CHAPTER 75

Design and Process Platform Characterization Methodology

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1. INTRODUCTION

Quality is ultimately defined by customers. There is significant literature available on how to measure quality and value as perceived by customers. In virtually every analysis, a major component of customer satisfaction is the ability of the company to provide a competitively priced product into which quality is designed, built, marketed, and maintained. A company-wide system for achieving that objective must be developed and deployed.

This chapter outlines a complete design and process platform characterization methodology and the system for deployment. The underlying principle of this methodology is to provide a vehicle that starts with identification of customer requirements and ends only when the product has been delivered to a customer who is thoroughly delighted.

This chapter is based on an actual corporate deployment. This provides clear evidence that the methodology works. It also demonstrates that this methodology is a critical part of strategic management that will dependably produce superior profits through satisfied customers.

The elements of design and process platform characterization methodology and system include:

- Product development
- Design characterization
- Process platform development
- Design and process platform characterization methodology

- Linkage of product design and process platform
- Deployment process

Each of these will be discussed in detail in subsequent sections.

2. PRODUCT DEVELOPMENT

Traditionally, product development includes initial research, prototype production, design finalization, and transfer to manufacturing. Today's fast-moving market requires a product-development process that is integrated and efficient. This demands up-front planning and execution of design optimization and manufacturing platform-development activities that ensure conformance to end-product requirements.

2.1. Product Development Process

The product development process consists of six stages; initial stage, specification alignment stage, initial models stage, product released to initial manufacture stage, production ramp stage, and product maintenance stage.

2.1.1. Initial Stage

The purpose of the initial stage is to assemble the relevant information for the product-development team, which includes marketing, design, manufacturing, supply chain, operations, and finance, and to make a fact-based go/no-go decision to develop the product. A go decision requires allocating the resources needed to document detailed specifications and plans for the development of the product. The specific goal of this stage is to evaluate the product concept efficiently and objectively as a function of strategic fit, competition, finance, operations technology, market window, and available resources.

2.1.2. Specification Alignment Stage

The primary function of the specification alignment stage is to generate the information that is required to decide whether to allocate resources to design and develop the proposed product. The product-development team develops detailed initial product specifications in response to market requirements. This permits proper project management by creating accountability for completion of the elements that make up this stage. The specification alignment stage is critical to ensure that sufficient lead time is available to develop, acquire, and prove in any new product and process platform facilities needed to ramp the product according to the business plan.

2.1.3. Initial Models Stage

In the initial models stage, product, test programs, software, and associated hardware are designed and developed. Completion is achieved when prototype hardware/software is fabricated and initial evaluation is started. This stage confirms that the initial model results match the initial product specifications. Finally, a ready-for-production checklist is reviewed by the product development team. One of the critical elements of this stage is the development and implementation of design and process platform characterization objectives and plans.

2.1.4. Product Released to Initial Manufacture Stage

The purpose of this stage is to ensure that product is released to production and validation of manufacturability, procedures, documentation, and customer demand is established. This activity verifies compliance of product and system performance, fixes design issues, and prepares for manufacturing ramps. At the end of this stage, the execution of design and process platform characterization plans are well in progress. This includes identification of critical design and process platform performance parameters, estimation of accuracy and precision for test systems, and planning and validation of experiments. In addition, product performance qualification testing, environmental testing, and final system testing progresses during this stage.

2.1.5. Production Ramp Stage

The launch through production ramps is where all the final product qualification, final manufacturing platform tests, design characterization, and process platform characterization requirements are completed. The purpose of this stage is to ensure that all required documentation is in place to efficiently support the release of the product to the market. The product development team also defines and implements plans for stable ongoing manufacturing, which includes validation of design and process models, control of critical platform processes, and surveillance testing. Appropriate product-

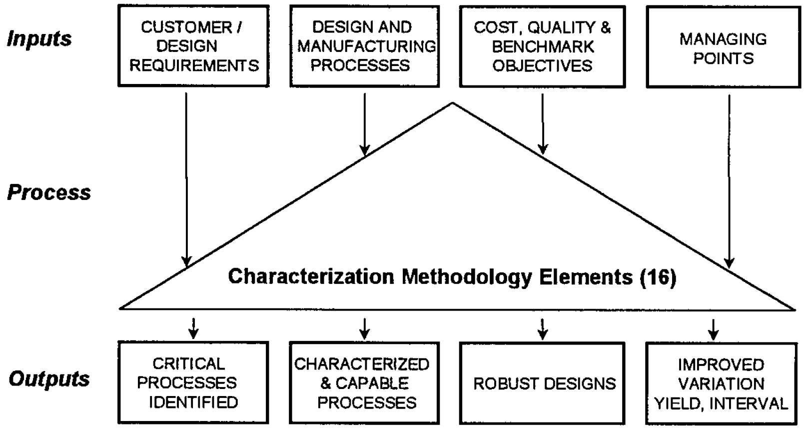


Figure 1 Characterization Overview.

maintenance plans, business strategies, and product-performance enhancements are established. This is the stage where product robustness and meeting all market and customer requirements are demonstrated.

2.1.6. Product Maintenance Stage

The focus of the product-maintenance stage is to ensure continued product success in the market. The manufacturing and operations teams ensure that product meets all requirements and continues to be robust. This activity ensures stable shipment of product to customers. In addition, periodic quality assurance audits are conducted to determine continued compliance relative to quality system requirements. This is the stage where all required design and platform activities are validated using large samples and appropriate corrective actions and continuous improvement activities are implemented.

2.2. Need for Characterization

Customer requirements and intense competition demand high level of product performance, reliability, and lower costs. This message has profoundly affected corporate America in its strategic goals and objectives as well as day-to-day business policies. During the 1990s we experienced an enormous advancement in all facets of technology. We now see products that have higher performance, more features, and in some cases lower costs. To meet these challenges, it is critical to characterize designs and processes/platforms to optimize the cause-and-effect relationships between customer performance requirements and process tolerances. The absence of this characterization can lead to a lack of consistency, resulting in ineffective planning and eventually higher costs.

2.3. Characterization Overview

Characterization is aimed at improving the overall business by enabling a better understanding of designs and processes. Characterization can be viewed as a process in itself defined by a set of inputs and activities to produce desired outcomes. One such view of a characterization process is shown in Figure 1. It includes a summary of inputs and expected outputs and a characterization methodology. The characterization methodology includes the specific steps for achieving robust designs and processes. The specific steps to the characterization methodology are described in Section 5.

3. DESIGN CHARACTERIZATION

3.1. Understanding Customer Requirements

Customer needs for product performance, reliability and quality are a given in today's market. Customers are no longer bound by national interests as they pursue quality products and services worldwide. To be competitive in this environment, businesses must exceed the needs of their customers by providing products that are high quality, cost effective, and reliable. The standard approaches for

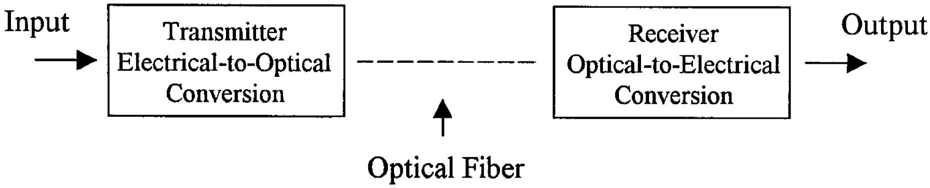


Figure 2 Fiberoptic System.

comprehending customer requirements include review of product specifications and drawings, performance evaluation of similar technology, and simulated testing for customer's application.

Communications with customers is the most important approach for understanding their requirements. This can be initiated by the customer as well as by the supplier. The customer-initiated feedback can be through formal product requests, product returns, field application data, and audits. The supplier-initiated feedback may include product-performance reviews, market trends, technology integration, competitive analysis, and design-characterization models.

3.2. Design Models

Design models are cause-and-effect quantitative models that translate product performance requirements to process requirements and identify key in-process output parameters and associated tolerances. Control of these parameters at in-process steps during manufacturing will generally ensure conformance to end-product requirements. In effect, design models establish the linkage between customer and manufacturing requirements. Design models are typically generated from current knowledge of existing technologies, proven theories, and data from planned experimentation. It is the experimental data that provides the new insight for a specific design. A formal characterization methodology is described in Section 5.

As an example, design models were developed for a fiber-optic system that includes three elements, the *transmitter*, which allows for data input and produces an optical signal, the *optical fiber*, which carries the data, and the *receiver*, which converts optical signal to electrical signal to output the data. Figure 2 depicts the key elements of a fiber-optic system.

3.2.1. Example: Optical Transmitter Design Model

An optical transmitter is the device that generates the signal that is sent through an optical fiber. One of the product parameters that is critical to transmitter performance is optical output power. The optical output power level that is delivered to the fiber is inevitably lower than what the light source generates because of transfer losses. The optical output power of a transmitter is affected by many design parameters, including parameters related to the laser chip, lens, optical fiber, and processing. Figure 3 depicts key elements of a transmitter.

As an example, a design model linking the relationship between key characteristics of these elements and optical output power is:

$$\text{Optical output power} = f\{\text{laser facet power, laser placement, lens placement, fiber alignment} \ldots\}$$

In this model, optical output power is impacted by the manufacturing processes, which include

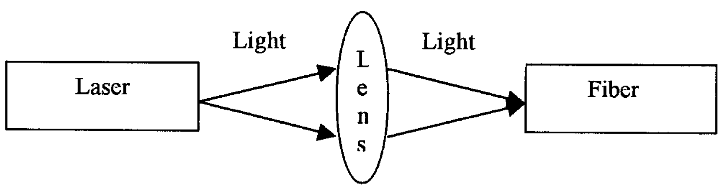


Figure 3 Transmitter Elements.

laser fabrication and the processes associated with laser, lens, and fiber attachment. Hence, control of these processes will ensure conformance to design requirements for optical output power.

4. PROCESS PLATFORM DEVELOPMENT

In addition to characterizing designs, manufacturing processes must also be characterized and controlled to achieve overall business objectives. When a design reuses well-established processes (i.e., platforms), improved time-to-market and reduced development and manufacturing costs can be achieved. This section describes an approach to developing these process platforms.

4.1. Process Platform Concept

All products are built on a series of processes to meet customer requirements and achieve desired performance measures. As products change or new products are introduced, many advantages are gained by the reuse of existing processes. These advantages include minimizing the cost in the development and introduction of new processes. In addition, overall time-to-market can be reduced by the elimination of process-development time in the product-development cycle. Also, requiring new process development as part of new product introduction reduces the probability of overall success of the project due to the additional variable of successful process development to achieve successful product development. However, reusing existing, well-understood processes makes both performance and impact on manufacturing known. The platform concept relies on establishing such processes and taking advantage of their capabilities to achieve new design goals. To introduce the platform concept into a business the following key elements will need to be developed for successful implementation:

- Common definition and understanding of platform concept
- Platform scope based on business plans
- Migration plans
- Characterization plans
- Platform capabilities and requirements

4.1.1. Platform Definition

The definition of platforms to a particular business needs to be jointly developed and communicated throughout all organizations (manufacturing, development, design, and marketing). This definition needs to be tailored to fit the company's infrastructure, systems, and culture for it to be effectively deployed. However, any definition of a platform should include elements of commonality, reusability, characterization, and capability. An example of one such definition is given in Figure 4. The platform definition will provide an organization with the basic framework to determine which processes are to be considered as platforms. In some instance, various levels of platform can be defined to allow for some additional platform flexibility. For example, a level one platform may mean no changes are allowed, a level two platform may allow for changes to process settings, a level three platform may allow for changes to fixturing, and so on.

COMMON:
- Process is used on a variety of product codes and families

REUSABLE:
- Process is used for several generations of product designs

WELL DEFINED:
- Defined Boundary Conditions & Design Guidelines (what it can and can't do)
- Characterized, Stable and Capable Process Inputs and Outputs
- Defined Characteristics, Documented

COMMON CHARACTERISTICS:
- Methods: Common procedures, sequence, recipe (inputs)
- Skills: Defined training requirements (skill needs - operating & engineering)
- Hardware: Machine, Equipment (function & features)
- Materials: Common piece part characteristics, Material composition
- Environment: Controls, Conditions

Figure 4 Process Platform Definition.

4.1.2. Platform Scope

To implement platform processes successfully, an organization needs to develop fundamental business plans in terms of market perspective, technology directions, and existing manufacturing capability. From a market perspective, detailed market plans need to be established that identify direction of future product performance requirements in the markets it serves. From a technology standpoint, technology roadmaps are needed to set design and technology plans that provide design direction to achieve future product performance requirements. From manufacturing, the capability of existing processes and technologies need to be well understood and defined to determine the impact of design changes on process capabilities. All of this information needs to be integrated to develop comprehensive platform plans and objectives.

4.2. Process Platform Implementation

4.2.1. Platform Migration

If the implementation of platforms includes processes already used in manufacturing, then individual platform-specific plans need to be developed to migrate existing products onto the platform. A typical process for the development of these migration plans is shown in Figure 5.

Each product should be evaluated to determine whether it should be migrated to the platform. This evaluation should also consider future products and designs. The evaluation has two key parts associated with it. First, a business case needs to be developed to determine what are the specific expected benefits in terms of cost, interval, capacity improvements vs. the cost of implementation of the platform. Second, there needs to be an assessment to establish the technical feasibility of manufacturing the product using the platform. The technical feasibility must be done from both the design and process viewpoints. This will require that both process and design characterization have been completed. Once both benefits and technical feasibility have been demonstrated, specific experimental and qualification plans can be developed and implemented to migrate products onto the platform.

4.2.2. Platform Characterization

As per the definition, a platform must be well characterized to provide the confidence that the performance achieved from this process is sustainable. This characterization activity will lead to the

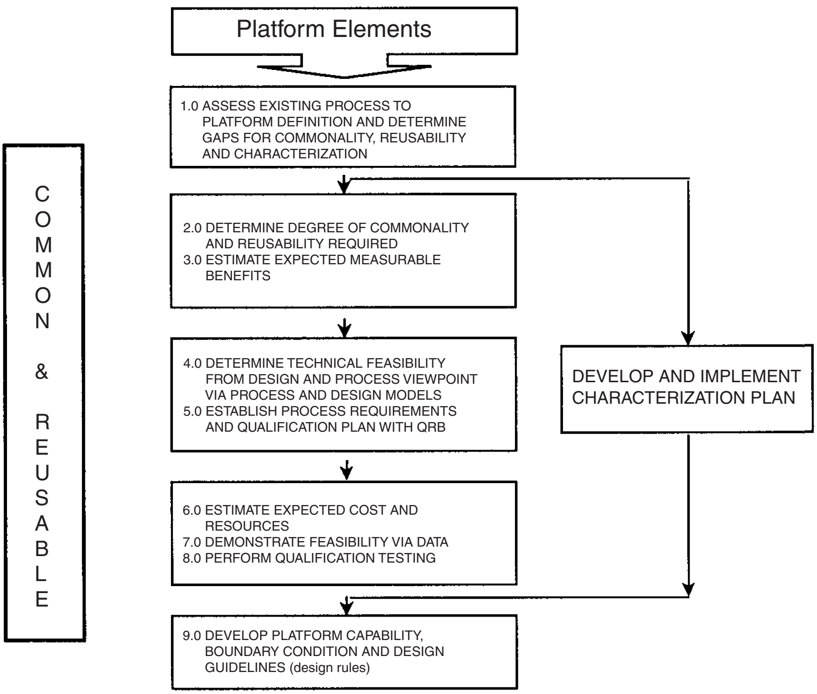


Figure 5 Platform Migration Methodology.

development of a process model, which is a cause-and-effect quantitative model that establishes the relationships between process requirements and process variables. The process model identifies key process inputs and level of control (i.e., tolerances) needed to achieve desired process performance. An example of such a model is given in Section 5. As with any tolerance, if it is unnecessarily tight it may lead to overall higher processing costs and if it is too loose it may result in producing defective product. A formal methodology to characterize platforms and processes is described in Section 5.

4.3. Process Platform Capability

4.3.1. Boundary Conditions

Upon completion of characterization, a platform's true capability can be determined. This capability provides design organizations with tolerances to design within. These capabilities must be defined relative to appropriate constraints on process conditions. These constraints are termed boundary conditions. Process boundary conditions must be defined that clearly specify any restrictions necessary to achieve the capability and benefits of the platforms. These boundary conditions can include restriction to process settings, fixture requirements, environmental conditions, process methods or sequences, and so on. Thus, these conditions provide design groups with what a process can and cannot achieve.

4.3.2. Platform Performance

For each performance characteristic, the associated process capability needs to be defined. Capability is evaluated in terms of the ability of the process to meet its target and in terms of reproducing results consistently (i.e., process variation). Capability is developed through collection and analysis of performance data after process characterization and control has been established. The resulting measures define the expected performance of a platform. This information is critical input into design in terms of expected product performance.

5. DESIGN AND PROCESS PLATFORM CHARACTERIZATION METHODOLOGY

Each business must have a sound approach for understanding and improving its processes and designs. The design and process platform characterization methodology presented here is one such approach that has been proven successful in modeling, controlling, and improving products and processes. This approach, shown in Figure 6, provides the detailed steps and associated tools to achieving process and design goals.

The methodology consists of five major elements:

- Process definition
- Measurement system characterization
- Design and process characterization (i.e., model development)
- Process control
- Process capability

5.1. Process Definition (Steps 1 and 2)

5.1.1. Step 1: Identify Critical Designs and Processes

Products are built on a series of processes, each with its own impact on the overall performance. The purpose of this step is to determine which processes need to be characterized. A process includes the combination of people, equipment, materials, methods, and environment that produces products or services. Any process whose inputs and outputs are measured, monitored, controlled, or observed should be evaluated. Designs and processes for characterization are typically identified based on their overall impact to the business. A critical design and process is one that has major impact on cost, quality, manufacturability, performance, reliability, or customer satisfaction. Some of the methods and tools available for determining this are given below:

- Product performance analysis
- Design and reliability reviews
- Customer field returns analysis
- Quality function deployment
- Quality improvement methodologies
- Cost of quality
- Fishbone analysis

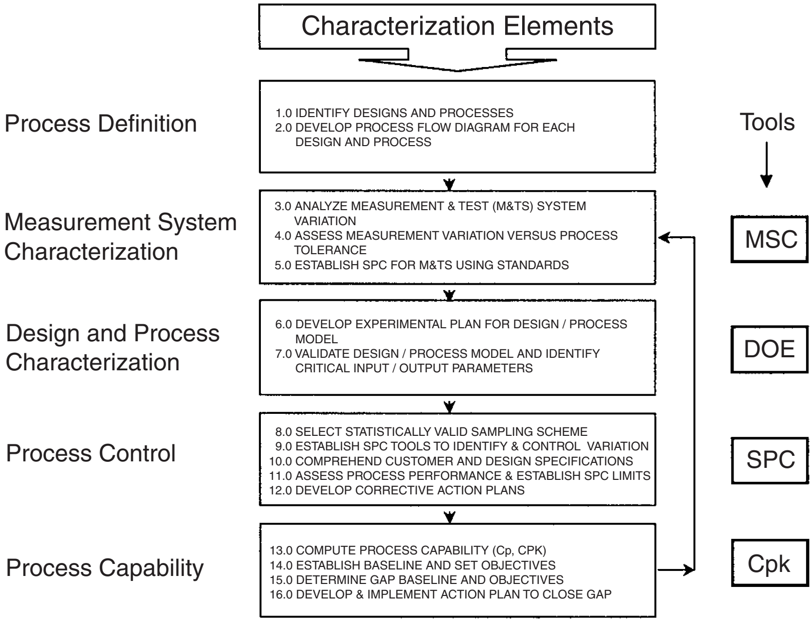


Figure 6 Design and Process Platform Characterization Methodology.

Example: Fiber-Alignment Platform

Platform Description:

This process consists of aligning a fiber to the lens for minimizing optical power loss and then welding the fiber to the lens while maintaining fiber alignment. A measure of this fiber alignment is the change in power loss due to welding (i.e., delta insertion loss).

Process	**Inputs**	**Outputs**	**Impact**
Fiber alignment	Weld energy, weld pattern, lens holder roughness, fiber gap, optical fiber, lens, package	Delta insertion loss	Optical output power
Design	**Inputs**	**Outputs**	**Impact**
Transmitter design	Laser facet power, laser placement, lens placement, fiber alignment (delta insertion loss)	Optical output power	System performance

5.1.2. Step 2: Develop Process Flow Diagram for Each Design and Process

For each design and process selected, a process flow diagram should be developed. A process flow diagram will aid in determining the scope of the characterization effort. The flow chart should be developed with inputs from engineering, design, manufacturing, suppliers, and customers to identify all potential design and process characteristics and includes items such as:

- Sequential process steps and/or material flow
- Relationship between process steps
- Rework loops
- List process step, setups, inputs (i.e., temperature, pressure, force)
- List outputs (i.e., epitaxial thickness, pull strength, wavelength, power)
- Decision points
- Process control and yield points

Example

The process flow diagram for the fiber-alignment platform is shown in Figure 7.

5.2. Measurement System Characterization (Steps 3–5)

5.2.1. Step 3: Analyze Measurement and Test System (M&TS) Variation

Once the process characteristics have been identified, it is then critical that appropriate measures of these characteristics be available. If data does not exist, an appropriate measurement method must be developed and evaluated. If data already exists, a thorough study on the measurement system variation in terms of both accuracy and precision needs to be completed to determine the overall measurement system capability. Excessive variation in the measurement and test system (M&TS) will adversely affect the sensitivity of the decision-making process and may be a source of unnatural variation.

To determine statistically the accuracy and precision of the measurement system, calibration and an error of measurement study must be completed.

Accuracy can be defined as the extent to which the average of a series of repeat measurements of the same item agrees with the "true" value. Accuracy is achieved via calibration, where calibration is the combination of checking and adjusting (if needed) M&TS to a known or traceable standard to bring the M&TS within its tolerances for accuracy.

Precision can be defined as the variation observed in individual repeated measurements of the same item. Precision is also referred to as measurement error, repeatability, or reproducibility. The common method of estimating precision is by performing an error-of-measurement study. This study

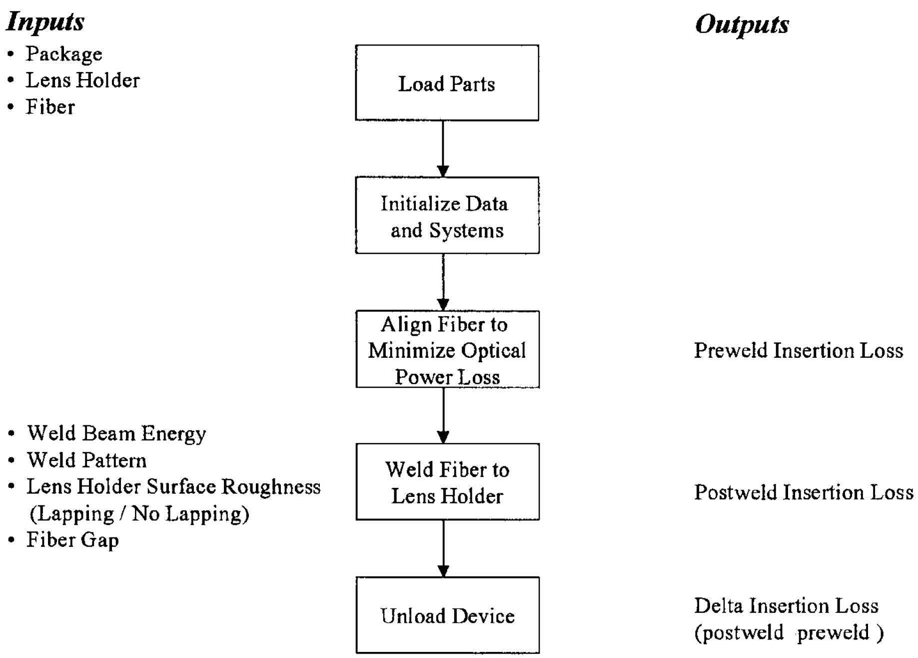


Figure 7 Fiber-Alignment Process Flow.

TABLE 1 Insertion Loss Error-of-Measurement Data.

Device	Reading 1 (dB)	Reading 2 (dB)	Average	Range
1	0.54	0.52	0.53	0.02
2	0.81	0.85	0.83	0.04
3	0.82	0.81	0.82	0.01
4	0.16	0.18	0.17	0.02
5	0.89	0.85	0.87	0.04
6	0.73	0.72	0.73	0.01
7	0.68	0.68	0.68	0.00
8	0.55	0.55	0.55	0.00
9	0.85	0.83	0.84	0.02
10	0.83	0.84	0.84	0.01
11	0.24	0.25	0.25	0.01
12	0.90	0.91	0.91	0.01
13	0.77	0.80	0.79	0.03
14	0.69	0.66	0.68	0.03
15	0.57	0.54	0.56	0.03
16	0.85	0.85	0.85	0.00
17	0.35	0.34	0.35	0.01
18	0.90	0.88	0.89	0.02
19	0.73	0.79	0.76	0.06
20	0.68	0.70	0.69	0.02

is performed by measuring several devices multiple times each and then estimating the error from the repeated measurements.

If more than one piece of equipment or measurement system is used to make measurements, then it is also necessary to perform appropriate correlation studies to demonstrate the compatibility of the multiple systems.

Example: Fiber-Alignment Platform

An error-of-Measurement study was performed to determine the measurement error of the insertion loss-measurement system. This study included measuring 20 devices repeatedly and creating control charts to evaluate measurement performance. The data and analysis are shown in Table 1 and Figures 8 and 9 respectively.

The X-bar chart in Figure 8 shows the discriminating power of the MT&S by plotting the average (i.e., mean) measurements vs. limits derived from the range of repeated measurements from the same device. Since this chart shows the ability of the MT&S to differentiate between different devices, ideally the data points should be out of control for this chart.

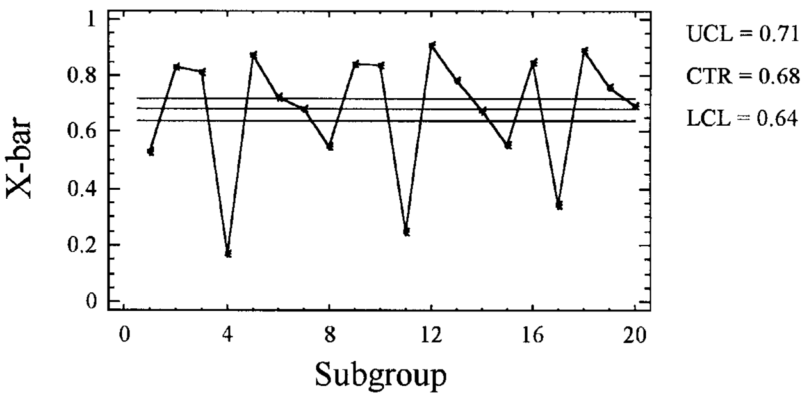


Figure 8 X-bar Chart for Insertion Loss Error of Measurement.

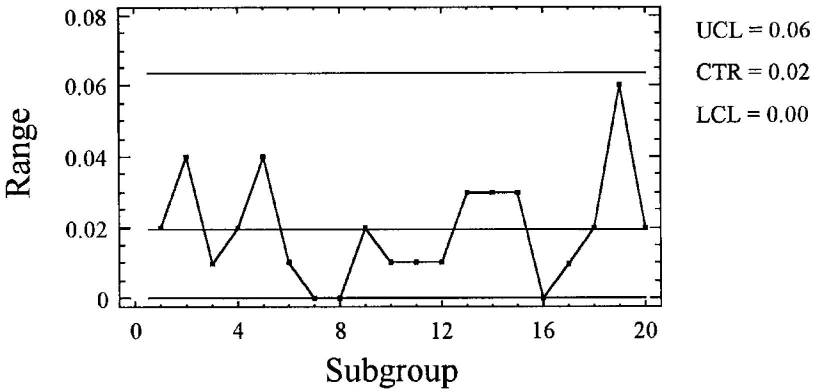


Figure 9 Range Chart for Insertion Loss Error of Measurement.

The range chart in Figure 9 shows directly the magnitude and consistency from device to device of the measurement error associated with this MT&S. The plot shows the difference between measurements made on the same device. Ideally, this chart should have a low centerline and be in control.

Based on the average range (r-bar), the measurement error (σ_m) was then estimated by using the formula as $\sigma_m = r$-bar divided by d_2, where d_2 is the factor that converts the range of a sample of size n from a normal distribution into an unbiased estimate of the standard deviation of that distribution. For a sample size of $n = 2$, $d_2 = 1.128$.

$$\text{Insertion loss-measurement error } (\sigma_m) = 0.02 \text{ dB}$$

5.2.2. Step 4: Assess Measurement Variation vs. Process Tolerances

Once the measurement variation has been estimated, one needs to determine its acceptability for its intended use. This is typically done by comparing the measurement system variation vs. process tolerances or product performance. These two methods are described below:

5.2.2.1. Precision to Tolerance (P/T) Ratio This method is used to compare the measurement error relative to process tolerance (i.e., a parameter with an upper and lower specification limit).

$$P/T \text{ ratio} = \left\{\frac{6 * \sigma_m}{\text{USL} - \text{LSL}}\right\} * 100\%$$

A recommended level is that the M&TS have a $P/T < 30\%$. This would be interpreted as meaning that 30% of tolerance interval could be used up by measurement error and still be acceptable.

5.2.2.2. Percent Measurement Error (Percent Error) This method is used to compare the measurement error relative to the total variation in the process and is typically applied for one-sided specification.

$$\text{Percent measurement error} = \left\{\frac{(\sigma_m)^2}{(\sigma_t)^2}\right\} * 100\%$$

where σ_t is an estimate of the variation from the process under study.

A recommended level is that M&TS have percent error < 10% . This would be interpreted as meaning the measurement component to the overall total process variation could be up to 10%.

Note that P/T ratio and % error objectives are only recommendations. These levels should be selected based on individual requirements and applications.

Example: Fiber-Alignment Platform

The following criterion was used to determine acceptability of the insertion loss-measurement system:

$$\text{Percent measurement error} < 10\% \text{ is acceptable}$$

For this example the measurement error was 0.02 dB and an estimate of total error from production data was 0.1 dB:

$$\text{Percent measurement error} = \frac{\{0.02\}^2}{\{0.1\}^2} * 100\% = 4.0\%$$

5.2.3. Step 5: Establish Statistical Process Control for M&TS Using Standards

The purpose of monitoring measurement and test systems is to determine whether the measurement system is stable, where stability is the absence of drift or other changes over time. This will ensure that the estimates of accuracy and precision remain the same over time. In many cases, when the measurement system is consistently stable over a long period of time, a reduced calibration frequency can be implemented.

A method to determine stability is to monitor M&TS using product or traceable standards via statistical process control. Measuring and monitoring standards at a specified frequency allows a measure of stability to be assessed. If traceable standards are not available, then devices that represent the behavior of a product on the M&TS can be used. It is recommended that two active and one reserve standard be specified. The reason for using two active standards is to determine the nature of the problem (i.e., is it due to malfunctioned standard or the M&TS). The active standards should be used to monitor the M&TS performance. The frequency of monitoring active standards depends upon a particular application (i.e., per shift or per day or before use). The reserve standard should be used to replace an active standard that degrades or no longer functions. The reserve standard may be used for confirmation or resolution of a problem. To accomplish these functions, the reserve standard must be measured regularly (typically at less frequency than active standard) to establish a performance history.

Some of the key elements for establishing statistical process control for measurement and test system include:

- Identification of critical parameters
- Determination of measurement error
- Selection of traceable (if available) and/or product standards
- Determination of the sample size and the frequency of measurements for each standard
- Selection of statistical tools (i.e., control charts) to monitor and control variation
- Development and implementation of corrective action procedure for out-of-control conditions

Example: Fiber-Alignment Platform

To assess the stability of the MT&S for insertion loss, two standards were measured and plotted once a day. Individual control charts were implemented to monitor and control this testing process. These control charts are shown in Figure 10.

5.3. Model Development (Steps 6 and 7)

5.3.1. Step 6: Develop Experimental Plan for Design/Process Model

In this step, the designer or process owner develops the hypothesized relationships (i.e., forms the tentative model to be estimated) between design or process inputs and outputs and associated experimental plan.

The two types of models that are developed are the design and process models. Design models are cause-and-effect quantitative models that translate product-performance requirements to process requirements. The design model identifies key in-process output parameters and associated tolerances. For example:

$$\text{Optical output power} = f\{\text{laser facet power, laser placement, lens placement, fiber alignment} \ldots\}$$

Inputs to include in the design model may be identified through:

- Physical (theoretical) relationship
- Previous design work
- Defect analysis via reliability monitoring

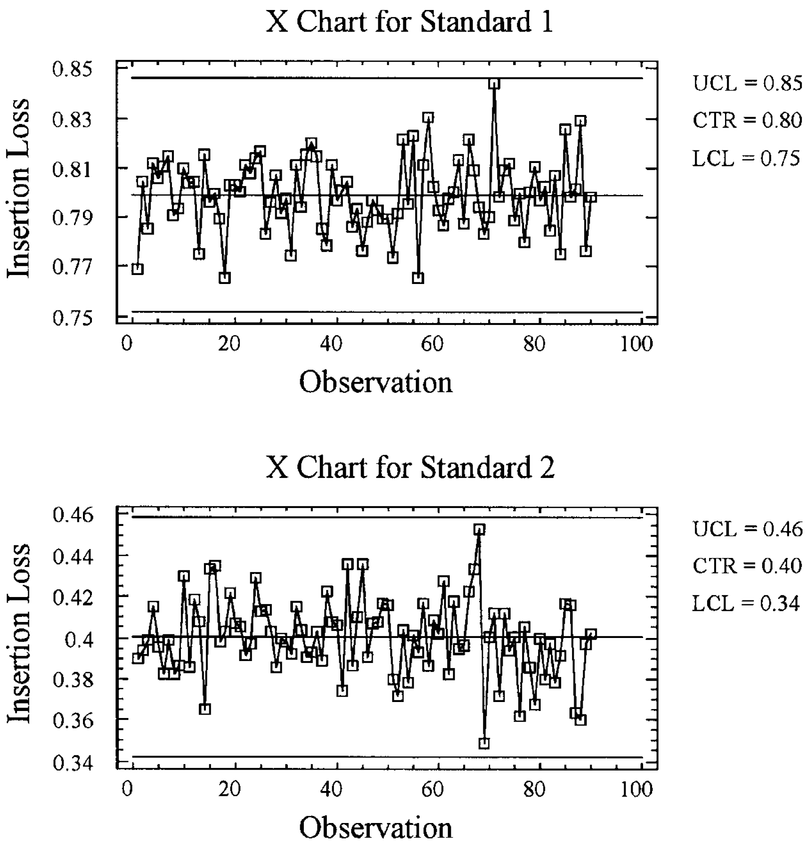


Figure 10 X Charts for Insertion Loss Measurement Standards.

- Device quality issues
- Customer feedback

Process models are cause-and-effect quantitative models that establish the relationships between process requirements and process variables. The process model identifies key process inputs and level of control (i.e., tolerances) needed to achieve desired process performance. For example:

$$\text{Fiber alignment} = f\{\text{weld energy, weld pattern, lens holder roughness, fiber gap} \ldots\}$$

Inputs to include in the process model may be identified through:

- Physical (theoretical) relationship
- Engineering design
- Defect analysis via manufacturing monitoring
- Customer feedback

Once the process or design variables have been identified, a statistically designed experiment should be employed to collect appropriate data to fit the model. This plan includes developing the experimental objective, design matrix, and sample size (i.e., number of experimental replicates).

Example: Process Model

Fiber-Alignment Platform

Experimental objectives: Determine the relationships and settings for key process variables to meet process objective of delta insertion loss less than 1 dB.
Response variable: Delta insertion loss (fiber alignment)
Process variables: Weld energy
Weld pattern
Lens holder roughness
Fiber gap
Experimental design: 2^4 factorial
Experimental matrix:

Weld Energy (joules)	Weld Pattern (# welds)	Lens Holder Roughness	Fiber Gap (μm)	Delta Insertion Loss (dB)
0.5	2.0	0	2.0	0.466
1.0	2.0	0	2.0	1.141
0.5	6.0	0	2.0	0.134
1.0	6.0	0	2.0	1.783
0.5	2.0	1	2.0	0.346
1.0	2.0	1	2.0	0.945
0.5	6.0	1	2.0	0.269
1.0	6.0	1	2.0	1.803
0.5	2.0	0	8.0	0.519
1.0	2.0	0	8.0	0.907
0.5	6.0	0	8.0	0.440
1.0	6.0	0	8.0	1.632
0.5	2.0	1	8.0	0.397
1.0	2.0	1	8.0	0.971
0.5	6.0	1	8.0	0.232
1.0	6.0	1	8.0	1.285

Example: Design Model

Transmitter Optical Output Power
Experimental objectives: Determine relationships and settings for key process variables to meet design objective of optical output power between 15–24 mW.
Response variable: Optical output power
Design variables: Laser facet power
Laser placement
Lens placement
Fiber alignment (delta insertion loss)
Experimental design: Replicated 2^4 factorial

Laser Facet Power (mW)	Laser Placement (μm)	Lens Placement (mils)	Fiber Alignment (dB)	Optical Output Power (mW)
20	1.5	1.2	0.6	16.31
30	1.5	1.2	0.6	25.26
20	6.5	1.2	0.6	13.42
30	6.5	1.2	0.6	20.42
20	1.5	5.8	0.6	16.57
30	1.5	5.8	0.6	23.80
20	6.5	5.8	0.6	12.38
30	6.5	5.8	0.6	19.52

Laser Facet Power (mW)	Laser Placement (μm)	Lens Placement (mils)	Fiber Alignment (dB)	Optical Output Power (mW)
20	1.5	1.2	1	15.62
30	1.5	1.2	1	22.94
20	6.5	1.2	1	12.51
30	6.5	1.2	1	19.72
20	1.5	5.8	1	14.77
30	1.5	5.8	1	22.80
20	6.5	5.8	1	12.18
30	6.5	5.8	1	19.34
20	1.5	1.2	0.6	16.13
30	1.5	1.2	0.6	24.21
20	6.5	1.2	0.6	13.88
30	6.5	1.2	0.6	20.47
20	1.5	5.8	0.6	15.58
30	1.5	5.8	0.6	24.10
20	6.5	5.8	0.6	12.84
30	6.5	5.8	0.6	19.35
20	1.5	1.2	1	15.61
30	1.5	1.2	1	23.72
20	6.5	1.2	1	14.47
30	6.5	1.2	1	20.61
20	1.5	5.8	1	16.16
30	1.5	5.8	1	23.26
20	6.5	5.8	1	11.91
30	6.5	5.8	1	19.03

5.3.2. Step 7: Validate Design/Process Model and Identify Critical Parameters

From the experimental data, a mathematical model is developed to identify significant input factors and quantify their impact on the output. From this, appropriate settings for the inputs can be determined as well as the level of control required during manufacturing. The statistical techniques to accomplish this are analysis of variance and regression analyses.

Example: Process Model

Fiber-Alignment Platform

Data from the experiment were analyzed using ANOVA and multiple regression techniques.
The results are shown in Figure 11.

The analysis of this data identifies weld energy and weld pattern as critical process variables and develops the following model:

$$\text{Delta insertion loss} = \{0.354 + 0.320\,(\text{weld energy}) - 0.240\,(\text{weld pattern}) + 0.399\,(\text{weld energy} * \text{weld pattern})\}$$

From this model and other processing considerations, the following process settings were implemented.

Parameter	*Setting*
Weld energy	0.6 J
Weld pattern	3
Lens holder roughness	0 (no lapping)
Fiber gap	5 μm

Example: Design Model

Analysis of Variance for Delta Insertion Loss

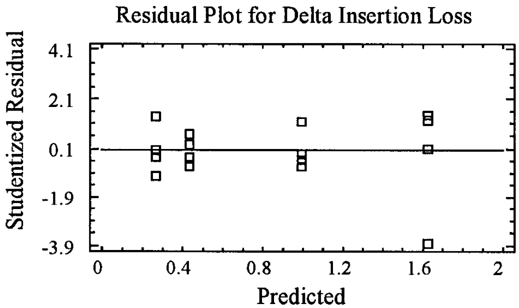
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A: Weld Energy	3.6710600	1	3.67106000	183.57	0.0000
B: Weld Pattern	0.2223120	1	0.22231200	11.12	0.0207
C: Lens Holder Roughness	0.0374422	1	0.03744220	1.87	0.2295
D: Fiber Gap	0.0158760	1	0.01587600	0.79	0.4137
INTERACTIONS					
AB	0.63680400	1	0.63680400	31.84	0.0024
AC	0.00129600	1	0.00129600	0.06	0.8092
AD	0.09765620	1	0.09765620	4.88	0.0781
BC	0.00004225	1	0.00004225	0.00	0.9651
BD	0.00547600	1	0.00547600	0.27	0.6231
CD	0.01276900	1	0.01276900	0.64	0.4605
RESIDUAL	0.09998970	5	0.01999790		
TOTAL (CORRECTED)	4.80072000	15			

Multiple Regression Analysis for Delta Insertion Loss

Dependent variable: Delta Insertion Loss

Parameter	Estimate	Standard Error	t Statistic	P-Value
CONSTANT	0.353625	0.2654340	1.33225	0.2075
Weld Energy	0.320000	0.3357500	0.95309	0.3593
Weld Pattern	-0.240313	0.0593528	-4.04888	0.0016
Weld Energy*Weld Pattern	0.399000	0.0750760	5.31461	0.0002

R-squared = 94.3644 percent, R-squared (adjusted for d.f.) = 92.9555 percent
Standard Error of Est. = 0.150152



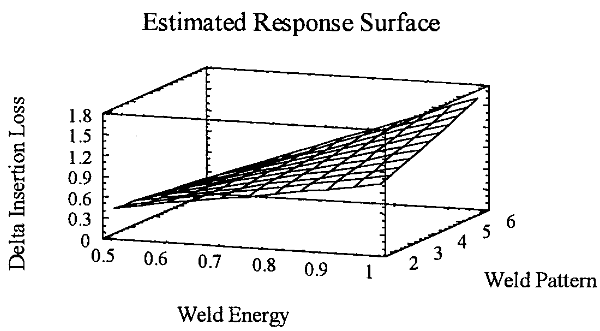


Figure 11 Results of Fiber-Alignment Platform Experiment.

Transmitter Optical Output Power

Data from the experiment were analyzed using ANOVA and multiple regression techniques. The results are shown in Figure 12.

The analysis of this data identifies laser facet power, laser placement, lens placement, and fiber alignment as critical design variables and develops the following model:

Optical output power = {1.527 + 0.824 (laser facet power) − 0.038 (laser placement)
− 0.025 (lens placement) − 1.498 (fiber alignment)
− 0.021 (laser facet power * laser placement)
− 0.034 (laser placement * lens placement)}

Based on the design model, customer requirements, platform requirements, costs, and other design considerations, the following specifications were developed.

Parameter	*Specification*
Laser facet power	22–28 mW
Laser placement	5 μm maximum
Lens placement	5.8 mils maximum
Fiber alignment	1 dB maximum

5.4. Statistical Process Control (Steps 8–12)

Once the critical inputs and outputs have been determined, appropriate statistical process controls can be implemented to control and improve process performance.

In the example, a design model was first developed that indicated that optical output power is a function of laser facet power, laser placement, lens placement, and fiber alignment. To control optical output power, statistical process control must be applied to these critical process output parameters and, where applicable, must be applied to corresponding process input parameters.

Below is the summary of the design model for optical output power and the corresponding process models associated with the critical process output parameters.

- Design model:

  Optical output power = *f*{laser facet power, laser placement, lens placement, fiber alignment ...}

- Process models:

  Fiber alignment = *f*{weld energy, weld pattern ...}
  Laser facet power = *f*{laser chip slope, epitaxial grating, metal doping composition ...}
  Laser placement = *f*{laser chip size, bond temperature, piece part quality ...}
  Lens placement = *f*{bonding temperature, ambient conditions, solder oxidation ...}

Hence, the control of process output parameters and associated input parameters will ensure conformance to optical output power requirements.

5.4.1. Step 8: Select Statistically Valid Sampling Scheme

Based on the process models, appropriate sampling plans for process controls can be developed. A sampling scheme using rational subgroupings is one that provides the valid or right data at minimal cost. The main effort is to ensure that the samples in any one subgroup have been produced under essentially the same conditions. Elements of a rational subgroup include:

- Samples are randomly selected within a subgroup.
- Subgroups are collected at proper frequencies.
- Subgroup size is adequate to detect desired level of change or shift in the process.
- Subgrouping minimizes variation within subgroups.

A typical guideline is to collect small samples frequently rather than large samples less frequently.

Example: Fiber-Alignment Platform

Analysis of Variance for Optical Output Power

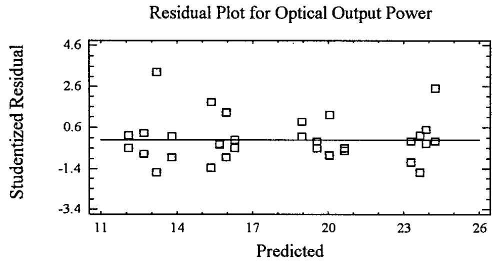
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A: Laser Facet Power	436.67500	1	436.6750000	1601.71	0.0000
B: Laser Placement	93.81080	1	93.8108000	344.09	0.0000
C: Lens Placement	4.28513	1	4.2851300	15.72	0.0007
D: Fiber Alignment	2.87400	1	2.8740000	10.54	0.0039
INTERACTIONS					
AB	2.24190000	1	2.24190000	8.22	0.0092
AC	0.01087810	1	0.01087810	0.04	0.8436
AD	0.10465300	1	0.10465300	0.38	0.5422
BC	1.19738000	1	1.19738000	4.39	0.0484
BD	0.65265300	1	0.65265300	2.39	0.1367
CD	0.00137813	1	0.00137813	0.01	0.9440
RESIDUAL	5.72524000	21	0.27263100		
TOTAL (CORRECTED)	547.579000	1			

Multiple Regression Analysis for Optical Output Power

Dependent variable: Optical Output Power

Parameter	Estimate	Standard Error	T Statistic	P-Value
CONSTANT	1.5266300	0.97379300	1.567720	0.1295
Laser Facet Power	0.8235130	0.03400110	24.220200	0.0000
Laser Placement	-0.0377554	0.19178400	-0.196865	0.8455
Lens Placement	-0.0245380	0.07391540	-0.331975	0.7427
Fiber Alignment	-1.4984400	0.45051400	3.326060	0.0027
Laser Facet Power*Laser Placement	-0.0211750	0.00720822	-2.937620	0.0070
Laser Placement*Lens Placement	-0.0336413	0.01567000	-2.146850	0.0417

R-squared = 98.8139 percent, R-squared (adjusted for d.f.) = 98.5292 percent
Standard Error of Est. = 0.509698



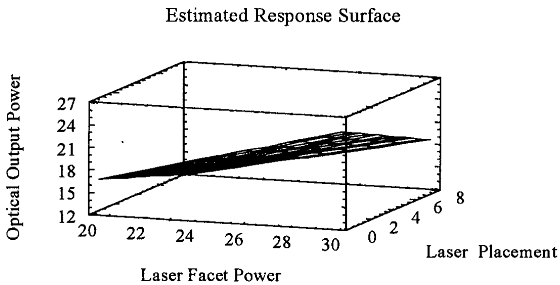


Figure 12 Results of Optical Output Power Experiment.

Based on costs, chosen risk levels associated with detecting assignable cause variation, magnitude of process change to be detected, and rational subgrouping considerations, a sampling scheme to weld and measure the first five parts of each shift was implemented.

5.4.2. Step 9: Establish Statistical Tools to Identify and Control Variation

Many statistical tools have been developed to control critical process parameters. The most commonly used is the control chart, which is an effective way to monitor and control processes and can be defined for both variables and attributes data. The selection of variables data will typically make basic statistical tools more efficient (i.e., lower sample size requirements to achieve necessary confidence levels).

Example: Fiber-Alignment Platform

In order to monitor and control this process, an X-bar and R control chart for fiber alignment (delta insertion loss) was established and data collection and analysis were implemented. These charts were used to identify and address assignable cause variation.

5.4.3. Step 10: Comprehend Customer and Design Specifications

The implementation and validation of design models in manufacturing ensures alignment of specifications. Implementation includes:

- Analyzing design specifications relative to the process capability
- Examining and understanding the reasons for process specifications
- Determining and implementing statistically valid specifications
- Enhancing the specification-alignment process

Example

Based on customer requirements and platform capabilities, the design model was used to align specifications to meet requirements. In this example, based on a customer requirement for optical output power of 15–24 mW, existing fiber-alignment platform requirement of <1 dB, and the design model, the following process tolerances were generated for the remaining processes:

Parameter	*Tolerances*
Laser facet power	22–28 mW
Laser placement	5 μm maximum
Lens placement	5.8 mils maximum

From these process tolerances, the fiber-alignment platform capability was maintained and the ability to meet customer requirement was met at a Cpk of 1.33. Depending on costs and other considerations, additional trade-offs between design and process requirements can be established.

5.4.4. Step 11: Assess Process Performance and Establish Statistical Limits

Assessment of process performance is a systematic procedure that uses statistical tools (usually control charts) to detect and eliminate (via corrective action) the unnatural (assignable) causes of variation until a state of statistical control is reached and hence statistical limits are established. A state of statistical control is a condition describing a process from which all assignable causes of variation have been eliminated via corrective action and only natural causes remain.

Example: Fiber-Alignment Platform

After assignable causes were eliminated, statistical limits were established for the control chart. Figure 13 shows the X-bar and R control charts for the last 90 data points.

5.4.5. Step 12: Develop Corrective Action Plans

Development and timely execution of corrective action procedures for out-of-control conditions is one of the most critical elements of effective implementation of process control. Corrective action procedures must be documented and should include the following information:

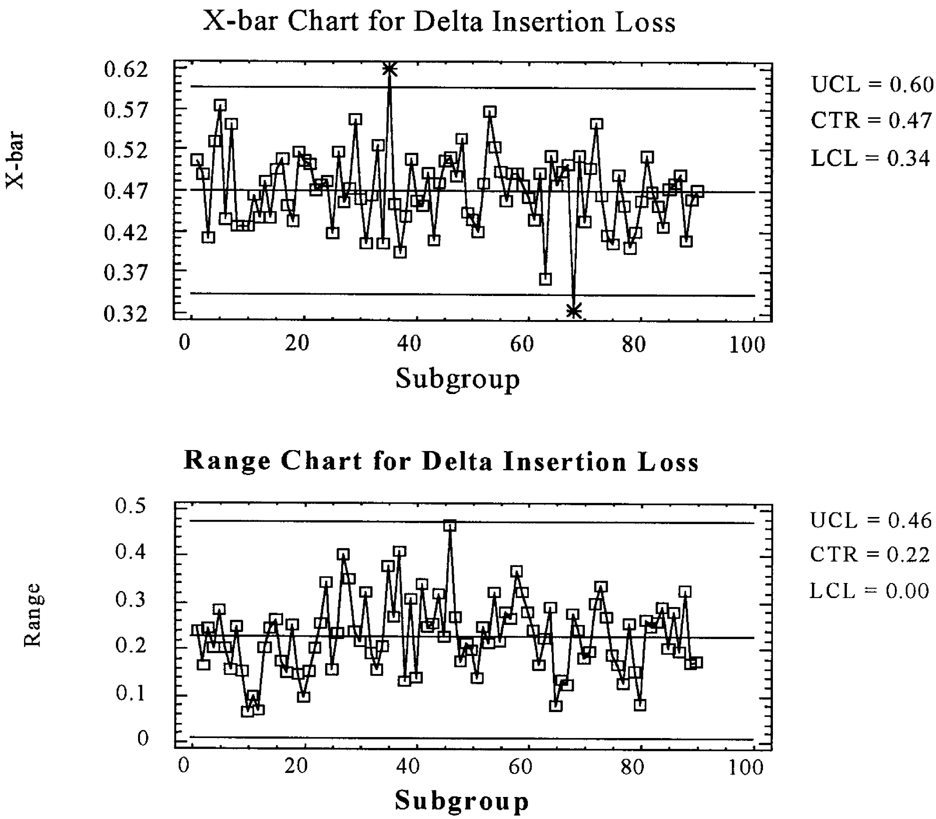


Figure 13 X-Bar and Range Chart for Fiber Alignment Process.

- When to take corrective action (i.e., when control chart signals an out-of-control condition)
- Who should initiate the corrective action procedure (i.e., operator, engineer)
- What corrective action should be performed per each failure mechanism
- What should be the disposition of the suspect devices/lots

It is also important to record properly the corrective action performed for Pareto analysis to further enhance the corrective action procedure.

Example: Fiber-Alignment Platform

Corrective action procedures were documented for this process and included items on verifying process conditions, such as weld beam energy and fiber gap position, establishing failure mode analysis procedures, determining disposition of work in process, and confirming procedures for restarting the process.

5.5. Capability Analysis (Steps 13–16)

Once a state of statistical process control has been achieved, process capability can be estimated.

5.5.1. Step 13: Compute Process Capability (Cp, Cpk)

In order to understand the true process capability for the critical processes, it is important to compute process capability indices using proper statistical procedures. These indices estimate the process's ability to meet design and customer requirements. Two of the most common capability indices are Cp and Cpk, where:

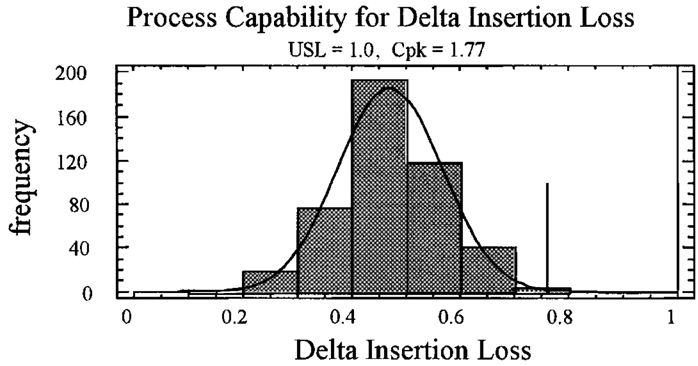


Figure 14 Fiber-Alignment Process Capability Analysis.

$$Cp = USL - LSL/6 \text{ sigma}$$
$$Cpk = \text{Minimum of } \{Cpl, Cpu\}$$

where

$$Cpl = \{\text{mean} - LSL\}/3 \text{ sigma}$$
$$Cpu = \{USL - \text{mean}\}/3 \text{ sigma}$$

A standard method for computing and reporting process capability indices for the critical designs and processes should be developed. Following are some of the key elements that should be considered for a process capability algorithm and report:

- Assessment and identification of statistical outliers from the data set
- Estimation of process capability indices for nonnormal data
- Warning for special conditions (i.e. insufficient data, multimodal distribution and excessive outliers)
- Estimation of Cp and Cpk indices, confidence intervals, summary statistics

Example: Fiber-Alignment Platform

The process capability index (Cpk) was estimated to determine the ability of the process to meet design objectives. Based on last 450 observations, the Cpk was estimated to be 1.77 and is shown in Figure 14.

5.5.2. Step 14: Establish Baseline and Set Objectives

For each process, estimates of process capability and yield for critical processes should be summarized and reported (baseline). Based on overall business objectives, realistic and attainable objectives for process capability and first pass yield should be set.

5.5.3. Step 15: Determine Gap between Baseline and Objectives

A gap analysis should be performed between the current baseline and objectives for each critical process to determine the extent of the improvement plans.

5.5.4. Step 16: Develop and Implement Action Plan to Close Gap

Based on gap analysis, an action plan should be developed and implemented to close the gap and promote continuous improvement.

6. LINKAGE OF PRODUCT DESIGN AND PROCESS PLATFORMS

In order to use the product and platform knowledge gained through characterization effectively, it needs to be documented and available to appropriate functions. This allows an organization to respond to customers more effectively in terms of new product development. One method is the development of platform and design manuals that would contain key aspects of platform elements and design characterization.

6.1. Process Platform Manual

6.1.1. Platform Description

A brief description of the function of the platform process should be included. The description should uniquely identify the scope and purpose of the particular platform.

6.1.2. Platform Characteristics

A list and associated description of the key attributes of the platform needs to be included. Attributes should be defined to document platform components sufficiently. These elements include hardware or equipment sets being used as well as necessary software algorithms. Elements also include what incoming materials are used on the process. Incoming materials may be from internal or external suppliers. When environmental controls are necessary, such as clean-room conditions, that also should be included. Also, items related to carrying out the process, such as methods, skills, and process conditions, should be summarized.

6.1.3. Platform Boundary Conditions

Boundary conditions should be established for each of the key platform characteristics. For each characteristic, the platform developer must determine the limits to which a characteristic can vary and still be manufactured on the platform to meet process and product features. These limits define the boundary conditions. These conditions include tolerance requirements on piece parts and materials, equipment and software specifications, and training requirements. These overall boundary conditions (i.e., what a process can and cannot do) will be the basis of the design guidelines that will be shared with design and marketing organizations.

6.1.4. Platform Characterization Model

For each performance characteristic, a process model must be developed and defined. The process model is a cause-and-effect quantitative model that establishes the relationships between process requirements and process variables. The process model identifies key process inputs and level of control (i.e., tolerances) needed to achieve desired process performance.

6.1.5. Platform Capability

For each performance characteristic, the associated process capability needs to be defined in terms of the ability of the process to meet its target and in terms of reproducing results consistently (i.e., process variation). The following items are typically included in the capability section of the platform manual:

- *Performance parameter*: lists critical platform outputs, as typically defined by design characterization activities, that must be met.
- *Process model*: establishes the relationship between platform inputs and performance parameters (platform outputs).
- *Parameter boundary conditions*: establishes platform requirements in terms of target performance that a platform will achieve. This may be a nominal target, single target, multiple targets, or a range of targets depending on the scope of the platform.
- *Nominal Performance (μ)*: defines actual performance of how well the platform is meeting its target.
- *Capability (1σ)*: defines the process variability associated with respect to each performance parameter.
- *Measurement methods*: describes the measurement method used to obtain performance results.
- *Measurement error*: defines the measurement error (1σ) for each performance parameter.

6.1.6. Platform Manual Example

6.1.6.1. Fiber-Alignment Platform Manual

- *Platform description*: The process consists of aligning a fiber to the lens for minimizing optical power loss and then welding the fiber to the lens while maintaining fiber alignment. A measure of this fiber alignment is the change in power loss due to welding (i.e., delta insertion loss).

Platform/Process Characteristics and Boundary Conditions (Design Rules)

Elements	Platform Characteristics	Boundary Condition
Hardware/equipment	Welder	
Software (algorithms)	Standard	Standard
Incoming materials	Lasers, Package, 3 × 3 Laser Carrier, Lens, Optical Fiber	3 × 3 laser carrier dimensions per drawing C1501 Package foot print dimensions per drawing C1432 Laser chip dimension of 20 by 25 mils Lens diameter (775 to 825 μm) and spherical shape Lens holder size must be 10–12 mm
Elements	Platform Characteristics	Boundary Condition
Environment	Class 10,000 clean room	Class 10,000 clean room
Method	Welding	Welding
Skills	Photonic processor	Photonic processor
Performance level	See below[1]	See below[2]

Platform/Process Capability (Performance Level)

Performance Parameter	Process Model	Parameter Boundary Condition[2]	Nominal Performance (μ)[1]	Capability (1σ)	Measurement Method	Measurement Error (1σ)
Delta insertion loss	Weld energy, weld pattern	1.0 dB maximum	0.47 dB	0.1 dB	Power meter	0.02 dB
Torque	Weld energy, weld pattern, focus, beam balance	10 in./lb minimum	17.8 in./lb	1.2 in./lb	Destructive	$<$ 0.5 in./lb

6.2. Design Manual

As a platform manual defines platform capability and requirements, a design manual defines design capability and requirements. Below is the description of a design manual.

6.2.1. Design Description

The design description covers a brief overview of the design scope and intent, including a description of the design construction, physical dimensions, electrical, optical, mechanical, and environmental objectives.

6.2.2. Design Parameters and Requirements

This includes a brief description of design parameters and their functions for a given product or family of products. The description may also include any special test conditions or requirements. In addition, specific customer requirements that must be met for each performance characteristic, including reliability, performance, maintainability, producibility, testability, safety, and cost objectives.

6.2.3. Design Characterization Model

For each performance characteristic, a design model should be developed and defined. The design models are cause-and-effect quantitative models that translate product performance requirements into process requirements and identify key in-process output parameters and associated tolerances.

6.2.4. Design Capability

For each design parameter, its associated capability needs to be defined and documented in terms of current and potential platform capabilities. Including potential capabilities enables improved market plans and offerings to be developed because design possibilities will be known.

6.2.5. Design Boundary Conditions

Boundary conditions should be established for each design parameter that define requirements to achieve design performance. These conditions define design limitations based on process and technology capabilities. They also provide marketing with the ability to develop better plans and respond to customer requests in a more timely fashion.

6.2.6. Design Manual Example

6.2.6.1. Transmitter Design Manual

- *Design description*: The transmitter is designed to operate at 2.5 Gb/sec with a NRZ data input format. The elements include housing, electrical interface, optical interface, drive circuitry, temperature control, optical sensors, data buffers, modulator, and attenuator.
- *Design parameters*: The absolute maximum ratings for supply voltage range from –5 to +5 volts with storage temperature range 0–65°C. The electrical and optical requirements include power supply current $<$ 500 mA, optical power output 15–24 mW. The environmental and mechanical requirements include 5 temperature cycles at 0–70°C. The targeted wavelength must be between 1523–1527 nm.

- Design Boundary Conditions
  - Lens must be spherical with a diameter range of 775–825 μ
  - Optical fiber must be single mode and polished at 5° with polishing flatness not to exceed 10 μ
  - Laser far-field angle not to exceed 35°
  - Laser chip facet coating reflectivity should be between 80–88%.

Design Capability

Performance Parameter	Design Model	Design Specifications	Nominal Performance (μ)	Capability (1σ)	Measurement Method	Measurement Error (1σ)
Optical output power	Laser facet power, laser placement, lens placement, fiber alignment	15–24 mW	19.5 mW	1.1 mW	Transmitter test set	0.25 mW
Targeted wavelength	Current, temperature	1523–1527 nm	1525 nm	0.5 nm	Wavelength test set	0.05 nm

7. DEPLOYMENT

Well-defined methodologies with broad objectives do not lead directly to results. They must first be deployed. However, successful deployment is by itself insufficient to guarantee program success. To maximize benefits and ensure longevity, the methodology must become ingrained as part of the culture of the organization. Achieving this is a complex process. It involves, at a minimum, recognition by the user that the methodology is a benefit to them, coupled with incorporation of the methodology into the structure of the business management processes that govern the organization. The following sections describe the deployment of the product design and process platforms methodology and the steps necessary to make it part of the culture of an organization. A case study of one organization is presented as an example.

7.1. Critical Components

In the deployment of the design and process platform characterization program, the critical components of success are, as expected, user education, management commitment, deployment infrastructure, and business process integration. A more subtle and ubiquitous component of success must also be recognized—the celebration of every success, no matter how small.

7.1.1. Education

The foundation upon which any program deployment is built is the knowledge base of the participants. In most organizations, the technical expertise in the use of the principles and the acknowledgment of their utility resides in the quality organization and the population at large has little or no training/recognition of this area. Hence, the initial step in the deployment must be the education of the user community. In addition, for a culture change to occur, the entire populace must speak the same language. Therefore, customized courses must be designed for all levels in the business, from manufacturing operators to the executive leadership team, including the chief operating officer (COO) of the business.

Example

The entire executive management team of the business was required to attend an overview session on the basics of measurement system characterization, design of experiments, statistical process control and process capability analyses. The objective of this course was to provide an overview of the principles of these methods, including how it works, when to use it, and what results to expect. The overall objective was to provide the manager with just enough information so that he or she could ask the right questions of the engineers and in so doing reinforce the objectives of the program.

All R&D and manufacturing engineers were required to attend 48 hours of training in measurement system characterization (4 hours), design of experiments (32 hours), statistical process control (8 hours), and process capability analysis (4 hours). These courses were presented on site by recognized experts in those fields from universities around the country. In addition, these courses were customized to its industry and each participant was required to bring his or her own problem to the class to be worked as an exercise. This brought relevance to the sessions and achieved timely recognition by the participant that "this stuff works." Over 90% of the engineering staff completed this training within 18 months.

Advanced training was also provided on a voluntary basis. Courses in advanced design of experiments/multivariate analysis (24 hours), regression analysis/ANOVA (16 hours), and DOE, modeling, and SPC using a platform software tool (16 hours) were provided. Seventy percent of the engineering population completed this level of training. These courses were also offered by external technical experts in those fields from the university community.

Finally, the manufacturing associates had required training in statistical process control (8 hours), which was provided by the quality organization. Eighty-five percent of the staff had completed this training in a 12-month period. Advanced training was also made available on a voluntary basis and 60% of the manufacturing staff completed this level of training.

The result of all this education/training was a whole population of believers in these methods and an engineering staff that uses them as a matter of routine.

7.1.2. Management Commitment

A company can undertake such drastic change in quality methodologies only if its executive managers are trained and supportive and are participants in the program. Management commitment can be demonstrated in many ways. However, the effectiveness of any specific approach will depend on the existing culture of the organization.

Example

An approach based on constant recognition of compliance rather than exception-based reporting was used. Teams at various levels of completion presented their results at the quarterly quality leadership council meetings with the executive leadership team and the COO in attendance. Within a 12-month period, all the teams in the business had this opportunity to demonstrate their progress. It was not required that a program be complete, only that it be actively worked in the methodology to get positive reinforcement from upper management.

The reward system for managers and engineers was tied to completion of milestones. This included the annual performance management system and special rewards. Every small success was celebrated, including participation. These were annual celebration banquets held off-site for the entire engineering staff. At this annual event, the teams that had progressed furthest in the program presented their report to their peers and the entire management staff, including the executive team and COO. Constant positive reinforcement with public recognition was a key component of success. The COO was the recognized leader of this activity. He reinforced his leadership role by including references and/or results of this program at every presentation he made to the organization. In addition, he was committed to personal involvement by meeting engineers on a regular basis and asking about their progress and offering any help to eliminate roadblocks.

Finally, to ensure that all levels of management were involved, it was required that first-level managers report the progress of the teams in their area of responsibility at the quality leadership council meetings.

7.1.3. Deployment Infrastructure

The success of every quality initiative is dependent on its acceptance by the receiving organizations. This acceptance is critically dependent on the means of deployment used. Successful deployment of this program cannot result solely from quality consultants assigned to support each functional area. Progress must be driven from within the functional area. Only then can a culture change result.

Example

Champions were designated in each functional area to drive and monitor actively and report progress. These were either the first-level managers or lead engineers in those areas. The methodology was promulgated by the active involvement of these acknowledged and recognized technical leaders. Engineers and managers had been trained and now were expected to apply that training according to the outline of the methodology. They were supported by the quality engineering staff, who provided significant assistance, guidance, and technical leadership initially, which decreased as time passed and competency increased.

The engineering community identified its critical designs and/or processes to which the methodology would be applied. Together with the quality engineering staff, individual customized project plans were developed. Biweekly meetings were held wherein all champions reported their progress and problems. Issues were escalated from these meetings and resolution was swift. In addition, sharing of problems resulted in opportunities for further education of the champions. By the end of the first 12 months, the champions were acknowledged by the engineering and management staff as subject matter experts in the methodology and its application.

7.1.4. Integration

Initially this program must be an adjunct to the quality system that governs the business. It must be viewed as a quality-improvement program and not officially required for design, production, or shipment of product. Since its application initially will be sporadic, management should not wish to raise customer expectations on a program that will not be uniformly applied throughout the business for some time. As customers are apprised of the methodology, they will desire it to be applied to their products.

Example

It took nearly three years of application of this methodology before it was widespread and uniformly applied sufficiently to formally incorporate it into the quality system. The quality system defines two levels of field grade products to customers: model code and full code. The latter has all aspects of the quality system applicable and complete. The former has some aspects of the quality system incomplete but recognized as low risk for customer use. The application of this methodology and its linkage to the quality system via the product level is shown in Figure 15. Review of the qualification review board (QRB) plan before acceptance and progress reporting by quality assurance in the regular monthly executive report are the significant linkages. In addition, the product robustness criteria used for QRB acceptance were also formalized and are shown in Figure 16.

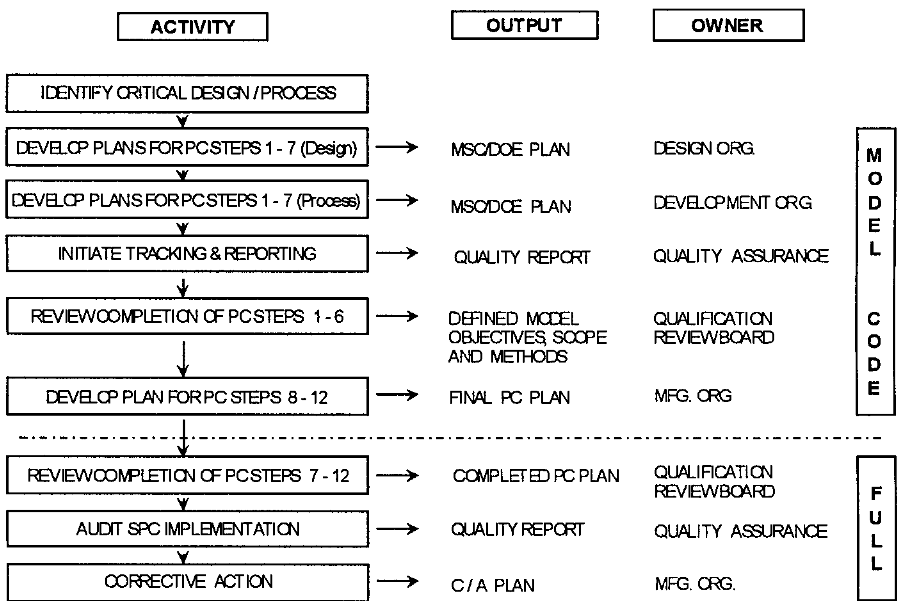


Figure 15 Quality System Linkage.

Modeling:	• Completion of Design Models (PC Steps 1-7) • Completion of Process Models (PC Steps 1-7)
SPC:	• Implementation of SPC for outputs/inputs (PC Steps 8-12)
Capability:	• Design Parameters Capable - Goal @ Cpk $\geq$ 1.33 (PC Step 13-16) • Process Parameters Capable - Goal @ Cpk $\geq$ 1.33 (PC Step 13-16)
Platforms:	• Use of Platform Processes

Figure 16 Product-Robustness Criteria.

Included and implicit in these criteria are achievements of minimum yield and variation targets before a design is transferred to manufacture. As with all the metrics in this program, these are customized for each design and process with regard to the complexity and technological capability of the design and process.

Reviews of the activity, required by the quality system, are the critical components to ensuring compliance and guaranteeing longevity of the program. It must be independent of the individuals administering or driving the program and ingrained in the fabric of the quality culture of the organization. It must be linked via appropriate documentation to the quality system, which are then audited regularly. It must simply become part of the way a company does business.

7.2. Performance Measures

Corporations generally set broad quality goals and leave the path to achievement to the discretion of the individual business units. However, these broad goals do not lead directly to results. They must first be deployed to lower levels of the organization via division and subdivision of the objectives until they identify specific activities to be carried out and allocation of responsibility for performing those activities. Execution of the activities incorporated in this program collectively results in improving operational excellence.

In addition, reviews of progress are an essential part of ensuring that goals are being met. The very fact that an executive team reviews progress sends a message to the rest of the organization as to the priority given to the program goals. The metrics chosen to review are critical to the success of the program. They must show steady progress to maintain program momentum, and at the same time they must measure actual operational performance, a much slower improvement process. This is a difficult but achievable combination.

7.2.1. Metrics

The quality adage ‘‘You improve what you measure’’ should be the operational credo. There are two categories of measurements: progress toward compliance with the methodology and operational performance. Progress reviews are also an essential part of ensuring that application of the methodology is resulting in the expected improvements. Reviews should be carried out in two major ways: summarized reports on actual operational performance and reports of program status.

Modeling:	• Percent of Design Output Parameters Modeled • Percent of Process / Platform Output Parameters Modeled
SPC:	• Percent of Process / Platform I/O Controlled
Capability:	• Percent of Design Output Parameters Capable at Cpk $\geq$ 1.33 • Percent of Process / Platform Output Parameters Capable at Cpk $\geq$ 1.33
Education:	• Percent of Engineering & Operating Completed PC Training

Figure 17 Metrics.

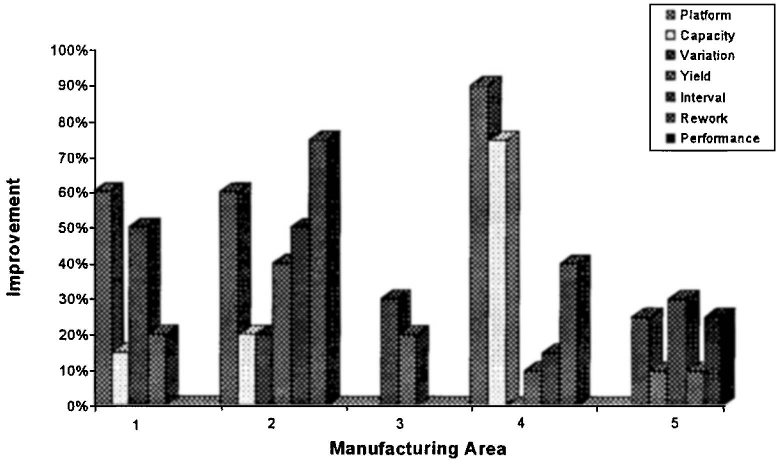


Figure 18 Performance Measures.

Example

The compliance metrics are shown in Figure 17. At the same time, measures were designed for key characterization elements and link to variation, performance, yield, and interval improvements. Results of improvements in operational performance for five manufacturing areas are shown in Figure 18.

Measures of each customized project plan and its specific schedule and reported progress against the steps of the methodology were summarized in a monthly report and also presented at the quality leadership meetings by the first-level manager with the COO and the executive team. In conducting these reviews, it was necessary (albeit difficult) for upper managers to maintain a constructive approach. In general, metrics were used to track progress and define cause for celebration.

7.2.2. *Progress of Culture Change*

The overall goal is to create a process control-minded culture and exceed customer expectations. On the road to achieving that goal, the foundation and a set of platforms unique to the specific industry should be developed. These goals can be deployed via the design and process platform methodology.

Example

After five years, a fundamental change in the culture of the business was demonstrated. The use of design of experiments is a way of life in this business. Designers and process engineers use it routinely (without quality organization expert assistance) to characterize and control designs and processes. In a three-year period, over 250 DOE were completed resulting in significant yield, variation and cycle time improvements. About 40–50 DOE are in progress at any given time. The designers and process engineers gained sufficient technical expertise to perform the quality engineering function as part of their existing assignments.

The methodology also became an integral part of the product-realization process. Comprehensive implementation of the methodology and achievement of minimum yield and variation targets are required before the design is transferred to manufacturing.

Although there was strong resistance at first, this changed to global acceptance by the technical community as their experience increased. The improvement in operational performance metrics led to a total embracing of the methodology by the management team.

Finally, the keys to success were the active involvement and support of executive management, recognition at executive meetings and peer events, education, and user involvement in the methodology development.

Computer Software

STATGRAPHICS, Manugistics, Rockville, MD.

ADDITIONAL READING

Box, G. E. P., and Draper, N. R., *Empirical Model Building and Response Surfaces,* John Wiley & Sons, New York, 1981.

Duncan, A. J., *Quality Control and Industrial Statistics*, 5th Ed., Irwin, Homewood, IL, 1986.

Feigenbaum, A. V., *Total Quality Control*, 3rd Ed., McGraw-Hill, New York, 1983.

Montgomery, D. C., *Design and Analysis of Experiments*, 4th Ed., Wiley, New York, 1997.

Goff, D. R., Hansen, K. S., and Stewart, J. G., *Fiber Optic Reference Guide*, Focal Press, Boston, 1997.

Grant, E. L., and Leavenworth, R. S., *Statistical Quality Control*, 6th Ed., McGraw-Hill, New York, 1979.

Hecht, J., *Understanding Fiber Optics*, 2nd Ed., Sams, Indianapolis, IN, 1993.

Juran, J. M., *Juran on Quality by Design: The New Steps for Planning Quality into Goods and Services*, Free Press, New York, 1992.

Juran, J. M., and Gryna, F. M., *Quality Control Handbook*, 4th Ed., McGraw-Hill, New York, 1988.

Western Electric Company, Inc., *Statistical Quality Control Handbook*, Delmar, Charlotte, NC, 1982.