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DPBO – A NEW CONTROL CHART FOR ELECTRONICS ASSEMBLY

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ABSTRACT
As six sigma (6σ) and better processes are demanded for higher yields and as organizations move from measuring defects in terms of parts-per-million (ppm) towards parts-per-billion (ppb), the resolution of extant control charts is becoming insufficient to monitor process quality. This work describes the development of a new statistical process control (SPC) chart that is used to monitor processes in terms of defects-per-billion-opportunities (dpbo). A logical extension of the defects-per-million-opportunities (dpmo) control chart, calculations used to derive the dpbo control limits will be presented and examples of in-control and out-of-control processes will be offered.

Key words: statistical process control, SPC, dpmo, dpbo, attributes data, ppm, ppb

INTRODUCTION

Long before Motorola made the term "six sigma" a buzzword in many industries, companies have strived to track their defects and improve their processes. Statistical process control (SPC) charts, developed by Shewhart dating back to the 1930s (see Shewhart (1931) for example) are useful for two purposes: 1) as a watchdog, an SPC chart can determine if a process is in-control; 2) data plotted on an SPC chart – particular for *variables types* of data (data that are measured on a continuous scale) – can be used as estimates for process parameters. For example, the centerline of a an *Xbar* chart can be used as an estimate of the process mean and the centerline of an *R* chart (or of an *s* chart) can be used to derive an estimate of the process standard deviation. For variables data, these estimates of mean and standard deviation can be used in process capability formulas such as C_p, C_{pk} and others to determine process yields (see Besterfield (2008) or Montgomery (2005) for more details).

When the types of data that are collected can be measured in discrete counts (such as the number of defects of a certain type (e.g., solder shorts on a PCB) or the number of bad printed circuit boards produced in a lot), then *attributes* control charts become appropriate for use.

The new SPC chart described in this work falls under the category of attributes control charts. The following is a list of the commonly used attributes control charts (others do exist) and a description of problem types for where their use is appropriate:

- *p* chart – assesses the proportion defective and is used in the situation in which the entire product is considered to be good or bad. Per period in which the data are taken, subgroup sizes are greater than 1.
- *q* chart – assesses the proportion good parts, is also used in the situation in which the entire product is considered to be good or bad; it is the complement of the p chart. Subgroup sizes are greater than one.
- *np* chart – assesses the number of defective parts in a subgroup. This is a scaled version of the p chart where "n" is the subgroup size.
- *c* chart – assesses the number of defects per part (i.e., each part can have multiple defects). In each period of which data are collected, only one item is inspected (i.e., the subgroup size is 1).
- *u* chart – similar to the c chart, but is used for situations where the subgroup size is greater than one in each period.

The *c* and *u* charts are utilized when a product can have multiple defect opportunities. Consider a printed circuit board for example. The PCB can have solder defects, could have missing components, could have components misoriented, etc. If the interest is in determining what the total number of defects per PCB is, then the use of a *c* or *u* chart – depending upon sample size per period – would be appropriate. On the other hand, if we were only interested in determining if, as a whole, the PCB was "good" or "bad", then the use of the other charts (*p*, *q*, *np*, and other variations not discussed herein) would be appropriate.

Traditional control charts were developed in an era in which products were not as complex as they are in today's age. Taking the electronics industry as but one example, some products (e.g., printed circuit boards (PCBs)) have thousands and others have even tens of thousands of opportunities for defects. When it is of importance to accurately track how many defects that occur per product (as opposed to just making a determination if the entire product is "good" or "bad"), the increased complexity of today's products drives the need for new control charting techniques.

Relatively recently, a new control chart (not the even newer one which is the focus of this paper) was developed primarily for use in electronics manufacturing. This control chart is the defects per million opportunities, or *dpmo* chart. One of the first references for the *dpmo* chart is an electronics manufacturing application by Ngo (1995).

A Packard Bell researcher has suggested (Revelino, 1997) that "world-class" in electronics manufacturing would drop so much that defect levels will eventually be referred to in parts-per-billion (*ppb*). In fact, it was in part due to this statement that the defects per billion opportunities (*dbpo*) control chart was inspired.

DPMO AND DPBO CONTROL CHARTS – EXTENSIONS OF THE U CHART

The reader familiar with SPC calculations and the *dpmo* chart will realize that it is a chart that is used when it is of interest to keep track of the total number of defects per product. As such, it is an extension of (i.e., the control limits and plot point calculations are modifications of) the *u* chart as referred to above.

U Chart Calculations

In order to understand the calculations of the new, *dpbo* chart, it is of interest to show the calculations of first the *u* chart and then the *dpmo* chart.

For the *u* chart calculations, we need to define the following:

- k = number of subgroups
- n_i = size of subgroup i ($i = 1, 2, \ldots, k$); subgroups are typically constant, but may be allowed to vary
- c_i = count of defects in subgroup i ($i = 1, 2, \ldots, k$)

Given the above, the point to plot on this chart is the average number of defects per unit, typically denoted as u_i, and is calculated per each subgroup, i, as follows:

$$u_i = \frac{c_i}{n_i}$$

Once all subgroups are gathered, the centerline for the *u* chart is $\bar{u}$ and is calculated as follows:

$$\bar{u} = \frac{\text{total defects found in all subgroups}}{\text{total number of items inspected}} = \frac{\sum_i c_i}{\sum_i n_i}$$

Now that the centerline is established, the control limits can be calculated. As in other control limits, they are ±3 standard deviations of the process output. As process output for defect counts is assumed to follow a Poisson distribution (refer to Montgomery (2005)), the control limits are the following:

$$\bar{u} \pm 3\sqrt{\frac{\bar{u}}{n_i}}$$

DPMO Chart Calculations

In order to understand the calculations of the new, *dpbo* chart, it is of interest to show the calculations of first the *u* chart and then the *dpmo* chart.

One of the first references to the *dpmo* chart can be found in relation to an electronics manufacturing application by Ngo (1995). Although this reference is more than a decade old, most recently published quality control textbooks (see Montgomery (2005), DeVor et al. (2007), and Besterfield (2008) for examples) still do not include the *dpmo* chart in their review of attributes control charts.

The *dpmo* chart is particularly useful in the monitoring of electronics manufacturing operations or any other process that has products with large numbers of defect opportunities. For another practical application of the *dpmo* chart, see Santos et al. (1997) and see Yepez et al. (2008) for other SPC applications for electronics manufacturing. As electronics products become more complex, the number of defect opportunities per product has increased tremendously in recent years. Electronics products (e.g., backplanes, complex motherboards for server systems, etc.) can have as many as thousands of opportunities for defects per circuit board. The defects can be traced to improper solder joints (potentially thousands on a PCB), missing components, improperly placed components, and others.

Just as the *np* chart is a scaled version of the *p* chart, the *dpmo* chart is a scaled version of the *u* chart. The *u* chart assumes a few defect opportunities per product, but the *dpmo* chart assumes there are a substantial number of defect opportunities per product.

In order to calculate the control limits for the *dpmo* chart, we need to define the following:

- k = number of subgroups
- n_i = size of subgroup i ($i = 1, 2, \ldots, k$); subgroups are typically constant, but may be allowed to vary
- c_i = count of defects in subgroup i ($i = 1, 2, \ldots, k$)
- Number of defect opportunities per product (1)

Given the above, the average number of defects per unit, dpu_i, is calculated per each subgroup in a similar fashion as the plot points for the *u* chart. However, dpu_i, shown (2) below, is not the plot point for the *dpmo* chart:

$$dpu_i = \frac{c_i}{n_i}$$

The plot point for this chart is $dpmo_i$, for each subgroup, i. The plot point is found by the following calculation which is a scaled version of the number of defects per unit provided in reference to one million defect opportunities:

$$dpmo_i = \frac{dpu_i}{\text{number of defect opportunities}} \; x \; 10^6$$

Once all subgroups are gathered, the centerline for the *dpmo* chart is $\overline{dpmo}$ and is calculated as the average of all the *dpmo* values as follows:

$$\overline{dpmo} = \frac{\sum_i dpmo_i}{k}$$

Now that the centerline is established, the control limits can be calculated. The control limits for the *dpmo* chart will also be based upon the Poisson distribution as the purpose is to still measure defect counts which are assumed to be distributed in a Poisson fashion; but, as expected, the *dpmo* chart limits are a scaled version of the *u* chart's as follows:

$$\overline{dpmo} \pm 3\sqrt{\frac{\overline{dpmo}\ x\ 10^6}{n_i x\,(\text{number of defect opportunities})}}$$

And the above can be simplified to the following:

$$\overline{dpmo} \pm 3000\sqrt{\frac{\overline{dpmo}}{n_i\ \ x\,(\text{number of defect opportunities})}}$$

DPBO Chart Calculations

It may be obvious to the reader that the *dpbo* chart represents yet another scaling of the *u* chart. In this case, and keeping in line with the earlier statement by Revelino, the scale/resolution of a *u* chart is just too large to be of practical use for dealing with defect levels at six sigma or beyond (i.e., very low defect levels with applications that have high opportunities for defects). Like the *dpmo* chart, the *dpbo* chart is of benefit to the variety of manufacturing operations that have products with very large numbers of defect opportunities such as the multitude of organizations in the various levels of the electronics packaging industry – from Level 0 (semiconductor fabrication) through Level 2 (printed circuit board assembly).

Aside from a new variable, $dpbo_i$, the variables in this chart are the same as those appearing for use in the *dpmo* chart discussion, above. The calculations to follow have been provided in both in an unpublished presentation (Santos, 2008) and in another that was recently published (Santos, 2009a).

The plot point for this chart is $dpbo_i$ and is calculated (based upon the dpu_i calculation as above) as follows:

$$dpbo_i = \frac{dpu_i}{\text{number of defect opportunities}}\ x\ 10^9$$

The centerline is $\overline{dpbo}$ and is calculated as follows:

$$\overline{dpbo} = \frac{\sum_i dpbo_i}{k} \qquad (6)$$

The control limits for the *dpbo* chart are the following:

$$\overline{dpbo} \pm 3\sqrt{\frac{\overline{dpbo}\ x\ 10^9}{n_i x\,(\text{number of defect opportunities})}}$$

The above limits simplify to the following:

$$\overline{dpbo} \pm 94{,}868.33\sqrt{\frac{\overline{dpbo}}{n_i\ \ x\,(\text{number of defect opportunities})}} \qquad (7)$$

DPBO CHART EXAMPLE

To illustrate the *dpbo* chart, a hypothetical example – but one indicative of a typical PCB assembly process – will be utilized. In addition to a *dpbo* chart, a *dpmo* chart for the same data will be presented. This is the same example as is demonstrated in Santos (2009a). This hypothetical example is intentionally designed to be of questionable (i.e., less than 6σ) quality levels so as to compare the *dpbo* chart with the *dpmo* chart and to demonstrate that it is, in fact, a scaled version of the *dpmo* (and, though not demonstrated, the *u*) chart.

For this example, assume the following are known:

- 100 PCB assemblies are inspected each day ($n_i = 100$ for all days)
- Each assembly has 3,000 opportunities for defects
- 24 days are used to establish the control limits ($k = 24$)

Table 1 lists, for each day, the total number of defects found (per 100 assemblies), the *dpu* values, the *dpmo* values, and the *dpbo* values.

Day	Defects	*dpu*	*dpmo*	*dpbo*
1	19	0.19	63.33	63333.33
2	19	0.19	63.33	63333.33
3	22	0.22	73.33	73333.33
4	19	0.19	63.33	63333.33
5	21	0.21	70.00	70000.00
6	17	0.17	56.67	56666.67
7	29	0.29	96.67	96666.67
8	13	0.13	43.33	43333.33
9	15	0.15	50.00	50000.00
10	17	0.17	56.67	56666.67
11	16	0.16	53.33	53333.33
12	17	0.17	56.67	56666.67
13	17	0.17	56.67	56666.67
14	15	0.15	50.00	50000.00
15	23	0.23	76.67	76666.67
16	22	0.22	73.33	73333.33
17	27	0.27	90.00	90000.00
18	17	0.17	56.67	56666.67
19	20	0.20	66.67	66666.67
20	22	0.22	73.33	73333.33
21	20	0.20	66.67	66666.67
22	23	0.23	76.67	76666.67
23	30	0.30	100.00	100000.00
24	24	0.24	80.00	80000.00
		Averages	67.22	67222.22

Table 1. Example Data for *dpmo* and *dpbo* Control Chart Calculations

To demonstrate the calculations, consider the first day (subgroup). In Day 1, 19 defects were found. From the earlier equation, dpu_1 = 19/100 = 0.19. The $dpmo_1$ value is 63.33 (= $10^6 \cdot 0.19/3000$). Of course, $dpbo_1$ is 63,333.33 (= $10^9 \cdot 0.19/3000$). Based upon the results in Table 1 and in the earlier equations, the control limits for the *dpmo* chart are approximately the following:

- UCL = 112
- Centerline = 67
- LCL = 22

The control limits for the *dpbo* chart are approximately the following, as based upon Table 1 and the earlier equations:

- UCL = 112,130
- Centerline = 67,222
- LCL = 22,315

Figure 1 displays the *dpmo* chart for this example and Figure 2 displays the *dpbo* chart for this example.

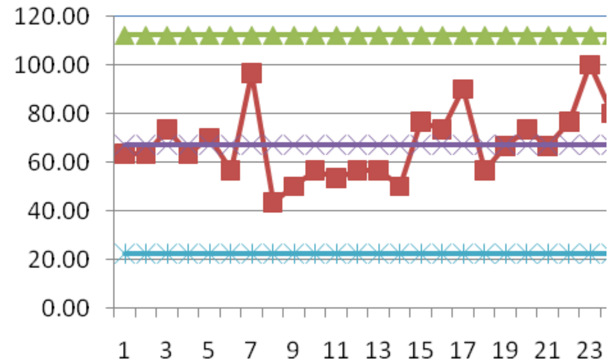

Figure 1. *dpmo* Chart for Example Problem

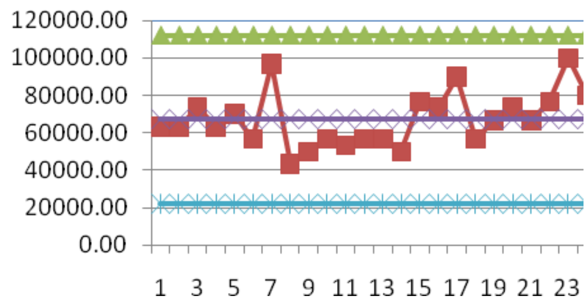

Figure 2. *dpbo* Chart for Example Problem

Analysis of DPBO Charts

Analysis of the *dpbo* chart is no different than the analysis of other attributes control charts. For this example, there are no plot points outside of the ±3σ bands. As such, it may be chosen to accept these control limits subject to periodic review. While there are no points outside the ±3σ control limits, there is an interesting situation in Days 8 through 14. Each of these plot points is below the centerline. Since these represent better-than-average defect levels as compared to the rest of the subgroups, it may be of interest (in a realistic situation) to investigate to determine if there are assignable causes for this.

An earlier point should be revisited that was discussed with this hypothetical example. This example intentionally does not reflect a 6σ process. So while the process appears to be in control, efforts should be made to reduce the defect levels. An additional comment can be made regarding high (whether out-of-control or not) *dpbo* values. Consider $dpbo_{23}$ which is the highest in this data set. Day 23 has the highest defect count of 30; even though this is in-control, one might be interested in determining why the value is high. What is not apparent from the data (and this is true whether we are using any of the other scaled charts – *dpmo* or *u*) is whether defects are indicative of all the parts in a subgroup (i.e., spread out among the 100 PCBs) or do these defects come from 1 or a few number of the PCBs on Day 23. If representative of the entire day, then investigation should be made to determine why that day was appreciably different from any other. On the other hand, the process, for that day, could be relatively similar to any other day, but the defects may have come from one bad (or very few) PCB(s) and perhaps the defects are traced more to supplied parts, than to process settings/parameters.

SUMMARY

From an examination of the example presented, it is apparent that the chart limits and plot points for the *dpbo* chart are 1000x their respective values for the *dpmo* chart – as they should be. The *dpbo* has been presented as a scaled version of not only the *dpmo* chart, but also of the *u* chart. The interested reader might then pose the question (which is similar to one posed in a recent graduate engineering class covering SPC concepts (Santos, 2009b): Why don't we just get the *dpmo* control limits and multiply those by 1000 instead of performing all of the calculations of the *dpbo* chart? The answer is simple – the author does not propose the use of both charts in realistic applications, only the use of one chart. Two charts were developed for demonstration and comparison purposes. Thus, if the *dpbo* chart is to be used, it is *not* suggested to be used *in addition to* the *dpmo* chart, but to *be used instead of* the *dpmo* chart.

The benefit from the use of the *dpbo* chart will ultimately become evident as processes with large opportunities for defect counts reach high quality (i.e., low defect) levels that are measured in terms of *ppb*, as opposed to *ppm*.

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