2016 Proceedings of PICMET '16: Technology Management for Social Innovation

Quality through Design: A Six Sigma Approach

Neslihan Alp, Jeremy Mau
University of Tennessee at Chattanooga, College of Engineering and Computer Science, Chattanooga, TN - USA

Abstract--**The terms Lean and Six Sigma are often heard within an organization in regards to improving the quality of products coming off the manufacturing floor. Changes in company culture that embrace continuous improvement are necessary for Lean and Six Sigma to work properly.**

One area that is not often addressed is how to utilize Six Sigma processes when designing a product from the ground up to ensure high quality, when the product is implemented into a manufacturing environment. Design teams need to go a step further than just producing a good product by controlling factors that are contributors to potential quality issues before they happen. This leads to a reduction of resources needed to fix quality issues, less scraped or reworked parts at the supplier level, and fewer customer service calls.

This paper examines methodologies utilized in the Design for Six Sigma (DFSS) process and discusses how these methodologies affect quality. It will also provide a roadmap for engineering design managers, who want to apply Six Sigma into their design before, rather than after the product hits the manufacturing floor.

I. INTRODUCTION

The cost of quality is a number that many companies struggle to understand. It can be quantified by how many warranties and defects customers report or by how many parts are rejected back to a supplier. These numbers start to blur when discussing the extra manpower needed to 100% sort parts, the cost of lost time due to rejected units, or the cost of the units scrapped. But how does a company quantify the cost of lost sales, or even more importantly the perceived value of the company in the eyes of consumers, investors, and shareholders? Each of these areas often costs a company more than what initially meets the eye. Understanding hidden costs that extend past simple currency is what companies struggle to comprehend.

Lean Six Sigma tools help to improve quality by reducing variation and waste in the manufacturing environment. The tools and methodologies employed by Six Sigma result in faster time to market, less overall cost, and better quality.

II. SIX SIGMA

There are two distinct categories of Six Sigma that are commonly used. These two systems are known as Design, Measure, Analyze, Improve, and Control (DMAIC) and Design for Six Sigma (DFSS). DMAIC is often applied when customer expectations are not being met for existing products. It focuses on improvement the quality when dealing with manufacturing or service processes. DFSS is used as a methodology to improve quality by reducing variation within a given system.

On the other hand, Define, Measure, Analyze, Design, and Verify (DMADV) is a technique used within DFSS. This method is the most common DFSS method and used 47% of the time DFSS is applied. This approach focuses more on the providing a road map to produce robust design when an existing product does not exist [1]. When comparing the two as shown in Table 1, it becomes clear that each process has its appropriate place and use.

TABLE 1. DMAIC VS. DMADV

DMAIC		**DMADV**	
Define	Define project goals and customer requirements	**D**efine	Define project goals and customer requirements
Measure	Measure process to determine current performance	**M**easure	Determine customer needs and specifications; benchmark competitors and industry
Analyze	Determine the root cause(s) of the defects	**A**nalyze	Analyze process options to meet the customer needs
Improve	Eliminate defect root causes to improve the process	**D**esign	Design process to meet the customer needs
Control	Control future process performance	**V**erify	Verify design performance and ability to meet quality specifications

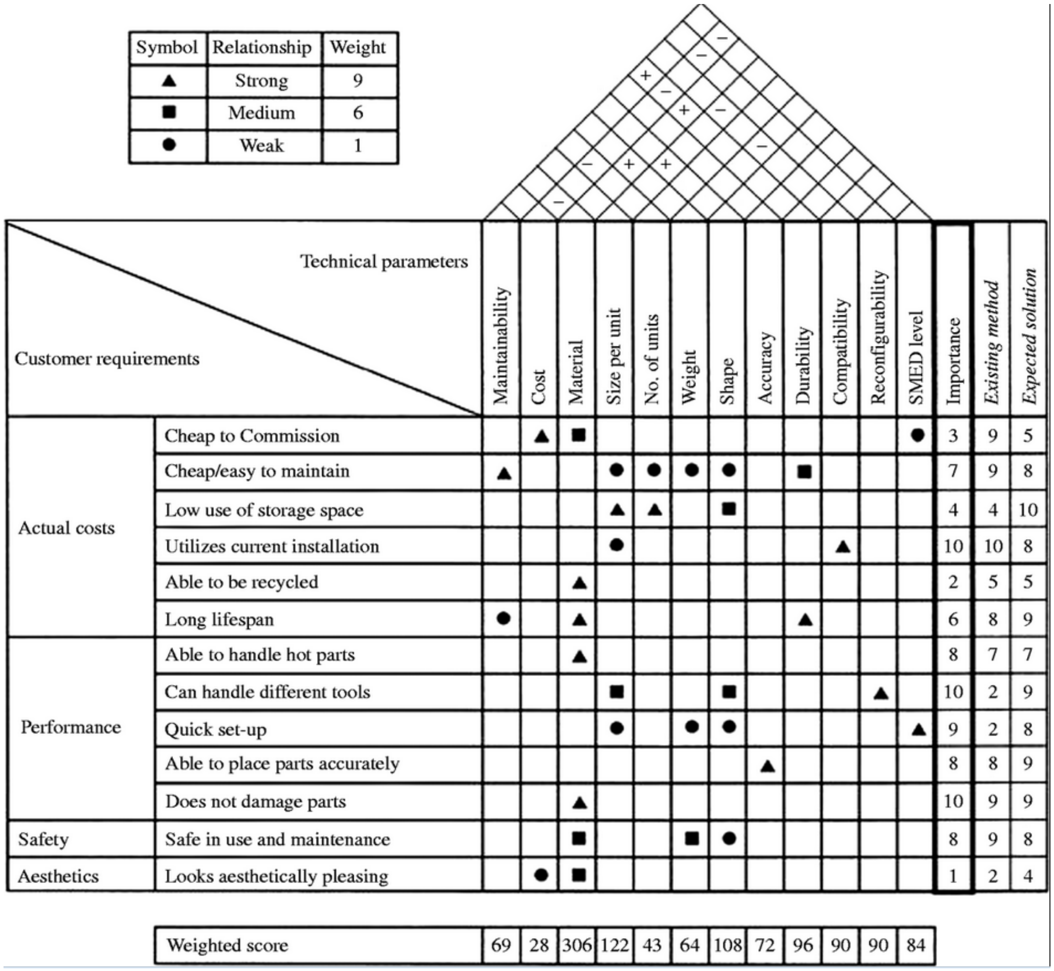
The DMADV process and tools are used primarily during the development and qualification process of designing a product [3]. Like all other Six Sigma processes, DMADV follows DFSS methodologies and tools to quantify each step of the design phase, so each process will be under statistical control before moving to the next phase of the project. DMADV should be used:

1. When a non-existent product or process needs to be developed in a company
2. When a process or product already exists, but still needs to meet a Six Sigma level or customer specification

III. DEFINE

The first stage of Define, Measure, Analyze, Design, and Verify (DMADV) is the Define phase. This stage involves the ground work that is laid in order to develop a product. Tools such as Quality Function Deployment (QFD), Voice of the Customer (VOC), and Kano Analysis shape what will be important to the end product. The design phase starts by identifying the customer, understanding the customer's needs, and then translating those needs into Critical to Quality (CTQ).

QFD is one of the tools used in the Define stage that transforms customers' wants into a matrix that shows levels of importance, value, and how those wants can be met. Developed in 1966 by Professors Shigeru Mizuno and Yoji Akao, the QFD process aims to include the voice of the customer into the design of the product. It takes customers' wants and needs and prioritizes those criteria that are translated into quantifiable features and functions in a product as shown in the Figure 1 [1].



Symbol	Relationship	Weight
▲	Strong	9
■	Medium	6
●	Weak	1

Customer requirements		Maintainability	Cost	Material	Size per unit	No. of units	Weight	Shape	Accuracy	Durability	Compatibility	Reconfigurability	SMED level	Importance	*Existing method*	*Expected solution*
Actual costs	Cheap to Commission		▲	■									●	3	9	5
	Cheap/easy to maintain	▲			●	●	●	●		■				7	9	8
	Low use of storage space				▲	▲		■						4	4	10
	Utilizes current installation				●						▲			10	10	8
	Able to be recycled			▲										2	5	5
	Long lifespan	●		▲						▲				6	8	9
Performance	Able to handle hot parts			▲										8	7	7
	Can handle different tools				■			■				▲		10	2	9
	Quick set-up				●		●	●					▲	9	2	8
	Able to place parts accurately								▲					8	8	9
	Does not damage parts			▲										10	9	9
Safety	Safe in use and maintenance			■			■	●						8	9	8
Aesthetics	Looks aesthetically pleasing		●	■										1	2	4
	Weighted score	69	28	306	122	43	64	108	72	96	90	90	84			

Figure 1: Example of the House of Quality

Kano Analysis is a third tool used to define the needs of the customer. The needs of the customer are usually broken into three categories: dissatisfiers, satisfiers, and attractive qualities as shown in Figure 2. Dissatisfiers are requirements that the customer expects and would cause dissatisfaction if not included. Satisfiers are requirements that are met to the customer's satisfaction. Attractive qualities are features that add value and please the customer, but do not cause dissatisfaction if excluded [2]. Within the example of a costumer buying a car, a dissatifier would be a new car that had no sound system. Although not necessary, a sound system is a feature a customer expects to have in a new car. A satisfier would be car that had a 6 speaker sound system with auxiliary cable ports for mobile devices and an antitheft device built into the system. An attractive quality would be an increase to 10 speakers, Bluetooth enabled, touchscreen with controls on the steering wheel.

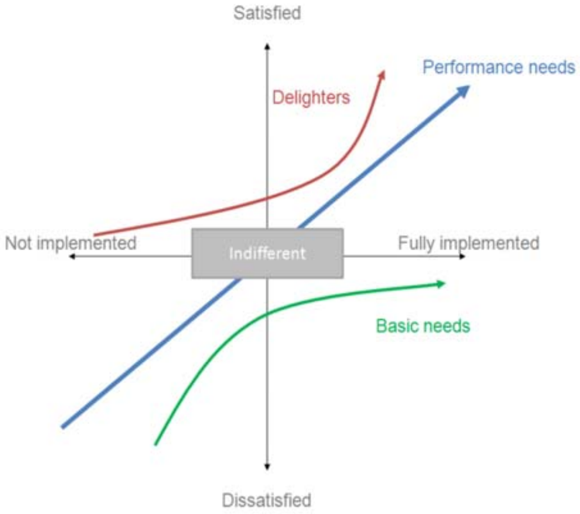


Figure 2. Kano Analysis

Gathering customer needs can be broken down into two methods: active and passive. Learning about the customer in an active way involves interviewing customers to determine their values, point of views, and expectations. It also includes working with small focus groups that represent the target customer demographic. Other ways to collect customer input include surveys, internal research, Kano surveys, QFD, Pugh Matrixes, and competitive analysis. Identifying the customer and listening to the voice of the customer is the most important step of the Define phase.

IV. MEASURE

The next step in Define, Measure, Analyze, Design, and Verify (DMADV) is the Measure phase. It transforms customers' requirements into Critical to Quality (CTQ) and specification limits that are organized within a structure that can fit within a system of components. It also analyzes whether those requirements can be met with the existing capability of the current system. [4]

CTQ requirements are derived from the voice of the customer. In order to properly measure against the customer requirements, tools are used to create a baseline that will be bases for all future CTQ measurements and analysis. Once a baseline has been established, defining the CTQs is the next step in the measure phase. Setting specification limits will define how tightly to set tolerances. The objective of the measure phase is to understand the CTQs as they relate to the system as a whole. [3]

Setting up a visualization of the Design Model is critical to being able to collect measurements to the system. The Design Model should branch into three separate categories. The System Structure breaks the system into subsystems and different parts. The System Performance specifies the expectations required from the system. And lastly, the CTQ Metrics shows the CTQs and quantifies the specifications.

V. ANALYZE

The analyze phase incorporates steps such as benchmarking, brainstorming, and conceptual designs. After these steps have been completed, a trade-off analysis can be conducted as well as any problem resolutions that apply to the design of the product. [2]

Benchmarking encompasses not only external products, but also internal products as well as processes. Learning how the new design compares to competitors provides a platform to create products that are competitive and also improve on previous designs. Understanding internal processes allow managers to anticipate any potential issues during manufacturing and assembly. Benchmarking allows teams to set up a strengths, weaknesses, opportunities and threats (SWOT) analysis as shown in Figure 3. Being able to develop an accurate SWOT analysis will enable design managers to make sound decisions to create a best-in-class product.

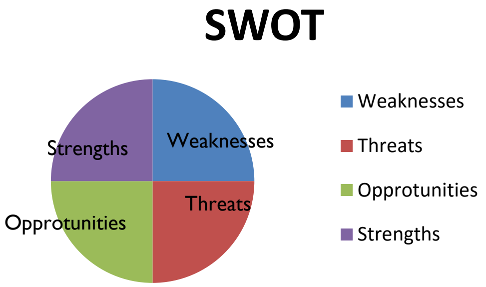
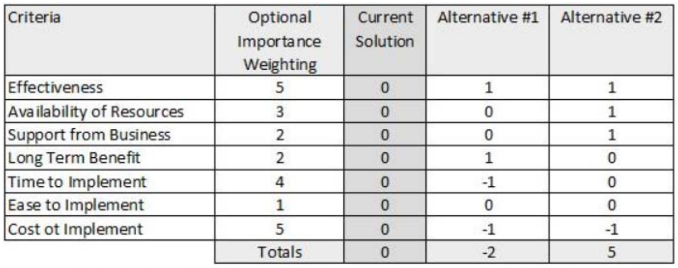


Figure 1: SWOT Analysis

Generating new ideas to remain ahead of the competitive curve can be accomplished through brainstorming sessions with experts, operators, managers, and designers. Permitting each individual to have an opinion and open floor to voice ideas allows all ideas to be considered and encourages creative thinking. Ideas should be written down and then grouped based on their similarities by category. Once all ideas have been organized, a decision needs to be made by design and program managers to determine a prime path. Alternative paths also need to be established in the event that the primary concept cannot be executed.

Lean design targets all aspects of design extending to the function of the design, the processes that will be required to create the product, the materials used, and the amount of manpower required to produce a specific design or product. Deciding which features to include and which to leave off often requires tradeoffs and can be difficult, but design managers can use tools such as a Pugh Matrix as shown in Figure 4 to determine which features are a priority. Safety, quality, functionality, and CTQs are all features in design that would represent priority criteria in a Pugh Matrix.



Criteria	Optional Importance Weighting	Current Solution	Alternative #1	Alternative #2
Effectiveness	5	0	1	1
Availability of Resources	3	0	0	1
Support from Business	2	0	0	1
Long Term Benefit	2	0	1	0
Time to Implement	4	0	-1	0
Ease to Implement	1	0	0	0
Cost ot Implement	5	0	-1	-1
	Totals	0	-2	5

Figure 2: Example of Pugh Matrix

VI. DESIGN

The Design phase of the Define, Measure, Analyze, Design, and Verify (DMADV) process involves defining a transfer function. A transfer function develops an equation that defines the dependant variables (Y's) in terms of the independant varibles (X's). It can then show which independent variables are important to the system and which independent variables are the greatest contributors to the function. The transfer function can predict behavior based upon changes to the equation, opening the door to optimization and creating an ideal design. The transfer function can also help design for robustness and reliability.

Designing a system requires a shift in approach different from traditional methods of thinking. For example, design engineering in its most basic form requires a trial and error approach to design. As more sophisticated methods are introduced, more accurate methods of prediction become available. Mathmatical bases for design comes into play, and the factor of safety and other traditional methods to quantify risk are used. The DMADV system uses statistical analysis to reduce risk. By reducing variation within a normal distribution and controlling a process to within +/- 3σ, the risk of failure to any signal component drops significantly for every degree of sigma gained.

The Defects per Million Opportunities (DPMO) defines the 6-sigma process as 3.4 failures per million. Table 2 shows the importance of being able to control the design for robustness, reliability, and quality.

VII. VERIFY

The last step of the Define, Measure, Analyze, Design, and Verify (DMADV) process is the Verification step. It includes validating, optimizing, and controlling design. Validating predictions established in the design phase is one step to verify design. An example of validating predictions would be an automotive design team measuring gaps between panels against predicted values and ensuring reliability of door hinge systems through cycle testing. [4]

Real world testing in the field, accelerated life testing, and tolerance loop validation are all methods to validate design. In order for all these tests to be validated, six sigma tools and statistical processes are necessary to ensure that all CTQs, specifications, and tolerances are correct. Collecting data is the first step in the validation process. Data collection should begin from the first build and continue through all builds and revisions until a final product is released. This method can track intended or unintended changes to CTQs. While collecting data, gauge R&R studies need to be conducted to validate measurement techniques. [4]

VIII. CASE STUDY

Four tools will be used to validate the design of component: Reliability Analysis, Gauge Repeatability and Reproducibility (R&R), Data Validation, and Tolerance Loop Verification. In order to set up the verification process properly, the design requirements and assumptions of the case study will be presented and established. Design requirements have been established during the Define, Measure, Analyze, and Design (DMAD) phases.

- **Assumptions**
  - All proper analysis has been taken into account in the define, measure, analyze, and design stage in order to reach the verify state
  - All CTQs have been established
  - Design has been optimized to its final state

- **Design Requirements**
  - 1 Year Usage: 99.98% Reliability at 90% Confidence
  - 10 Year Usage: 99.65% Reliability at 90% Confidence
  - Test to Failure: Weibull Plot
  - CTQs must maintain Zero Latency Transfer (Zlt) equal or greater than 4.5
  - Safety critical CTQs must maintain Zlt equal or greater than 6.0
  - Must pass manufacturing and assembly lean criteria, poke yoke, assembly

IX. FUNCTIONAL BLOCK DIAGRAM (FBD) DIAGRAM

In order to understand the background of Component A better, a Functional Block Diagram (FBD) has been included to show the basic functions of the component. In the FBD diagram shown in Figure 5, the relationships between the motorized components and the user can be seen in an interaction of using a series of mechanisms and actuations of switches to activate the motor.

TABLE 2. THE SIGMA LEVEL

Sigma level	Sigma (with 1.5σ shift)	DPMO	Percent defective	Percentage yield	Short-term C_{pk}	Long-term C_{pk}
1	-0.5	691,462	69%	31%	0.33	–0.17
2	0.5	308,538	31%	69%	0.67	0.17
3	1.5	66,807	6.7%	93.3%	1.00	0.5
4	2.5	6,210	0.62%	99.38%	1.33	0.83
5	3.5	233	0.023%	99.977%	1.67	1.17
6	4.5	3.4	0.00034%	99.99966%	2.00	1.5

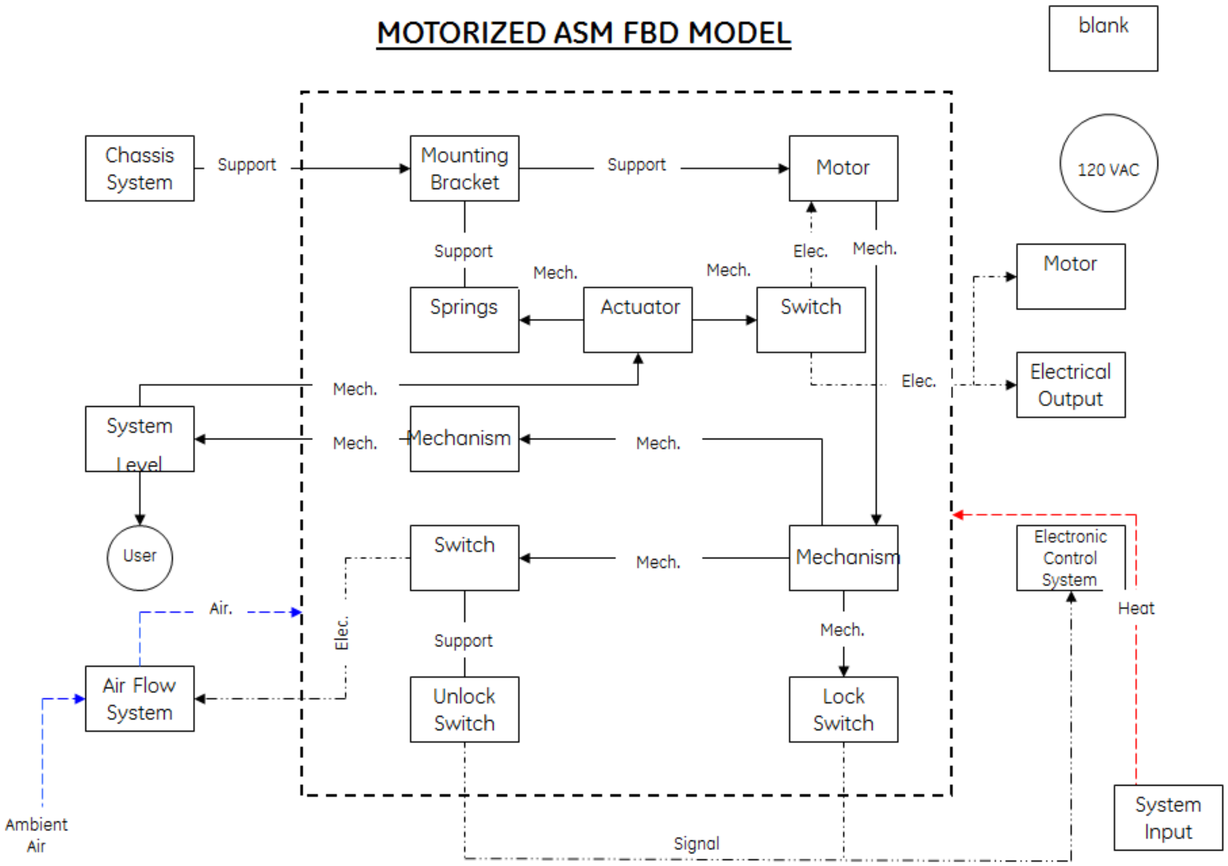


Figure 5. FBD Diagram of a Motorized Assembly

X. RELIABILITY ANALYSIS

The reliability requirements for this case study have been established with the input from management and established CTQs set by safety councils and regulatory agencies. The motorized assembly has a low annual usage but is critical. One year of usages is defined as 4.6 cycles and 10 years is 46 cycles. Table 3 outlines the level of confidence and the reliability requirements necessary to consider the component safe to use. At one year of use, the reliability is defined at 99.95% with a confidence level of 90%. [5]

The results of the reliability testing clearly show that there is no concern meeting the one-year and ten-year requirements. When comparing the failure data to the reliability goals, it would be possible to be even more conservative on reliability and confidence goals [7]. When set to 99.99% reliability and 99% confidence the data shows that components would be able to pass the criteria.

XI. GAGE REPEATABILITY AND REPRODUCIBILITY (R&R) STUDY

Gage R&R studies are important because they help to measure variance within a system of measurement. A Gage R&R study can show if there is variation in the measurement equipment, parts, operators, or the test methods. The results of the study will determine the repeatability and the reproducibility of the system. Repeatability is determined by the variation when a single operator measures a part multiple times. Reproducibility is determined by the variation between multiple operators. [8]

TABLE 3. RELIABILITY GOALS

Reliability Requirements							
Component “A’		1yr Reliability	1yr Confidence	1yr cycles	10yr Reliability	10yr Confidence	10yr cycles
Requirements	#1	99.95%	90.00%	5	99.65%	90.00%	46

TABLE 4. GAGE R&R RAW DATA

GAUGE R&R STUDY

Part Number

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Operator 1										
1A	0.0715	0.0695	0.0695	0.0695	0.0690	0.0690	0.0690	0.0715	0.0735	0.0735
2A	0.0695	0.0690	0.0695	0.0690	0.0695	0.0685	0.0690	0.0685	0.0695	0.0680
3A	0.0690	0.0685	0.0685	0.0700	0.0685	0.0695	0.0685	0.0680	0.0700	0.0685
Operator 2										
2A	0.0720	0.0720	0.0715	0.0710	0.0720	0.0705	0.0715	0.0710	0.0700	0.0705
2B	0.0715	0.0715	0.0710	0.0715	0.0705	0.0700	0.0715	0.0705	0.0720	0.0720
2C	0.0720	0.0695	0.0710	0.0715	0.0715	0.0715	0.0705	0.0700	0.0720	0.0705
Operator 3										
3A	0.0705	0.0705	0.0730	0.0720	0.0690	0.0705	0.0705	0.0700	0.0710	0.0710
3B	0.0705	0.0700	0.0705	0.0695	0.0715	0.0715	0.0715	0.0705	0.0710	0.0710
3C	0.0700	0.0710	0.0710	0.0710	0.0715	0.0715	0.0705	0.0695	0.0710	0.0700

The method of data collection for this case study follows the traditional method utilized in most Gage R&R studies. Ten parts are labeled marked and the dimension to be measured identified. Three operators are then asked to measure the specified dimension a total of three times. In order to collect more accurate results, the operators were instructed to measure parts in sequential order three times rather than measuring one part three times and moving on to the next part. This ensures more accurate measurements and introduces less bias into the data. The data can then be entered into MINITAB for analysis [6].

The gauge study that is shown in Table 4 uses a dimension of 0.070 +/-0.010. The measurement comes directly from the motor assembly and utilizes three operators and ten parts.

This Gage R&R study shows that there is a room for improvement in the measurement system as well as between operators. One possible implementation would be training all operators to use the same methods and techniques to measure parts more accurately.

XII. DATA VALIDATION & TOLERANCE LOOP VERIFICATION

Safety loops are critical in the sense that a failure is considered a serious safety hazard to the consumer and could result in injury or death. In this case study, safety critical components and loops require that the Z score, which is a statistical measurement of a score's relationship to the mean in a group of scores, be a 6.0 at a minimum to increase the confidence level of the robustness of the design. In order for Loop #1 to be considered robust, an interference of 0.250 is necessary. If the interference drops below 0.100 then there is a risk of a failure. The upper specification limit is defined as 0.400.

Nuisance loops are not considered safety critical, but can drive customer complaints or service calls if a failure occurs. Nuisance loops can range from mechanical systems being difficult to operate to electrical systems being too sensitive to user inputs. As shown in Table 5, Loop #2 describes a loop that addresses ensuring a clearance gap within a system. A failure would cause a door to become stuck on another component due to interference. A robust system requires a Z score of 4.5. If the gap drops below 0.0 then interference has occurred and the system will not operate correctly. Conversely, if the gap grows past .179 then interference can occur on the other side of the component [7].

XIII. MANUFACTURING PROCESS

Validating the manufacturing process is another step within the validation stage. This step ensures that when the design is implemented in the manufacturing environment that the transition is smooth from design to assembly. One way to validate and ensure that this happens is by using a Poke Yoke between models. Poke Yoke design between parts ensures that the wrong components aren't assembled to the wrong system. Many parts have slight variations that are used between different models and assembling the wrong one can cause issues. [8]

The motor assembly in this case study uses two different configurations but is assembled to multiple models many of which are different. In order to ensure that the correct assembly is placed with the correct model, the motor switches and associated wire harnesses are Poke Yoked with different sized terminals to prohibit incorrect assembly as shown in Figure 6.

TABLE 5. TOLERANCE LOOP REQUIREMENTS BASED ON CTQS ESTABLISHED IN THE DEFINE STAGE

Tolerance Loop Requirements					
Loop #	**Loop Type**	**CTQ value**	**Required Z score**	**LSL**	**USL**
Loop 1	Safety: Interference	0.250	6	0.100	0.400
Loop 2	Nuisance: Gap	0.041	4.5	0.0	0.179

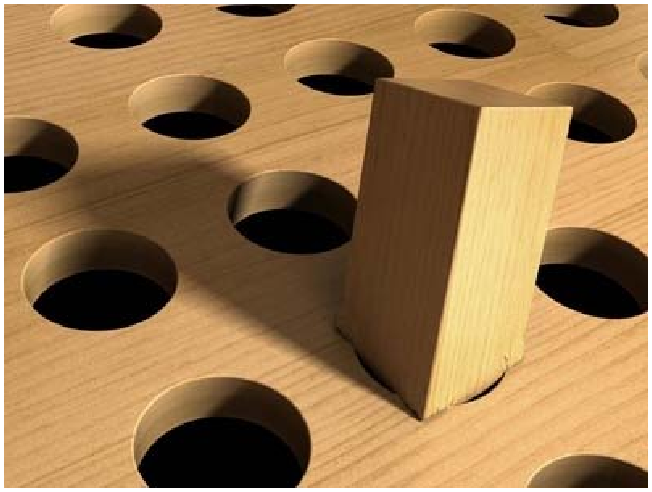


Figure 6. Poke Yoke Theory - Wrong Parts DO NOT Match With Each Other

XIV. CONCLUSION

Designing for quality means not waiting till failures occur to address a problem. It means that quality is a major factor to consider during the conceptual stages of the product design. When quality is designed into the product, it should be measurable, quantifiable, and prioritized as a critical factor of design everybody benefits.

The tools used to validate the component design show that the design is robust enough to meet the Critical to Quality (CTQ) requirements. The only caveat to this validation is the Gage Repeatability and Reproducibility (R&R) study [8]. The Gage R&R showed that variance in the process came more from the repeatability and reproducibility (97.5%) rather than part-to-part variation (25.6%). Variation in a Gage R&R should come from part-to-part rather from operator variance. It is an indication that a better gage is needed with better operator training, better measurement techniques, or better equipment [9].

Since the Gage is being called into question, the accuracy of the data points collected to validate the tolerance loop must also be called into question. However, in this case, the data set used to validate the loops the manufacturing line could only support one operator with one tool taking one measurement before the unit moved on down the line. The recommendation is that the Gage R&R be analyzed further before it can be accepted for long-term measurement use. Reliability of the component is excellent. Due to the low usage on the motorized assembly, the one-year and ten-year reliability is not any concern for quality or safety. The component can meet the CTQ requirement of 99.65% reliability at a 90% confidence level. [9]

Overall the tools and methodologies used verify that the design is robust. The design indicates that defects are minimized to less than 3 Parts Per Million (PPM). This keeps quality higher, defects low, and results in lower service calls and warranty claims filed. The design is not only statistically validated through the DFSS process but it is also driving quality through the Lean process such as Poke Yoke in the manufacturing environment. The bottom line is that costs decrease due to increased quality.

REFERENCES

[1] Gardner, M. “GE DFSS BOK” In-text: (Gardner, 2007) Bibliography: Gardner, M. 2007.*GE DFSS BOK*. [e-book].

[2] Hooks, Julian. "What Is DMADV?" *Six Sigma Daily*. N.p., 10 Dec. 2012. Web. 02 Nov. 2013.

[3] Jai-Hyun, Byun. "Content of Present Issue - A Design for Six Sigma: A Robust Tool in Systems Engineering Process." *A Design for Six Sigma: A Robust Tool in Systems Engineering Process*. Industrial Engineering & Management Systems, 16 Nov. 2012. Web.

[4] Johnson, Albert. "Six Sigma in R&D. (Managers at Work)." *Research Technology Management* 45.2 (2002): 12(5). Print.

[6] Johnson, JA, et al. "A “Six Sigma” DMADV/DFSS Case Study." *Quality Engineering* 18.3 (2006): 299-323. Print.

[7] Linderman, Kevin, et al. "Six Sigma: A Goal-Theoretic Perspective." *Journal of Operations Management* 21.2 (2003): 193-203. Print.

[4] Office of Planning and Institutional Assessment. "DMADV: An Approach for Developing New Initiatives." *Innovation Insights* 20th ser. (2008): 1-4. The Pennsylvania State University, 1 Nov. 2008. Web. 05 Nov. 2013.

[8] Sloop, Rick. "Understand Gage R&R." *Quality* 48.9 (2009). Print.

[9] Snee, Ronald D. "When Worlds Collide: Lean and Six Sigma." *Quality Progress* 38.9 (2005). Print.