. (Ellis 1998)

Finally a good root cause analysis program helps in permanently removing the problem by a study of cause/effects using a structured program with the understanding that each effect has at least two causes in the form of actions and conditions. (Gano 1999) Weibull process reliability analysis helps to define the problem, which is the first step in performing an effective root cause analysis. Likewise the Weibull process reliability analysis provides the evidence needed for root cause analysis. The Weibull process reliability problem tells where to look for problems and provides the magnitude of the problem----it does not solve the problem for you--this requires blood, sweat, and tears.

Here are proven areas to evaluate for reducing variations and increasing production output:

- Look for fast and efficient changeovers in your process for maximizing output time while minimizing lost time, to increase productivity and profits.
- Consider your supply chain for materials to arrive on time without delays to the process and also remember that product produced must be shipped to avoid production halts.
- Make the process mistake-proof so scrap is eliminated and output-robbing problems are eliminated for reducing waste and process delays.
- Invigorate your people for solving local problems to avoid global difficulties, which restrict output and make the process unpredictable thus guaranteeing lower output.
- Build process reliability as a measurable concept for using a new tool to ferret out problems to the system to solve old, nagging, problems to reduce losses and increase profits by making the process more reliable.
- Identify the problems requiring resolution by monetary value (not nose counts of problems) and solve the most important problems first—some problems may require management actions, other technical action, and so forth.
- Do not underestimate the value of graphics, such as the Weibull probability plot, to enlighten the manufacturing team so they can identify problems, make corrections, and solve problems efficiently---production people are straightforward, logical, and visual: No “cartoons” to explain the situation—No comprehension of the problem!

Definitions

Crash and burn output: A euphemism for seriously deficient production quantities during periods of substantial process upsets or deteriorations.

Cutbacks: A production quantity recorded during a period when output is restricted by partial failures resulting in a slowdown from the intended/scheduled production rate. The zone is often characterized by a cusp at either end of the zone on a Weibull plot.

Demonstrated Weibull production line: A straight-line trend in upper reaches of the Weibull probability plot defining “normal” production when all is well—as quantities deviate from this segment, failures occur (by definition) because the process loses it’s predictability.

Demonstrated capacity: A single “talk about” number at 63.2% CDF or 36.2% reliability which best represents a “stretch goal” for production output.

Efficiency/utilization losses: The difference between the nameplate capacity and the demonstrated Weibull line; generally a result of efficiency losses or under-utilization of the facility.

Nameplate capacity: a) For a single piece of equipment, it is the maximum production capacity of the equipment under ideal operation and control as described by process planners or supplier of the equipment. b) For a process comprised of many different components of equipment it is the maximum production capacity of the factory under ideal operation and control as provided by the site contractor that designs and constructs the factory.

Pareto principle: A few contributors are responsible for the bulk of the effects—the 80/20 rule whereby 10% to 20% of the things are responsible for 60% to 80% of the impact. Named for the Italian economist Vilafredo Pareto (1848-1923) who studied the unequal distribution of wealth in the world and by Dr. Juran who described the Pareto concept as separating the vital few issues from the trivial many issues.

Processes: Processes are collections of systems and actions following prescribed procedures for bringing about a result. Using a set of inter-related activities and resources to transform inputs into outputs often uses processes for manufacturing saleable items.

Production losses: The difference between the demonstrated Weibull line and the actual production data point associated with the same % CDF.

Process reliability: The point on a Weibull probability plot where the demonstration production line shows a distinct cusp because of cutbacks and/or crash and burn problems.

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BIOGRAPHY:

Paul Barringer is a manufacturing, engineering, and reliability consultant with more than thirty-five years of engineering and manufacturing experience in design, production, quality, maintenance, and reliability of technical products. Experienced in both the technical and bottom-line aspects of operating a business with management experience in manufacturing and engineering for an ISO 9001 facility. Industrial experience includes the oil and gas services business for high pressure and deep holes, super alloy manufacturing, and isotope separation using ultra high speed rotating devices.

He is author of training courses: **Reliability Engineering Principles** for calculating the life of equipment and predicting the failure free interval**, Process Reliability** for finding the reliability of processes and quantifying production losses, and **Life Cycle Cost** for finding the most cost effective alternative from many equipment scenarios using reliability concepts.

Barringer is a Registered Professional Engineer, Texas. Inventor named in six U.S.A. Patents and numerous foreign patents. He is a contributor to **The New Weibull Handbook**, a reliability text, published by Dr. Robert B. Abernethy.

His education includes a MS and BS in Mechanical Engineering from North Carolina State University. Participant in Harvard University's three-week Manufacturing Strategy conference.

For other issues on process reliability refer to the Problems Of The Month at http://www.barringer1.com.

February 7, 2000