Readiness Plan

TRANSFER FUNCTION-BASED DESIGN TO IMPROVE PRODUCT RELIABILITY AND ROBUSTNESS IN DESIGN FOR SIX SIGMA

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System reliability is a key requirement for a system to function successfully under the full range of conditions experienced in the oil industry. From a probabilistic viewpoint, reliability is defined as the probability a system will meet its intended function under stated conditions for a specified period of time; therefore, to predict reliability, you must know three things:

1. Function.
2. Stated conditions.
3. The specified useful life or time period.

A typical textbook that addresses reliability will present a set of probabilistic concepts, such as a survival function, failure rates and mean times between failures. These concepts are related to a model of the causes of failure, such as component reliabilities or material and environmental variability. To quantify, specified operating conditions are defined as an agreed-upon range of allowable conditions or an estimated probability density function for uncertain or variable parameters. This approach is well suited to calculating predicted failure rates when all of the data are available.

To improve reliability prediction capability when useful data are not available or not sufficient, an alternative approach can be:

- Identify all potential function failure modes, make a risk assessment and implement countermeasures.
- Make the product insensitive to user environments.
- Identify shortfalls in verification test plans and enhance verification tests to ensure detection of all failure modes.
- Execute efficient verification tests that demonstrate a product is mistake free and robust under real-world use conditions.

System reliability requires fulfilling two critical conditions: mistake avoidance and robustness.[1]

Mistake, in this case, is defined as the error due to design decision and manufacturing operations. Examples of mistakes in product development include missing components, installing a component backwards or interpreting a software command as being expressed in inches when it's actually in centimeters. Product reliability can be improved by reducing the incidence of such mistakes through a combination of knowledge-based engineering and problem-solving processes, such as Six Sigma's define, measure, analyze, improve and control (DMAIC).

Robustness is the ability of a system to function (that is, insensitive to the user's environment to avoid failure) under the full range of conditions that may be experienced in the field.

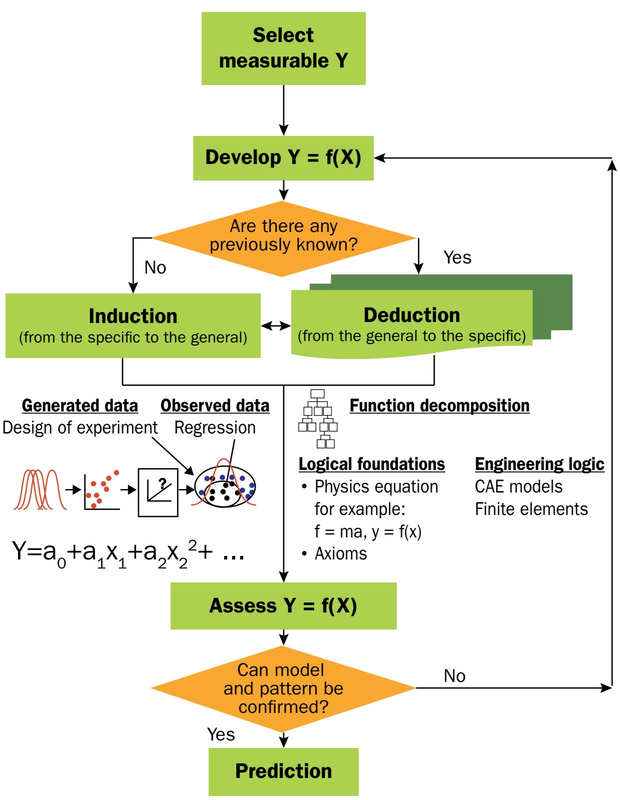
System design faces two different challenges:

1. Developing a system that functions under tightly controlled conditions, such as in a laboratory.
2. Making that system function reliably throughout its life cycle as it experiences a broad set of real-world environmental and operating conditions.

An example of this real-world challenge is effective system reliability engineering. The most cost effective and least time consuming way to make a reliable product—one that's insensitive to the user environment, or robust—is to start in the development or design phase by discovering and preventing failure modes soon after they are created, and implementing countermeasures before production.

This article covers the second challenge—robustness—by proactively factoring design for reliability (DFR) efforts through transfer function-based robustness improvement in the design for Six Sigma (DFSS) approach. DFSS is a method that calls on many of the fundamental design tools such as robust design. By using DFSS along with a well-defined reliability plan, you can know when to use which tool and how to integrate each together to produce a reliable product in the shortest amount of time.

Figure 1. **Transfer function development process flow**



CAE = computer-aided engineering

Adapted from Matthew Hu and Kai Yang, "Transfer Function Development in Design for Six Sigma Framework," *Society for Automotive Engineering Journal*, April 11, 2005.

A transfer function is a useful tool, if it's validated properly, that you can leverage to understand physics, explore design space and optimize a design in terms of reliability and robustness. Knowing the transfer function Y = f(X) between input and output, you're able to simulate the design performance with minimum hardware requirements or without building prototypes or building minimum prototypes. The variables in the transfer function can be characterized from an engineering viewpoint. Transfer functions then can enable engineers to introduce variation into the models to understand how the distribution of variation can alter the desired performance by the following:

- Find the combination of control factors settings that allow the system to achieve its ideal function.
- Remain insensitive to those variables that cannot be controlled or that are not intended to be controlled.

This approach allows engineers to predict what will happen in actual applications. The essence of the robust design approach is to design built-in quality. Instead of trying to eliminate or reduce the causes for product performance variability, it is preferable to adjust the product design so product performance is insensitive to the effects of uncontrolled (noise) variations through transfer function deployment.

Transfer function overview

A transfer function is a relationship between input (lower-level requirements) and output (higher-level requirements). Transfer functions are set up as equations and are expressed in Y = f(X) terms. Transfer functions are either developed analytically or experimentally that directly measure the customer needs.

Y is the output response measurement such as product strength or customer satisfaction. The transfer function explains the transformation of the inputs into the output. X is any input process step that is involved in producing the output, and Y is the intended design functions cascaded from critical to satisfaction (CTS) and others. The transfer function may be mathematically derived (for example, spring force and displacement [Y = kx]), and empirically (inductive) obtained from a design of experiment (DoE) or regression based on the historical data (for example, Y = a0+a1x1+a2x22+… polynomial approximation).

In general, a transfer function is established through an analytical or empirical approach. For a proper transfer function development, a rational structure of a design is needed to assess where to start the transfer function development. The transfer function development process is similar to the inductive and deductive feedback loop. The process of developing or updating a transfer function is highly iterative, moving frequently between the inductive and deductive paths. Occasionally, the transfer function is known explicitly and can be determined through the understanding of the physics of the system. At other times, the transfer function is unknown and must be estimated empirically through directed experiments or by the analysis of already available data. Figure 1 shows how a transfer function can be established.[2]

Deductive reasoning is the process by which an engineer makes conclusions based on previously known facts such as:

- Logical foundations—for example, physics equations, the study of structure, change and space patterns, and axioms.
- Engineering logic—for example, finite element and mathematical modeling-proposed engineering design.

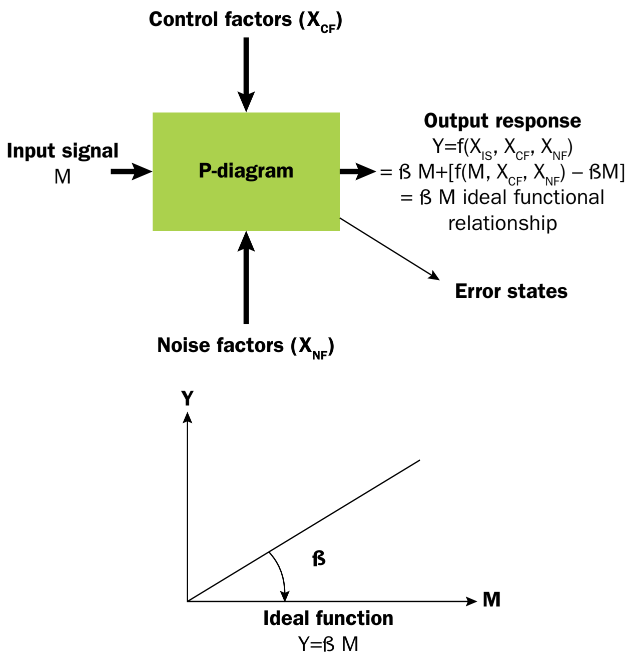
This method of reasoning is a step-by-step process of drawing conclusions based on previously known truths from engineering validation. Although deductive reasoning seems rather simple, it can be misleading in more than one way. When deductive reasoning leads to faulty conclusions, the reason is often that the premises were incorrect; thus, the model validation is important.

Transfer functions can be schematically represented by the P-diagram used in robust engineering design, as shown in Figure 2. A product can be divided into functionally oriented operating systems. Function is a key word and basic need for describing your product or behavior. Regardless of what method is used to facilitate a design, they all have to start with the understanding of functions. Questions include: "What is the definition of function?" and "How is the function defined in these disciplines of a specific design?" Understanding the specific meanings of function (or the definition of function) within each of these disciplines could help take the advantages of tools to improve design efficiency and effectiveness.

Transfer functions can enable engineers and scientists to introduce variation into the models to understand how the distribution of variation can alter the desired performance. A flowchart showing development of a transfer function using the computer-aided engineering (CAE) model is shown in Figure 3 (p. 12).

Inductive reasoning is the process of arriving at a conclusion based on a set of observations (from the specific to the general—for example, through DoE or

Figure 2. **P-diagram**



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regression analysis). Inductive reasoning is valuable because it allows engineers or scientists to form ideas about groups of things in real life. In engineering, inductive reasoning helps organize what is observed into engineering hypotheses that can be proved using more reliable methods. The process of inductive reasoning almost always is the way ideas are formed about things. After those ideas form, it is possible to systematically determine (using formal validation) whether the initial ideas were right, wrong or somewhere in between.

Robust design overview

Robust design, also known as Taguchi parameter design, can be used to achieve robust reliability; that is, to make a product's reliability insensitive to uncontrollable user environments. Robust design is the heart of DFSS.

An important development in reliability engineering is robust design pioneered by Genichi Taguchi.[3] For any design concept, there is a potentially large space of control factor settings that will nominally place the function at the desired target value. Taguchi's method employs orthogonal arrays to explore the design space. At the same time, outer arrays or compounded noises are used to explore the range of possible operating conditions. Further case studies and research show that compound noise factor theory turns out to be the sufficient conditions for robustness and reliability improvement. In a reliability engineering test, compound noise strategy can be considered an effective way of improving reliability confidence tests.

Robust design requires the evaluation of product control factors in the noisy environments from which classical multi-factor designed experiments seek isolation. Taguchi recommended that noise factors be considered in any experiment to improve reliability where it is practical. Robust reliability design is closely related to accelerated life testing and worst case analysis in this requirement for exposure of design to combinations of extreme noise conditions under experimenter control.

Taguchi and other authors have written extensively on designing quality into products and processes.[4, 5] Their concepts have been widely adapted to design for reliability. The first concept of Taguchi that must be discussed is what he refers to as noise factors, which are viewed as the causes of performance variability, including why products fail. Figure 4 shows the reliability bathtub curve and Taguchi's type of noise.

By consciously considering the noise factors (environmental variation during the product's use, manufacturing variation and component deterioration) and cost of failure in the field, the robust design method helps ensure customer satisfaction. Robust design focuses on improving the fundamental function of the product or process; thus, facilitating flexible designs and concurrent engineering. When variability occurs, Taguchi said this is because the physics active in the design and environment promote change. Taguchi categorized noise into five categories:

1. Piece-to-piece variation, such as rubber thickness.
2. Change over time, such as failure from material wear, or changes in force or dimension with time.
3. Customer use, such as open-hole wellbore size.
4. The environmental condition, such as temperature variation.
5. System interactions, such as elements outside dimension variations and open-hole size.

The result of noise may be degradation in quality (soft failure) or a malfunction failure (hard failure). A product is said to be robust when it's insensitive to the effects of sources of variability, even though the sources themselves have not been eliminated.

Figure 4 illustrates how Taguchi's noise factors neatly

Figure 3. **Transfer function development using CAE model flowchart**

Step 1: Develop and validate a CAE model for a given design.

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Step 2: Develop a P-diagram with identified measurable ideal response (CTQ).

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Step 3: Generate a matrix for experiments over concerned design boundary.

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Step 4: Use CAE model to calculate response based on the experiment matrix.

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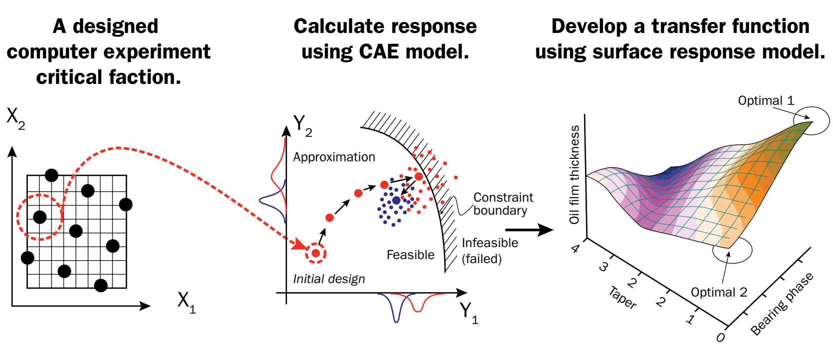
Step 5: Develop response surface capturing relationship between input and output using surface response modeling, for example, Kriging model.

CAE = computer-aided engineering
CTQ = critical to quality



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fit within the accepted model of product failures in reliability and their relation to the bathtub curve.

Robustness and reliability improvement

Categorically, there are five strategies for improving robustness and thus reliability:

1. Change the design concept or technology.
2. Make the design insensitive to noise factors.
3. Reduce or remove the noise factors.
4. Use a compensation device (for example, dynamically tuned absorbers).
5. Send the failure mode to another part of the system (trade-off) where it will do less harm.

As noted earlier, the second strategy for making the design insensitive to noise factors is the focus of this article.

M.S. Phadke stated that there are three fundamental ways to improve the reliability of a product during the design stage:[6]

1. Reduce the sensitivity of the product's function to the variation in the product parameters.
2. Reduce the rate of change of the product parameters.
3. Include redundancy.

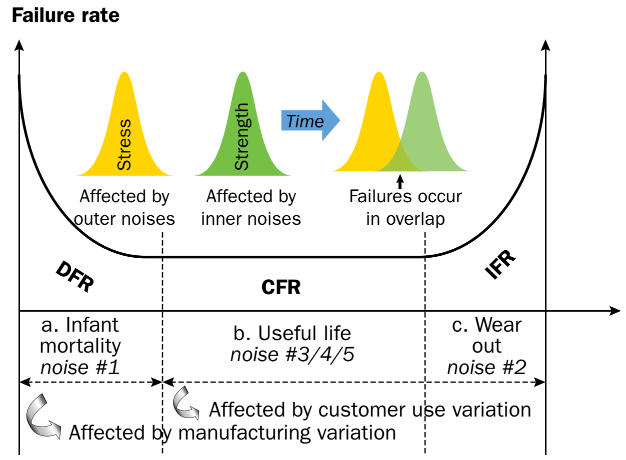
The most cost-effective approach for reliability improvement is to find appropriate continuous quality characteristics and reduce their sensitivity to all noise factors. Phadke provides simple examples of a robust design approach. In actual application, however, more than one strategy may be necessary.

DFR overview

DFR is a process. Specifically, DFR describes the entire set of tools that support product and process design (typically from early in the concept stage all the way through to product obsolescence) to ensure that customer expectations for reliability are fully met throughout the life of the product with low overall life cycle costs. In other words, DFR is a systematic, streamlined, concurrent engineering program in which reliability engineering is woven into the total development cycle.

The purpose of the DFR process is to provide requirements for DFR activities, which are intended to be an integral part of every product development effort to continuously improve product reliability and robustness. The reliability process integrates with a generic technology and product development process, and can be tailored as specified in the technology and product development process. The product development process defines the scope and applicability. The reliability plan documents the tailoring of the DFR activities.

Figure 4. **Reliability bathtub curve and types of noise mapping**



CFR = constant failure rate
DFR = decreased failure rate
IFR = increased failure rate

The reliability plan is created by the design team. It is the responsibility of the design team to implement the DFR by completing the activities outlined in this plan. The team must leverage a set of reliability engineering tools along with a proper understanding of when and how to use these tools throughout the design cycle. This process encompasses a variety of tools and practices, and describes the overall order of deployment that an organization must follow to design reliability into its products. The reliability is part of the DFSS scorecard. DFR tasks can be well aligned with and embedded in a DFSS roadmap.

To make reliability a key product requirement and understand where reliability efforts stand in terms of the DFR process for designing and manufacturing for reliability, a DFR assessment scorecard can be helpful. The DFR assessment drives reliability goal setting, understanding the quality history, tool selection activities, testing strategies and reliability demonstration through DFR gates review.

The DFR process can follow the DFSS roadmap—for example, the identify, design, optimize and validate (IDOV) framework. With reliability in mind, product program teams can identify the boundary and scope of system requirements and design the product. Meaningful test progression strategies can be developed and emphasized through optimizing the design over the time domain and functional validation of the product.

DFR activities are part of various elements in technology and product development activities during the complete product life cycle. Goals of the DFR process are:

- Integrate voice of customer (VOC) into product requirements to improve reliability and robustness of the product.
- Provide requirements for activities involved in the DFR/DFSS process. Optimize the design over the time domain and functional validation of the product using a test progression strategy.
- Identify methods for defining product reliability requirements and activities involved at each stage of product development.
- Provide the practitioner a means of prioritizing the reliability projects and studies that must be undertaken.
- Continuously improve product reliability and robustness over time.

DFSS overview

DFSS describes the application of Six Sigma tools to product development and process design. The goal is to "design in" Six Sigma performance capability. DFSS is an approach to designing (or redesigning) a product or service. It is equally useful in developing business processes or technical products. DFSS is a defined method—a culture and a way of viewing value creation.

The focus of DFSS begins with critical VOC analysis and rational business planning. After gaining an understanding of the market and customer needs, design personnel work to understand and characterize critical design parameters and functionality. To achieve a cultural shift—focused on continuous improvement—you must go beyond DMAIC by leveraging a full suite of performance improvement tools. The time to develop new products is a critical success factor in almost any business today. DFSS helps reduce development time by deploying lessons learned throughout the development and manufacturing setup process.

DFSS provides many tangible benefits to organizations. For instance, the DFSS approach results in long-term cost reductions for a product. There are many ways these savings are realized. Instead of debugging products and processes that already exist, DFSS is a re-examination of the function and design parameters.

DFSS starts from scratch with the goal of designing virtually error-free products or processes. This strategy effectively replaces the trial and error or built-test-fix processes, and results in product designs that consistently meet customer requirements. There are several different DFSS roadmap models:

- Invention, innovation, develop, optimize and verify (I2DOV).
- Define, concept, design, optimize and verify (DCDOV).
- Identify, define, develop, optimize and verify (IDDOV).
- Define, measure, analyze, design and verify (DMADV).
- Identify, characterize, optimize and verify (ICOV).

Each has a different focus on generic technology development or product commercialization. The roadmap names are not important,[7] but the contents and tasks at each phase as defined to enhance product development process are.

A typical DFSS approach includes the four ICOV phases:

1. Identify—Identify market needs. Define customer requirements and project goals. Identify critical to satisfaction (CTS) and related functional targets. Reliability is often a key CTS on the reliability aspects of a product.

The purpose of this stage for the reliability effort is to clearly and quantitatively define the reliability requirements and goals for a product, as well as the end-user product environmental and use conditions. These can be at the system, assembly, component or even the failure-mode level. Requirements can be determined in many ways or through a combination of those different ways. Requirements can be based on contracts, benchmarks, competitive analysis, customer expectations, cost, safety and best practices. Some of the tools worth mentioning that help quantify the VOC include Kano models, affinity diagrams and pair-wise comparisons. Of particular interest to DFR are the requirements that are critical to reliability (CTR).

The system reliability requirement goal can be allocated to the assembly, component or even the failure-mode level. After the requirements have been defined, they must be translated into design requirements and into manufacturing requirements.

2. Characterize—Understand the system and select design concepts. Map CTS characteristics to lower-level y factors. Relate y factors to critical to quality (CTQ) or CTR x design factors. Determining use and environmental conditions is an important early step of a DFR program. Know what it is to be designed for and what types of stresses the product should withstand.

DFSS IS A POWERFUL METHOD THAT CAN BE INCORPORATED INTO AN ORGANIZATION'S PRODUCT DEVELOPMENT PROCESS TO PROVIDE CUSTOMERS WITH SUSTAINED VALUE WHILE GENERATING GROWTH, REVENUE AND HEALTHY PROFITS.

The conditions can be determined based on customer surveys, environmental measurement and sampling.

The tendency for the potential failure-mode occurrence is aggravated by noise factors, which are those that engineers have little or no control and negatively influence designed system performance. Fundamental to designing for reliability and robustness using transfer function is the inclusion of noise factors during analysis that challenge the design and uncover potential failure modes.

After uncovered, these failure modes can be avoided by developing appropriate counter measures—either in the design or manufacturing process. Including noise factors in up-front design analysis has encouraged engineers developing transfer function to consider appropriate noise factors and realistic levels, as well as strategies to include them in simulations.

It is important to estimate the product's reliability, even with a rough first-cut estimate, early in the design phase. This can be done with estimates based on engineering judgment and expert opinion, physics of failure analysis, transfer functions-based simulation models, prior warranty and test data from similar products and components (using life data analysis techniques), or standards-based reliability prediction.

3. Optimize—Design for robust and reliable performance. That minimizes product or process sensitivity to uncontrollable user environment to have better manufacturability and higher reliability.

In this stage, robust parameter design helps further factor reliability tasks into the design process by optimizing design function in the presence of noise factors to:

- Identify important variables.
- Estimate their effect on a certain product characteristic.
- Optimize the settings of these variables to improve design robustness.

Noise screen experiments may be necessary to identify high-impact noise factors to single out significant factor results in more realistic reliability tests and more efficient accelerated tests (because resources are not wasted on including insignificant stresses in the test) prior to the robust optimization efforts.

Within the DFR concept, you are mostly interested in the effect of stresses on your test units. Robust design plays an important role in DFR because it assists in identifying the factors that are significant to the product's life, especially when the physics of failure are not well understood. The robustness of the given concept design can be used to assess the limitation of the given concept design from a reliability improvement perspective.

4. Verify—Assess the integrated system and subsystem effects on performance. Use reliability and manufacturing verification to assess design performance and the ability to meet customer requirements.

If the design has been "demonstrated," the product can be released for production. When reaching the manufacturing stage, the DFR efforts should focus primarily on reducing or eliminating problems introduced by the manufacturing process. Manufacturing introduces variations in material, processes, manufacturing sites, human operators and contamination. Because manufacturing piece-to-piece variation has been considered as part of noise factors and was optimized in the optimize phase, the product's performance should be insensitive to manufacturing variation if the noise factors were identified and incorporated in the optimize phase for the robustness study.

However, reliability may be re-evaluated in light of additional process variables. Design modifications might be necessary to improve robustness. For example, a design should require the minimal possible amount of nonvalue-added manual work and assembly. Whenever possible, it should use common parts and materials to facilitate manufacturing and assembling. It should also avoid tight design tolerances beyond the natural capability of the manufacturing processes.

Managing a DFSS project is not a trivial matter, and all of the key enablers must be in place to realize maximum benefit. DFSS is the way for an organization to realize Six Sigma's full potential. DFSS has substantial effects on long-term profitability through improved products and efficiencies. It results in increased customer satisfaction, improved market share and increased profit potential.

As you already have seen, reliability is a function of time and, therefore, depends on age. This implies that the useful life of a particular item may be defined. It turns out this concept is useful in Six Sigma because—by definition—DFSS is interested in designing a product to a specified life. The assessment of reliability usually involves testing and analysis of stress, strength and environmental factors, and should always include improper use by the end user. A reliable design should anticipate all that can go wrong. DFR can be viewed as a means to maintain and sustain Six Sigma capabilities over time and is one tool set in the DFSS method.

Using a structured process to gain insight to the customer's needs and translate them to tangibles, CTQ product specifications significantly reduces cycle time and ensures a higher probability of success. Using metrics, data and a rigorous approach, you can gain fundamental knowledge about the critical parameters of the product. This shared knowledge is instrumental in producing and selling high quality, consistent, cost competitive and profitable products.

DFSS is a powerful method that can be incorporated into an organization's existing product development process to provide its customers with sustained value while generating growth, revenue and healthy profits for itself.

Reliability and DFSS

Reliability is one of the most important characteristics of an engineering system. Reliability can be measured as robustness over time. A reliable product is insensitive to noise (uncontrollable user conditions) over time. Insufficient data or lack of useful reliability field data presents challenges of conducting meaningful reliability analysis, prediction and, therefore, proper decision making.

Analytical reliability and robustness using transfer functions enable engineers to introduce variation (for example, manufacturing piece-to-piece variation and aging) into the analytical models to understand how the distribution of variation can alter the desired performance. Reliability and robustness can be analyzed and optimized through transfer functions. Potential failure modes may be uncovered and discovered through a properly developed transfer function. Noise factors can be identified and included in transfer functions to uncover potential failure modes for reliability improvements in the up-front design phase. The design of swell packers for use in the energy industry is a perfect example of being challenged for proper reliability prediction when useful data are not available.

Product development has a huge impact on revenue stream and reliability. Enhancing product development process with DFSS disciplines will improve the product delivery process to develop a customized DFR process with required tools to support specific reliability tasks. It's more cost effective and less time consuming to make design insensitive to uncontrollable user environments using transfer function. DFR tasks can be best accomplished through a DFSS roadmap. σ

EDITOR'S NOTE

Six Sigma Forum Magazine will publish the second installment of Hu's article in the November 2013 edition. That article will present a case study of swell packer reliability improvement using transfer function.

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