Design For Six Sigma (DFSS) as a Proactive Business Process

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Abstract

Historically organizations have had a difficult time achieving Six Sigma levels of performance. Six Sigma level of quality consists of 3.4 defects per million opportunities (DPMO). Optimizing a product or process to this level required an extensive redesign. By redesigning the process or product engineers were essentially enabling Six Sigma levels by design. This is the premise of Design for Six Sigma (DFSS). DFSS is a proactive business process utilizing the voice of the customer into the design of products and processes. Designing a product that the customer wants rather than what the engineering thinks they want yields to greater customer satisfaction and market share. During the 1950’s Dr. Genichi Taguchi developed a methodology similar to how the DFSS process is used today. Dr. Taguchi’s methods to DFSS make use of some unique tools and terminology. Dr. Taguchi’s use of system thinking, approach to DOE’s using orthogonal arrays, Quality Loss Function, and using Signal to Noise Ratio in Robust Optimization are unique to the DFSS process. Dr. Taguchi’s framework for DFSS and tools will be discussed in this paper.

1. Introduction

DFSS is a business process management methodology similar to traditional Six Sigma. While traditional Six Sigma focuses on improving or optimizing an existing product or process, DFSS aims to create a new product or process driven by the needs and wants of the customer. Dr. Taguchi’s DFSS methods focus on designing a robust product at the lowest possible cost. By following the IDDOV framework a product is designed around the customer needs and wants. The product is developed to achieve Six Sigma levels of quality by utilizing many different design tools. The product or process is then optimized further at the lowest possible cost by utilizing statistical techniques, orthogonal arrays, and the Quality Loss Function. The optimized product is than tested to verify that it still meets the customer needs.

2. IDDOV Framework

Dr. Taguchi’s DFSS methods follow the IDDOV – Identify, Define, Develop, Optimize, and Verify – process. The 5 phase IDDOV model (Figure 1) is a closed loop process that starts and ends with the customers. Features of the product / process are completely defined by the customer.

![Figure 1: Five Step IDDOV Model](image-url)
Identify Phase
The Identify phase begins by developing the project plan. It defines what the purpose of the project through supporting evidence. The project purpose will come from customers requirements or needs in a particular product or process. These needs will require the product or process to perform in a certain way. A plan is developed on how to satisfy the customer’s needs. The project team is formed and each member is aware of their role in the project. A project charter is drafted and published. The scope of the project is well defined in the Identify Phase. Clear objectives and boundaries are very important to minimize scope creep. Typically a project will be focused on a specific subsystem. Different tools are used to help define scope such as developing a function model, In / Out of scope diagram, and a SPIOC chart. The Identify Phase should produce a project that is specific, measureable, actionable, relevant, and time bound (SMART).

Define Phase
The Define Phase begins by first identifying internal and external customers. It is important to understand who your customers are to understand their wants and needs. For instance an assembly line worker is an internal customer to a design engineer. The assembly line workers require products that are easy and ergonomic to assemble and mistake proofed. Next Quality Function Deployment (QFD) is performed. QFD is a process of translating the Voice of the Customer (VOC) into engineering requirements. Engineering requirements are specific ways of ensuring the customer needs are met. It is a way to best assure that the products designed will be purchased by customers over other competitive offerings. The House of Quality (HOQ) matrix (Figure 2) is a tool utilized in QFD to graphically link engineering requirements to the VOC. It also prioritizes VOC in relative importance to the customer. The HOQ will aid to analyze the VOC and prioritize them into “Critical to Quality” (CTQ) needs. CTQ’s are key measureable characteristics of product or process whose performance standards or specification limits must be met in order to satisfy the customers. CTQ’s will then be mapped to functional requirements to ensure engineers have something to design towards. Functional requirements are what the product or process must do to satisfy the customer. Each functional requirement will have a specific design metric that must be met. These metrics will be tested in each prototype design to ensure the product meets or exceeds the customer expectations.

Other tools such as the Kano Model (Figure 3) are used to determining customer requirements. The Kano Model maps customer requirements into basic, performance, and excitement needs against the competition in order to determine where the product design is weak. Focus groups, market surveys, or interviews are other means to capture what the customer wants and how they use the product.

The Define Phase will produce well defined customer requirements that are translated into engineering requirements. Engineers now can begin developing a product that is defined by the customers. Engineers will design a product to meet the engineering requirements that were determined by the VOC.

Develop Phase
It is in the Develop Phase where 80% of the cost of a product is spent. The most important decisions are made in this phase. Opportunity for innovation is greatest in the Development Phase. Validation tests are generated to ensure that each of the engineering requirements is met. Performance metrics are set for each validation test that must be reached or exceeded. Design constraints are set such as costs or quality targets. Design concepts are generated for the product or process. The concepts are sorted using a Pugh Matrix to determine which concepts work the best. The Pugh Matrix may rate the design concepts based on cost, complexity, function, ease of implementation, quality, etc.
Figure 2: The House of Quality (HOQ) matrix
Functional requirements are mapped to design parameters in a process called Axiomatic Design. The functional requirements are the “what it does” of a design while the design parameters are the “how it does it”. For example in a bathroom faucet a functional requirement is control flow rate while the design parameter would be to turn on tap. An excellent design concept is one that is uncoupled. An uncoupled design has no performance tradeoffs. A facet for example may have two functional requirements: to control flow rate and to control temperature. A coupled design would be to use two valves for the design parameters: one hot and one cold. The design is coupled because you can’t control temperature and flow rate independently. An uncoupled design could use an alternative faucet that uses the handle lift to control flow and the handle rotation to control temperature. Axiomatic Design uses this methodology to map design parameters to functional requirements in a matrix form. Coupled and uncoupled designs are easily recognized in a matrix form.

The Develop Phase will produce design concepts that are uncoupled (if possible) because they will be have no performance tradeoffs, little system complexity, and will allow for effective robust optimization in the Optimize Phase because the effects are additive and are not interactive.

Optimize Phase
The Optimize Phase is the most comprehensive Phase. The purpose of the Optimize Phase to develop the product to be robust. Robustness is defined as …

"the state of performance where the technology, product, or process is minimally sensitive to factors causing variability (either in the manufacturing or end users environment) at the lowest possible cost."

Robust optimization uses orthogonal arrays to develop efficient Design of Experiments that are balanced. The Optimize Phase begins by conducting the eight step parameter design process.
3. Eight Steps to Parameter Design

1. Define Scope for Optimization
2. Identify Ideal Function / Response
3. Develop Signal and Noise Factor Strategies
4. Establish Control Factors and Levels
5. Execute and Control Data
6. Conduct Data Analysis
7. Predict and Confirm
8. Document and Verify

Robust design strategies employ system thinking. A design concept can be looked at as a system with inputs and outputs. A system is a set of connected activities or functions that are designed to work together to perform a specific function and produce an intended outcome. It is often best to think of the system as energy going in, undergoing some sort of transformation, and then going out. A brake system for example would have hydraulic pressure (potential energy) going into the system and this pressure being transformed into kinetic energy to move a pad against a rotor. The pad would create friction and brake torque, creating heat energy.

3.1 Define Scope for Optimization

The scope is used to focus on a particular subsystem to simplify the project. A system can be broken down into individual subsystems working together. A project scope would define systems that are included and not included. A brake system is a subsystem of a vehicle for example. The brake subsystem will be the projects focus. It can be simplified further by breaking the subsystem down into individual components such as rotor, pads, caliper, etc. focusing the project further.

3.2 Identify Ideal Function / Response

In every engineered system, there exists some form of perfect or ideal relationship between the input to the system and the output. This ideal relationship is the ideal function. The ideal function of a brake system for example, is to take pressure generated from a pedal and translate that into brake torque to stop the vehicle. It is helpful to create a P-Diagram to illustrate graphically a brake systems function. A P-Diagram will show the energy inputs, transformation, and outputs of the system. It will also have noise factors that enter the system. Noise factors are sources of uncontrollable variation that affect a systems function. There are three types of noise factors: outer noise such as environmental conditions, inner noise such as aging or deterioration, and between product noise such as manufacturing variability. Control factors are also included and affect the systems functionality. Control factors are any design parameters of a system that engineers can specify their nominal values for and maintain cost effectively.

![Figure 4: A-P diagram for system functionality](image)

3.3 Develop Signal and Noise Factor Strategies

To test the system engineers will develop various input signals over the systems range of use. For the above brake system example three different input levels of pressure will be used representing the range of the braking system: M1=light pressure, M2=medium pressure and M3=heavy pressure. The system will be tested in an environment conducive to variation. By testing the system in its worst possible environment engineers can determine which systems are better at mitigating this variation. Noise factors are chosen that will likely cause the system to perform at lower levels of performance. The noise strategy is to compound these factors together to introduce maximum variation. Each of the combination of parts used in the DOE will be tested at a worst case environment and a normal
operating environment. For the brake system example the noise factors chosen are: hot rotor, wet pad, and 80% worn pad + rotor. The noise strategy consists of creating two levels of noise to test the parts at. The first level is the worst case environmental conditions and the second level is the best case operating conditions. By testing at both these levels engineers can get a large contrast. The first noise level N1 = hot rotor, wet pad, and 80% worn pad, 80% worn rotor. The second noise level N2 = cold rotor, dry pad, and brand new pad. This creates contrast and will add variation to the system so engineers can later analyze what configuration produces the best result.

3.4 Establish Control Factors and Levels
An orthogonal array is selected to clarify how many different control factors and levels are going to be selected in the DOE. An orthogonal array is used to run a balanced DOE. By basing the experiments on an orthogonal array it is ensured that all possible combinations and levels occur together equally often. This is a much more efficient way of doing DOE’s than doing a full factorial. A full factorial would have hundreds or perhaps thousands of different combinations depending on the amount of control factors and levels selected. There are hundreds of different types of orthogonal arrays. Taguchi prefers to use an L-18 array because it forces a large variety of control factors and levels. An L-18 array will run 18 different combinations of a system with eight control factors at three different levels. Control factors are any part of the product system the engineer has design control over. They are carefully selected for each project. Engineers would like to see how much they contribute to the total variation of the system. The control factors for the brake system example could be rotor design, pad material, rotor material, etc. Each control factor will have a different design level. For instance the pad material is a controlling factor that could have three different types of material used. You could also use three different pad design shapes as another control factor. It is important to select large contrasting materials and design shapes in order to get large contrast. After the experiments are run the data will show how much each control factor contributes to the total variation of the system. This will allow engineers to make important decisions and get the best “bang for their buck”. Below is an L-18 Orthogonal array (Figure 5), it represents eight control factors listed on top P1, P2, …P8, and the numbers in the middle correspond to the levels at which the control factors will be tested at.

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Figure 5: L-18 Orthogonal Array with 3 Levels

3.5 Execute and Control Data
The orthogonal array will dictate that 18 design configurations will be run. Each of the 18 design configurations will have different combinations of control factors. These control factors are completely balanced to ensure all combinations occur equally together. Each experiment number will be run at three different input levels (M1, M2, M3) producing three different outputs Figure6. This experiment is repeated at two different noise strategies (N1 and N2) to get contrasting outputs. Each of the 18 experiments will produce outputs similar to the graph below. Notice a good combination of control factors and levels will produce lines that are very close together because the output will be less affected by the noise factors.
3.6 Conduct Data Analysis
After all the 18 experiments have been completed at two different noise levels the data can begin to be analyzed. Data analysis consists of six steps:

1. Calculation of Signal to Noise Ratio (S/N) and slope ($\beta$)
2. Response Table
3. Interpretation
4. Two-step Optimization
5. Predictions

For each experiment a S/N and $\beta$ will be calculated. The S/N is an index of robustness. The higher the S/N, the more the system is doing what it is intended to do. It measures the quality of energy transformation that occurs within a design. $S/N = \frac{\text{useful output energy}}{\text{harmful output energy}}$. As the input signal, energy transformation, output response, and noise factors come together, their combined effect creates the design’s S/N. The slope of the output response ($\beta$) is the sensitivity of the input signal to the output response. The equation for the brake system is similar to a slope of a line:

$$Y \text{ (output response)} = \beta \text{ M (input signal)}.$$  

A larger $\beta$ indicates the system is more sensitive towards the energy transformation.

Response tables are created by calculating the level averages for each control factor. A response table will sum up each of the S/N and $\beta$ for all the P1, P2, ... P8 control factors at each individual level 1, 2 and 3. This will give an engineer an idea of how much each control factor affects the S/N and $\beta$ and what level is the best choice for the optimal system design. Interpretation involves plotting the S/N and $\beta$ into a response graph. These graphs help visualize which level of control factors contributes the most to the S/N ratio and $\beta$ levels. Remember that these graphs represent the averages of all the control factors (from 18 experiments) at each level. Using the graphs engineers can interpret which control factors have the largest contribution to the S/N and $\beta$. Two step optimization begins by first selecting the control factor levels with the highest S/N. This process is aided with the response graph. Next $\beta$ is adjusted to the desired level. In the brake system example we wouldn’t want the brake to be too sensitive because this would equate to a customer tapping the petal and the car immediately stopping. $\beta$ would probably be adjusted to a lower level. A prediction is made of the optimal design vs the initial baseline design. By taking all the control factor levels with the highest S/N and best suited $\beta$ and then adding all the contributing S/N and $\beta$’s to the baseline an analytical prediction can be made. This will give engineers an idea of how much better the new design should be.
3.7 Predict and Confirm
The analytical prediction is now compared to the actual optimal design. All the selected control factor levels are built it into a final design. In the brake example it could be that pad material three, rotor design one, rotor material two, and pad design three is the optimal combination. This part is built and tested using the same procedure as the other 18 experiments. The final S/N and $\beta$ is calculated.

3.8 Document and Verify
After final S/N and $\beta$ is compared to the baseline. There should be a significant improvement. If for some reason there isn’t then engineers may need to pick different control factors or a different noise strategy. The ideal function could be adjusted also.

4. Tolerance Design
After the 8 step parameter design is complete the system will move into tolerance design. This is the final step of the Optimize Phase. In the 8 step parameter design process, optimum control factor levels are determined to assure that the system output becomes minimally sensitive to noise factors. This means that even if wider tolerances are used around theses factor levels, the system output will still yield minimal variability. Then the proper tolerances around these factor levels need to be fine tuned further, since some tolerances may further reduce the output variability. Tolerances not greatly affecting variability should remain the same. In Tolerance Design there will be a trade-off between quality improvement (variability reduction) and the cost to upgrade these improvements. The use of Analysis of Variance will determine the improvement as the tolerance of a factor is tightened. The Quality Loss Function will translate this quality improvement into monetary units. These cost values will be compared and then decided upon by management. The 6 main steps in tolerance design are:

1. Conduct an experiment using existing tolerances, or least cost tolerances.
2. Perform analysis of variance (ANOVA) on the experimental data, and obtain the current total variance and the percentage contribution from each factor.
3. Establish the Loss Function for the system output response, and calculate the current total loss.
4. For each factor, calculate the existing monetary loss using the Loss function.
5. For each factor, calculate the new monetary loss, the quality improvement (in loss) using the upgraded tolerance, then compare to the cost increase to decide if the upgraded tolerance should be used.
6. For factors to be upgraded, calculate the total quality improvement (in loss) and the total upgrade cost to determine the total net gain.

The Quality Loss Function was developed by Dr. Taguchi. His objective was to place a quantitative monetary value to quality loss resulting from functional variation. Dr. Taguchi determined that a quadratic equation is representative of relating economic loss and deviation of the output response from its target value. The loss function that Dr. Taguchi uses is an approximation of a Taylor Series expansion around the target value, $m$.

The Quality Loss Function Figure 7, is given as:

$$L(y) = k (y-m)^2$$

$L$ = is the loss in dollars per unit product when the output response is equal to $y$.
$y$ = the value of the output response (length, width, concentration, etc.).
$m$ = target value of $y$.
k = a proportional constant based on financial importance.
By estimating the cost of repairing a part of the system, knowing the target value, and using the design tolerance limits, engineers can place a monetary quality loss value to parts that are even in the specification limits. Traditionally quality was defined by parts being in the specification limits and if you were in specification then the parts were equally all good. Look at the diagram below. If you were trying to hit the blue target what shooter would you prefer?

A study was done at Ford Motor Company, showing that transmissions with parts closer to target values functioned better and operated more quietly even though all the parts were in specification. The closer a part is to its target value the more satisfied a customer will be with the parts performance and this translates into higher profits. Dr. Taguchi’s Quality Loss Function shows that even though parts are in specification someone is paying for the cost of quality as the part deviates from its nominal value.

Engineers will follow the 6 step to tolerance design to determine what how much each individual part of their system contributes to the output response using ANOVA, establish a Quality Loss Function to determine if it is worth the cost to upgrade the parts, determine possible new upgrades and the associated costs and their performance improvements to the output response, and relate these improvements to the ANOVA results to see if the upgrade is worth the added cost of the new part. Tolerance design is an excellent tool for engineers to justify an upgrade or improvement to their system. By establishing a Quality Loss Function engineers can calculate return on investment to help persuade management to go forward with the improvements or upgrades. The Optimize Phase should produce a system that is minimally sensitive to environmental conditions that cause variability. The system will be at the lowest possible cost after completing tolerance design.

5. Verify Phase
The objectives of the Verify Phase are to assure that the customer receives all the benefit possible from the product. A series of tests are performed on the optimal system. High priority requirements derived from the Define Phase are used to validate the design. These tests are usually included in the products DVP&R. The tests are subjected to various noise factors to ensure they perform adequately. The brake system might be tested in a vehicle using wet pads while driving down a 20% grade. This test would be done on the baseline brake system and the new brake system to get contrast. A series of performance tests would be conducted to fully assess the new design.
6. Conclusions
Taguchi’s methodology is not the only approach to DFSS. Six Sigma’s approach uses a DMADV (Define, Measure, Analyze, Design, and Verify) framework rather than the IDDOV framework. Either method has their strengths and weaknesses. Dr. Taguchi’s tools and techniques are invaluable to the DFSS process. Dr. Taguchi’s use of orthogonal arrays vastly simplifies DOE’s. It is the most efficient and effective way to properly run balanced DOE’s without having to run a full factorial. The S/N methodology is unique. It forces engineers to look at their product as a system of energy transfer. Engineers can optimize their product by directing the energy to go where it is intended. The Quality Loss Function places a monetary value to loss of quality. Quality is no longer intangible and can be measured and calculated to persuade management towards or against certain decisions. DFSS does not have to follow the entire IDDOV process. Projects can follow an IDD path where a design concept of a subsystem is identified, defined, and developed. Or projects can follow an IDDOV path where a previous product design is made to be more robust. Utilizing certain areas of the DFSS process reduces the project size and complexity. DFSS is being practiced and accepted more and more in industry. Thousands of case studies have been published showcasing its success in all sorts of industries from farming to science & biology. As more and more emphasis is placed on efficiency and quality DFSS will continue to grow.

References