An Introduction To Six Sigma With A Design Example

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Abstract - **This paper is an introductory tutorial on the concepts, principles and application of Six Sigma in the design of electronic circuits. The first part of the paper introduces Six Sigma starting with a review of the underlying statistics. The statistics are then combined with the description of quality goals in units of defects per million opportunities and the origin of the term Six Sigma becomes obvious. The Six Steps to Six Sigma are presented and discussed. The second part of the paper applies this methodology to the design of a simple electronic circuit. Statistical simulations are used to predict defect density. Iteration of design revision and simulation is performed until the design is predicted to meet the desired quality goals.**

INTRODUCTION

This paper is intended as a tutorial introduction to the topic of Six Sigma. The approach is simple and lacking in rigor. The first part of the paper presents the discussion of what Six Sigma quality means, its statistical underpinnings, and methodology for working towards Six Sigma. The second part of the paper illustrates the application of these techniques. The design of a simple electronic circuit is the vehicle for this demonstration. The starting point for this paper is information presented in a three day internal training course [1].

A. *What is Six Sigma?*

The term "Six Sigma" is heard often today. Suppliers offer "Six Sigma" as an incentive to buy, customers demand "Six Sigma" compliance to remain on authorized vendor lists. We know it has to do with quality, and obviously something to do with statistics, but what exactly is it?

Six Sigma is a lot of things: a methodology, a philosophy, an exercise in statistics, a way of doing business, a tool for improving quality. What it is *not* is the be all and end all of anything. Six Sigma is a not goal in and of itself. Six Sigma is only one of several tools and processes that an organization needs to achieve world class quality.

Six Sigma places an emphasis on identifying and eliminating defects from one's products - be they power converters, sales quotations, proposals to a customer or a paper presented at a conference. The goal is to improve one's processes by eliminating waste and opportunity for waste so much that mistakes are nearly impossible. The goal of a process that is Six Sigma good is a defect rate of only a few parts per million. Not 99% good, not even 99.9% good, but 99.9996% good!

B. *Why Pursue Six Sigma?*

The answer is purely and simply economic. Customers are demanding it. They want components and systems that work first time, every time - because their customers are demanding the same. A company that cannot provide ever increasing levels of quality, along with competitive pricing, is headed out of business.

There are two ways to get quality in a manufactured product. One is to exhaustively test every product headed for the shipping dock. Those that pass are sent back for rework and retest. And rework can introduce new faults, which only sends product back through the rework loop once again. Make no mistake, much of this test, and all of the rework, are overhead. They cost money but don't contribute to the overall productivity.

The other approach to quality is to build every single product perfectly the first time. Provide only a minimal test, if any at all. Drive the reject rate so low that those units not meeting specification are treated as disposable scrap. This does cost - in training, in process equipment, in developing partnerships with customers *and* suppliers. But in the long run, the investments here will pay off. Eliminating excessive test and the entire rework infrastructure releases resources for truly productive tasks. Overhead goes down, productivity goes up, costs come down and pricing stays competitive.

Every organization has to do the cost benefit tradeoff for themselves. Every process and plant are different. There are no claims that this is an easy process. There are no claims of overnight cures available for the taking. A firm has to make the commitment at all levels to a total quality management program. It takes time, years even, to fully implement. But it can be done because it has been done. Motorola is the shining example in the United States of how business success follows a commitment to quality and customer satisfaction.

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THE STATISTICS OF NORMAL DISTRIBUTIONS

Six Sigma draws its name form the properties of the Guassian, or normal, distribution that describes the vast majority of natural phenomena. If one plots the frequency of occurrence of natural phenomena, e.g. the number of kilograms of corn harvested per hectare, the result is the familiar bell shaped curve. This is a direct consequence of the Central Limit Theorem [2] [3].

This curve is described by two parameters, the mean and the standard deviation (or equivalently, the mean and the variance). The equation that describes the normal distribution is given by:

$$f(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left[\frac{(x-\mu)}{\sigma}\right]^2} \qquad (1)$$

where x is the distance from the mean.

Simply stated, the mean is the average value of samples from or all the members of a given population. The standard deviation, which is the positive square root of the variance, describes how widely scattered are members of the population. For describing the characteristics of a number of samples drawn from a given population, the symbols used are $\bar{x}$ for the mean and s for the standard deviation. For describing the mean and standard deviation of an entire population, the symbols are μ and σ, respectively.

A distribution with a small standard deviation will have most of its members close to the mean. A distribution with a large standard deviation will have its members spread widely. Examples of two normal distributions are shown in Figure 1. Both distributions have a mean of 1. For the tall, narrow distribution, $\sigma = 1$ and for the broad, flat distribution, $\sigma = 3$.

Note that the normal distribution is a *density* function. As this is a function of real numbers, asking what is the probability that the result of a trial or experiment will have a particular value is meaningless. The proper question to ask is what is the probability that the result will fall within a given range. The answer is the area under the curve between the two values.

One way to get that value would be to integrate (1) over the desired range. Fortunately, however, this has been done many times and the results are readily available in tables. These tables can be found in textbooks on probability and statistics as well as collections of standard mathematical tables. To use these tables, one first normalizes the values at the end of the interval of interest with respect to the standard deviation. One then consults the tables, looks up the values, and adds or subtracts the values as necessary. For more information, consult an introductory probability text, e.g. [4].

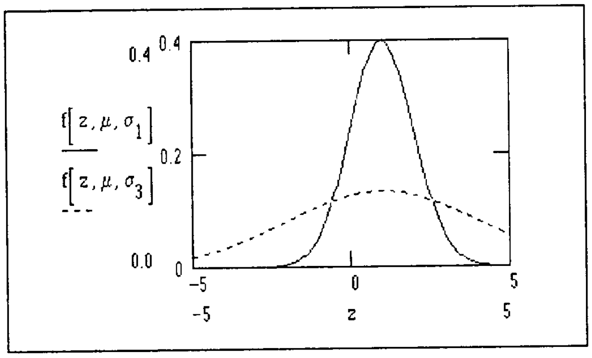

Figure 1. Examples of the Normal Distribution ($\mu = 1, \sigma_1 = 1, \sigma_3 = 3$)

To illustrate this, consider the hypothetical example of 5V power supplies being made by the Hog Swamp Power Electronics Company. The specification is 5V ± 250 mV (5%). Sampling of a production run gives a mean of 5.05V and a standard deviation of 100 mV. Assume that this is representative of the design and process capability. The distance then between the upper specification limit (USL) of 5.25 V and the mean is 200 mV, which is two standard deviations. Referring to a table of the error function, only 47.73% of the units with an output greater than 5.05 V will meet the specification. On the lower side, the distance between the mean and lower specification limit (USL) is three standard deviations and from the tables, 49.87% of the units with a low output voltage would meet specification. If this is truly typical of the process, then the overall yield would be 97.60% - only 24 units in a thousand would not pass outgoing inspection.

One might think that a yield of 98% is acceptable. Many companies would be pleased that only 24 units in a 1000 were bad. However, this is not world class quality or process. World class is not even a thousand times better with a fallout of 24 per million! World class quality is now defined as Six Sigma - that the specification limits cover a range of ±6 sigma of the production output. This is a defect rate of only 3.4 defects per million!

DEFECTS

A. *What Is A Defect?*

The whole definition of Six Sigma rides on that definition - a defect rate of 3.4 per million opportunities (DPMO). Before exploring the origin of the magic 3.4 DPMO, what counts as a defect and what counts as an opportunity must first be defined.

The simplest, most global definition is that a defect is *anything* that causes customer dissatisfaction. This may be a product that does not work, an incorrect component inserted on the manufacturing line, a delivery that is not on time, or a quotation with an arithmetic error. Specifically for a product, a defect is any variation in a required characteristic that prevents meeting the customer's requirements. An opportunity is just that - any operation that introduces a chance for error.

B. Counting Defects and Opportunities

With those definitions in hand, one might think that it is straightforward, though perhaps tedious, to simply count defects and opportunities and to divide.

Consider the case of writing a specification. An obvious defect would be any wrong value. What about typographical errors? Should a misspelled word be counted as a defect? Yes, but what is the unit of opportunity? Is it pages, words, or letters? If the unit is pages, and a ten page specification has three errors, then the defect rate is 300,000 per million. If the unit is characters, then the defect rate is ~85 per million - a value much more likely to impress management. What if the unit of opportunity is each word or numerical value? The the defect rate is ~500 per million, a factor of a hundred away from Six Sigma.

Consider the case of manufacturing a circuit board. If one is interested in the process of soldering parts on to the board, how are the defects counted? Two possible ways of counting defects are per pin and per component. For a simple, low cost PC type power supply, there won't be a large difference between the two counts as the average pins per component is probably between 2 and 3. For a high density logic board, the difference is much larger. Devices with tens or even hundreds of pins are common. Counting solder errors per pin would give a much smaller defect rate than counting solder errors per device. Which is the proper way to count? Each organization must decide for itself. If one bad solder joint on a device means that the whole device needs to be resoldered, then counting per device is a "fairer" count. If the error can be corrected a pin at a time, then counting pins may more accurately reflect process quality.

TABLE I

Sigma Level	DPMO
3	68,157
4	6,241
5	233
6	3.4

C. Defect Count and Sigma Level

Jumping immediately from today's practices to demanding Six Sigma performance levels is unrealistic. The typical process today, be it Purchased Material Lot Reject Rate or the writing of a prescription by a doctor has a typical error rate of 1-10,000 per million. If an organization is serious about reaching a Six Sigma level of quality, then a plan must be made to reach that level in stages. Allowing two to five years is not unreasonable. Looking at Table I, an organization working today a 3σ level (remember, that is 99.7% error free) must improve by a factor of 11 to reach a 4σ level, another factor of 27 to reach 5σ, and another factor of 69 to reach 6σ.

MEASURES OF PROCESS CAPACITY

Now that we have defined defects and opportunities, from where did the values in Table I come? To answer this, we consider two measures of process capacity.

A. Cp

To simply characterize the quality of a process a normalization is performed to generate the process capability parameter C_p. This is given by the equation:

$$C_p = \frac{\text{(Upper Spec Limit - Lower Spec Limit)}}{\text{Normal Process Variation}} \tag{2}$$

The Normal Process Variation is by definition the difference between the $+3\sigma$ and -3σ points of the distribution of the process output. The goal is to have a process for which the specification limits are twice the normal process variation. That is, the upper specification limit should be 6σ greater than the mean and the lower specification should be 6σ less than the mean. If this is true, then:

$$C_p = \frac{+6\sigma-(-6\sigma)}{+3\sigma-(-3\sigma)} = \frac{12\sigma}{6\sigma} = 2 \tag{3}$$

With a process C_p of two, then all of the process output will lie within ±6σ of the mean. Checking the tables for normal error will show that the expected fallout rate is only about 2 per *billion*! This certainly is acceptable quality, but this is three orders of magnitude better than 3.4 DPMO.

B. Cpk

Let us look back to the hypothetical example of the Hog Swamp Power Electronics Company. If we try to calculate the C_p of that process we encounter some difficulty. The nominal value of the specification and the mean of the actual process are not the same. The specification calls for a mean of 5.0 V and the process is hypothetically producing product with a mean of 5.05 V.

This is not uncommon, especially in fabricated metal parts. Variability is easily introduced by operator to operator differences in machine setup, the wear of tools and machines and perhaps even changes in temperature.

In a power electronics circuit, sources of unaccounted variability are fewer but present. For example, a change in vendor of a transformer may brings parts with different leakage inductances and interwinding capacitances. Even small changes in these parameters could have large effects in EHT applications. Another possibility for a previously unaccounted variability is a change in semiconductor vendors. Schottky diodes with a slightly higher drop, PN diodes with a faster, sharper recovery or a power MOSFET with a lower on resistance can introduce small changes in an output voltage. While feedback loops will correct most of these errors on a regulated output, an output voltage that relies on open loop cross regulation could change significantly.

Consider now a process that is 3σ good, i.e. a $C_p = 1.0$, with the mean of the output exactly equal to the specification nominal. Now suppose the mean of the process shifts up by half a standard deviation. This is illustrated in Figure 2a.

The dashed trace represent the distribution with the shifted mean. The area under that curve and to the right of the vertical line. representing the Upper Specification Limit, represents product that does not meet specification. This is about 6.7%, an increase in defective units by a factor of twenty!

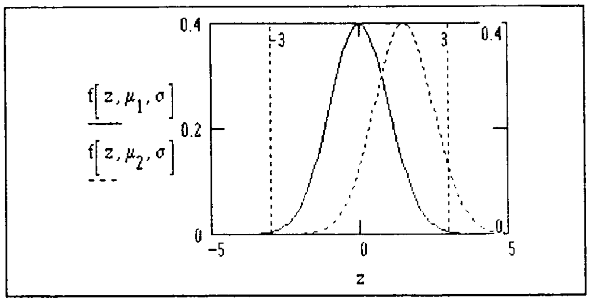

Figure 2a. The effect of shift of mean on the yield from a process with a $C_p = 1.0$. ($\mu_1 = 0, \mu_2 = 1.5, \sigma = 1$)

Suppose instead the process had a $C_p = 2.0$ before the mean shift. This is illustrated in Figure 2b. With the shift in process mean, the upper tail of the distribution crosses the specification limit at 4.5 standard deviations. The number of units that can be expected to exceed the specification limit in this case is 3.4 per million. Similar calculations with processes that have specification limits from ±3σ to ±6σ are the source of the defect count versus sigma level given above in Table I.This leads to the definition of another measure of process capability which accounts for a ±1.5σ shift in the mean. First, the factor k is introduced:

$$k = \frac{|\text{Specification Nominal - Actual Process Mean}|}{0.5*(USL-LSL)} \tag{4}$$

This is used to create an adjusted measure of process capacity, C_{pk}:

$$C_{pk} = C_p * (1 - k) \tag{5}$$

Another way of expressing C_{pk} is through the formula:

$$C_{pk} = \frac{|\text{Distance of the process mean to nearest spec limit}|}{3\sigma} \tag{6}$$

Where as before the goal was a $C_p = 2$, if the mean of the process can vary, the goal is now a $C_{pk} = 1.5$. This definition, based on a mean shift of up to 1.5σ is based on experience and is not analytically derived.

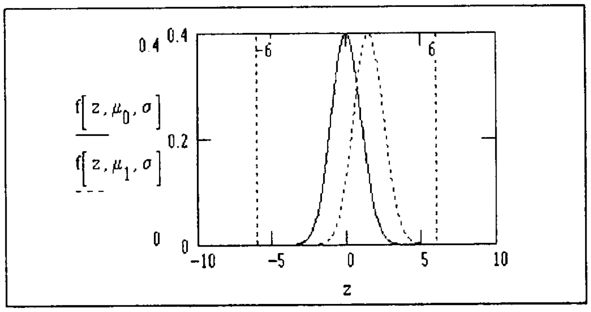

Figure 2b. The effect of a shift of mean on the yield from a process with a $C_p = 2.0$. ($\mu_0 = 0$, $\mu_1 = 1.5$, $\sigma = 1$)

THE SIX STEPS TO SIX SIGMA

A. *The Six Steps*

The Six Steps to Six Sigma were originally pioneered at Motorola. There are now several forms tailored to particular applications. The list below is a basic version.

1. Identify your products and services
2. Identify your customers and their needs
3. Identify what you need to provide your products and services and those who supply those needs
4. Describe your process as it is today
5. Eliminate effort that does not contribute to the end products and services and eliminate opportunities for error
6. Repeat these steps continuously - constantly strive to improve the process so that the output is of higher and higher quality

These six steps simply describe a process of taking inventory of how one does business today and then taking a no holds barred approach to making improvements. Improvement here is defined and measured by the creation of fewer and fewer defects.

B. *The Six Steps Interpreted For Electronic Design*

Consider now how these six steps can be interpreted and applied to the design of an electronic circuit.

Step 1 calls for the identification of products and services. In circuit design, I take this to mean carefully define the required functionality. Be specific. What function is *really* needed?

Step 2 calls for the identification of one's customers. In circuit design, this has two meanings. The first is to really know what it is your customer needs. Not what you think they need, what do they *really* need? These are often very different sets of ideas. The other interpretation applies to the circuit itself. Be specific about the interface between the output of the circuit under consideration and other circuits to which it connects. Be thorough. For example, have all transient or dynamic conditions been fully and completely described?

Step 3 calls for the identification of one's suppliers. This is difficult. To use a statistical design approach, one needs to know the statistics of the components used in design. Component specifications, however, tend to be stated in terms of minimums and maximums - and often offer only one or the other, not both. For example. how can one properly design a feedback loop for the output of a power supply without knowing both the minimum and maximum ESR of the output filter capacitors? Capacitor specifications, however, generally only give a maximum. Without knowledge of the minimum how does one calculate the upper bound on the zero introduced by this parasitic element?

What is needed is not just minimum and maximum limits on data sheets, but statistical information. What is needed is the mean and standard deviation of a component's characteristics. This will be a long time coming. It will start first with large volume customers. Their requests will be filled on a custom basis. As the experience builds statistical information will eventaully find its way into the data books. In the meantime, some additional information would be helpful. The minimum value of a capacitor's ESR is one example. A minimum leakage inductance specification on a transformer is another area - how else can one properly design a snubber circuit?

Note that the references above to component suppliers does not just mean sellers of resistors, capacitors, semiconductors, enclosures and the like. It also refers to the suppliers of finished goods. Already, internally some of my group's clients are requiring that we characterize the distribution of selected parameters on significant numbers of prototypes. This is to assure that we have a design and manufacturing process that meets *their* goals on the path to Six Sigma.

Step 4 is the description of the process today. For a circuit design problem, this requires characterizing the circuit performance. The first step is to analyze the circuit using the best available knowledge of the component and manufacturing process tolerances. Use a Monte Carlo analysis (described below) to predict the variation in parameters and process defect rate. Answer the question, "Does this proposed circuit design meet the yield and quality requirements?"

Step 5 calls for the elimination of unproductive effort and waste and to make the process as mistake proof as possible. In designing a circuit, this means building in robustness. Pursue alternatives in design, components and manufacturing processes so that the circuit can be built without error and will perform to Six Sigma criteria.

Step 6 calls for continuous improvement. In circuit design, this means monitoring the circuit during its useful life. Is the actual mean and standard deviation as predicted? Is the yield as predicted? Whether they are or not, how can it be done better? Go back to Step 1 and start all over again.

DESIGN EXAMPLE

A. Introduction

The application of the Six Steps to Sigma in the design process will be illustrated by the design of a hypothetical overcurrent detector circuit. The output to be protected is rated for 9 A maximum continuous output current.

B. Step 1: Identify Required Function

The required function is entirely driven by the customer's requirement that any condition of overload on the output damage neither the customer's load circuits nor the power supply itself. Neither may any protection plan interfere with normal operation. In the event of an overload, the power supply must latch itself off. Operation is to be restored by cycling the input power.

To perform this function, it is decided to use a simple detector circuit on the output in question. The comparator output is of the open collector type. A low level voltage is to indicate that an excessive amount of current is flowing and that shutdown is to be initiated.

C. Step 2: Specify Performance Requirements

To allow margin for dynamic loading, and to assure that normal operation won't be affected, the minimum overcurrent detector threshold is to be 10 A. After examining the output wiring and internal components and thermal design, it is determined that the maximum output current that can be allowed to flow is 12 A. The nominal threshold is chosen as the arithmetic average of the minimum and maximum thresholds, 11 A. A circuit that will perform the required function is illustrated in Figure 3. Component values and specified tolerances are given in Table II.

For this example we will only be concerned with the DC characteristics. Dynamics will not be considered. The effects of temperature and aging will not be considered. While the comparator has three parasitics that affect DC response (the input offset voltage, V_{OS}, and input bias currents, I_B+ and I_B- [5]), only the offset voltage will be considered here.

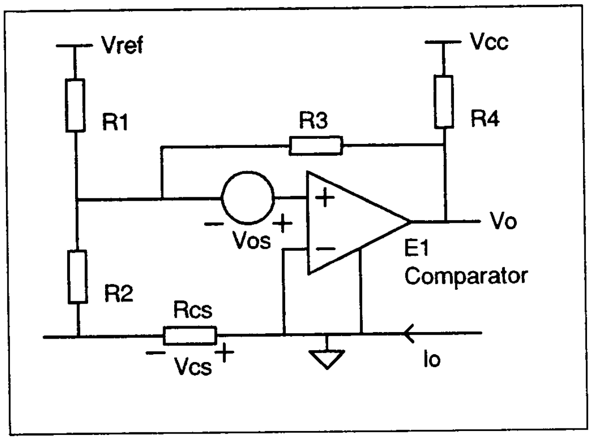

Figure 3 Overcurrent Detector Model - Circuit Schematic

TABLE II

Ref. Des.	Nominal	Tol.
R1	2.49 KΩ	1%
R2	100 Ω	1%
R3	10 KΩ	1%
R4	110 KΩ	1%
Rcs	0.01 Ω	3%
Vref	2.495 V	2.5%
Vcc	12.0 V	5%
Vos	0.0 mV	9.0mV

D. Step 3: Determine Component Variations

As mentioned above, it would be ideal to have available the statistics and distribution of the components used in one's design. But this isn't readily available today. One needs to make an assumption and later check the results against prediction. For this exercise, the assumption will be that the component values are uniformly distributed within the specified tolerance band.

Note that the uniform distribution is rather severe. It is likely to give predictions of process variation that are larger than will actually be observed. This is because in reality most processes generate results that are normally distributed. When randomly sampling a normal distribution, one is more likely to pick a component with a value close to the mean than when randomly sampling a uniform distribution. Work on analyzing the normally distributed case is being done as this paper goes to print.

E. Step 4: Characterize Circuit Performance

With that, the analysis proceeds. First, direct calculation of the nominal and worst case minimum and maximums. If these exceed the specification limits, a statistical analysis is undertaken to estimate the defect rate. To calculate the worst case minimum threshold, each component was set to either its minimum or maximum tolerance value, which ever acted to reduce the threshold current. The worst case maximum was calculated similarly. These are given in Table III.

TABLE III

Threshold Current	Amperes
Worst Case Minimum	9.290
Nominal	11.020
Worst Case Maximum	12.870

The statistical analysis is more involved. One possible approach is to directly solve for the probability density function of the threshold current as a joint probability distribution of each of the circuit elements. Perhaps this could even be done. The preferred approach, given ready access to a computer, is to do a Monte Carlo simulation [6].

TABLE IV

Mean value of simulated thresholds	11.025 A
Standard deviation of simulated thresholds	0.605 A
Minimum threshold generated	9.730 A
Maximum threshold generated	12.506 A
Number passed	919
Percent passed	91.9%
Number failed low	34
Number failed high	47
Number failed total	81
Percent failed	8.1%

Monte Carlo simulations rely on the fact that as one increases the number of samples from a population, the mean and variance of the samples approaches the mean and variance of the population. For each sample to be simulated, the component values are independently and randomly chosen. The threshold of a detector with those component values is computed. This is repeated until a sufficient number of samples values are obtained. These samples are then analyzed for mean, variance, minimum and maximum values and a prediction of defect rate is made.

A Monte Carlo simulation was carried for this circuit. The number of trials was 1000. A summary of the results are shown in Table IV. Figure 4 shows both the distribution of the calculated threshold values. Shown for comparison is a normal distribution with the mean and variance values of the 1000 simulated thresholds.

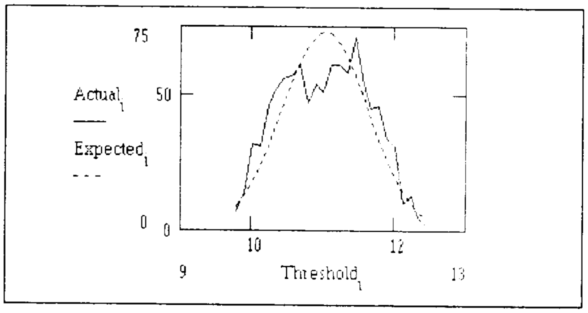

Figure 4. Monte Carlo simulation results and normal distribution with the same mean and variance

This design clearly has problems. The C_p is only 0.55. C_{pk} is not meaningful here. The mean of the simulation data is 11.025, which is very close to the nominal threshold with these component values (11.02). Actually, that the simulated mean is so close to the nominal is a good check that the random number generator used is free of bias.

F. Step 5: Revise Design To Meet Six Sigma Requirements

Step 4 was a characterization of the circuit as designed. In Step 5, the application and design are revisited until the desired quality level is achieved. The first exercise is to understand how the output threshold varies with variation in each circuit element. While all other circuit elements were held at nominal value, each component was set to its minimum and maximum value and the threshold calculated. The results of these calculations are shown in Table V.

As might be expected, the comparator offset voltage, variation in value of the current sense resistor and variation in the reference voltage are the major contributors. Resistors R1 and R2 are second rank contributors to the variation in threshold current. Variations in R3, R4 and the Vcc supply make insignificant contributions to the defect rate.

The obvious next step is to explore tighter tolerance components. For example, for an additional cost it is certainly possible to get a current sense resistor with a 1% tolerance. Reference voltage sources with a 1% (or even a 0.2% tolerance) are readily available. And comparators with a smaller offset voltage, e.g. 5 mV maximum over all conditions, are readily available for a minimal price increase. The additional material cost, however, must considered against a lower defect rate, and thus a lower manufacturing cost.

With only three candidate components, it is a reasonable next step to perform the seven additional Monte Carlo simulations that would cover all combinations of the next grade tighter tolerance parts. Each result is then examined and the least expensive combination that meet the required quality level selected. In this example, the results are not so good.

TABLE V

Ref. Des.	Min/Max	Threshold	Error
R1	Min	11.121	0.101
R1	Max	10.921	-0.099
R2	Min	10.910	-0.110
R2	Max	11.130	0.110
R3	Min	11.029	0.009
R3	Max	11.011	-0.009
R4	Min	11.021	-0.001
R4	Max	11.019	0.001
Rcs	Min	11.361	0.341
Rcs	Max	10.669	-0.321
Vref	Min	10.770	-0.251
Vref	Max	11.271	0.251
Vcc	Min	10.970	-0.050
Vcc	Max	11.070	0.050
Vos	Min	10.083	-0.937
Vos	Max	11.957	0.937

Consider the case where the maximum offset voltage is 5 mV and the tolerance of the reference voltage and current sense resistor are each 1%. The results of a Monte Carlo analysis are given in Table VI and Figure 5.

TABLE VI

Worst case minimum	10.03 A
Worst case maximum	12.04 A
Minimum threshold generated	10.296 A
Maximum theshold generated	11.815 A
Simulation mean	11.0215 A
Simulation standard deviation	0.330 A

At this point we begin to see the limits of the assumptions that have been made. Without thinking, the C_p is calculated to be 1.01. This is less than the desired value of 2. Figure 2a shows this kind of situation. But look at the worst case possible minimum and maximum threshold values (given that the components so stay within their specification limits!) of 10.03 A and 12.04 A. These numbers are very close to the specification limits of the circuit itself. Close enough that one would rightfully expect a defect rate that approaches the requested 3.4 per million.

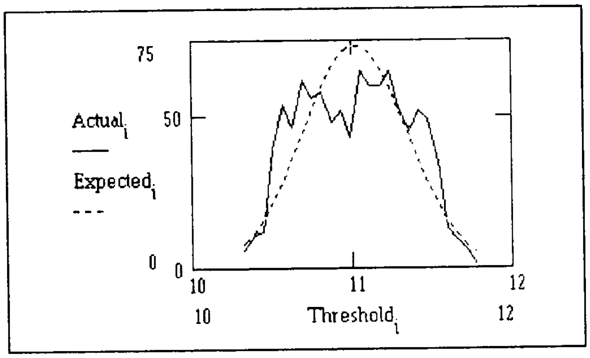

Figure 5. Monte Carlo simulation results and normal distribution with the same mean and variance; tight tolerance component case

This all then comes back to the critical issue in pursuing Six Sigma for electronic design - good, solid information about the component values and statistics. And in real life, not hypothetical situations, the designer needs to have accurate information about the manufacturing processes. For example, unless the current sense resistor is a four leaded component with a Kelvin connection internally, variations in solder joint resistance will add more variability than the 1% tolerance of the part itself.

G. *Step 5: Alternate Method to High C_p*

In the previous section, the solution pursued to achieve a low defect rate circuit was to use components with a tighter tolerance. This approach, while apparently successful, came with an additional material cost. A reference source with a 1% tolerance instead of 2.5% might cost US$0.30 instead of US$0.20. The low offset comparator may be an incremental cost of only US$0.05. A 10 mΩ current sense resistor with a 1% tolerance might cost US$0.25 more than one with a 3% tolerance. These add up to an additional cost of US$0.40 - a significant amount in a price conscious market.

The tighter component tolerance approach focused on the denominator portion of the equation for C_p. What about the numerator? For example, if what limited the maximum overcurrent threshold to 12 A was the junction temperature of the output diode, perhaps much less than US$0.40 can be spent on additional heatsink material. Raising the maximum allowable threshold current may be a less expensive way to quality than arbitrarily buying better quality components.

H. *Step 6: Measure Actual Performance*

This is only a theoretical example but in real life, follow up is critical. The loop of synthesis, analysis and verification by measurement must be closed. This can be difficult, but not for technical reasons. Asking production to add in additional monitoring and reporting may be met with resistance. Those with a focus that is too short term will resist expenditures of labor and capital that won't yield immediate results. Such thinking is foolish at best, fatal to business at worst.

COMPUTATION NOTES

All of the calculations performed for this paper were done on a no-name personal computer. The processor was an i486, 33 MHz clock, 128 KB secondary cache and 8 MB of main memory. The calculations for the Monte Carlo simulations were done by custom programs written in C by the author. Compiling and debugging were done with Borland International's Turbo C®, Version 2.0. Further analysis and plotting were done with the Mathsoft's Mathcad® program, Version 3.0, running under Microsoft® Windows™ V3.0. Note that all these tools, hardware and software (with the exception of the author's own code), are commercially available and (relatively) inexpensive.

The calculation time for a Monte Carlo simulation of 1000 random samples was approximately 2 to 3 seconds.

SUMMARY

The principles of Six Sigma and its statistical roots have been presented. The Six Steps, applicable to any process, were listed and discussed. A hypothetical design example illustrated the application of Six Sigma design techniques.

The principle issue raised for the electronic circuit designer is that to have quality output, quality information about the components used in the design is critical. Yet today, the necessary information about the quality of these components is generally missing. This will be one of the toughest challenges on the road to 3.4 DPMO quality.

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