INNOVATION, PRODUCT DEVELOPMENT AND COMMERCIALIZATION
Case Studies and Key Practices for Market Leadership

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EXCELLENCE IN DESIGN AND PRODUCT RELIABILITY

Selected best-known methods for product design, prototyping, and testing as well as topics in product reliability are discussed in this chapter. The chapter is intended to provide design guidelines for practicing engineers and to provide a broad knowledge of design rules for management personnel, including business unit (BU) general managers, vice presidents of engineering, and program managers, who are responsible for guiding product development teams to success in product development and commercialization. A number of references providing more in-depth coverage of the subject are also cited.

Design for excellence is satisfying the myriad requirements that success in product development and commercialization entails. Some of these requirements are briefly reviewed:

**Design.** Successful products are usually built on an expandable platform architecture, have a modular design, and deploy synergistic common technology and design knowledge to continuously expand the business of a firm by commercializing new applications and derivative products. Sustained product leadership at Sony (compact discs) and Intel (microprocessors) over several decades is a testimonial to having this winning strategy.

**Reliability and robustness.** Product reliability and robustness are critical to customer satisfaction and the perception of quality in consumer and industrial markets.

**Low-cost production.** Designing a product to have a low cost of production improves profitability and enables flexibility in pricing to gain competitive advantage. A new product should be designed to the target cost so that its “should cost” is equal to the target cost of the MRS. The target cost must be achieved at the engineering prototype level (in the alpha phase) through collaboration with material and component suppliers. Toyota follows this approach in car manufacturing by working with suppliers to design to cost for a win-win outcome.

**Product development and commercialization.** Fierce global competition in high-tech markets demands efficient implementation of the product development process and timely commercialization of the product. Reuse of common subsystems/components and best-known solutions; application of solid modeling in design, systems engineering, and rapid prototyping;
deployment of e-business in PDCP; and excellent program management must be standard practices.

**Value.** A product design approach must emphasize customer value and a firm’s desired position in the value chain through creative modular architecture, discriminating interface definition, and careful choice of product features and capabilities.

**Customer and stakeholder requirements.** Excellence in design requires not only a thorough understanding of the customer and other stakeholder requirements, but also a deliberate effort to meet these requirements by incorporating the necessary design concepts and attributes from the beginning of a PDCP.¹

### 6.1 PRODUCT DESIGN—GUIDELINES FOR EXCELLENCE

Adhering to certain guidelines will significantly improve the quality of design in product development. Engineering managers and program managers should discuss these requirements periodically at staff and project meetings. Engineers should be required to demonstrate adherence to these guidelines to engineering and program managers at design reviews. The guidelines include:

- Customer needs and benefits to the customers are paramount considerations in design. Give priority to customer **needs**, not to customer **wants**.
- Understand the **purpose** and the **why** of an engineering specification before designing to specification.
- Take a risk **if** success results in a product differentiator.
- Do what the competition cannot!
- Design-in provisions for a long product life and an opportunity for market extension. Consider modifying the design, without compromising compliance to the ERS, to extend the product utility in a different application.
- Elegant, aesthetically pleasing, and simple designs are good designs. A product must look (at least) as good as it is claimed to perform. The design must look state of the art (per the principle of suggestiveness).
- Benchmark the design practices of other companies, outside and inside your industry. Take advantage of other people's clever designs and build on them.
- Past practices (“we have always done it that way”) are not a good justification for a design approach.

![Design Structure Matrix](image)

**Figure 6.1.** Design Structure Matrix.
• Doing less than one’s best should not be tolerated.
• Cost and schedule requirements are no justification for a less-than-quality design. The only allowable compromise is in the number of features that are designed into the product, i.e., the scope of the project. Better design does not necessarily take longer or cost more money.
• The primary drivers of product cost are the design concept and the capabilities of the design.
• In a detailed design review, assess what component or subassembly can fail and design-in an improvement. Ask: What is insufficient in the design?
• Use of one part in many different subsystems and for different applications may appear to be attractive (for minimizing the number of parts and for economy of scale), but doing so might be an expensive compromise. Some companies have tried to find (or, even worse, to design) a “universal” component that will have application in multiple subsystems or product lines in the company. Except for the single use for which the universal component was optimized, for most applications, such practices result in a poor and costly design.
• Design parts so that incorrect assembly and incorrect installation will be impossible (i.e., poka-yoke techniques).
• The design should not require special tools to assemble or to repair the product.
• Minimize the use of special components (except for machined parts). Use standard catalog components.
• Excellent designs do not require any adjustments, alignments, or calibrations to assemble, set up, or operate properly.
• In a CIP (continuous improvement practice), do not change (“improve”) the original design until the reasons (the whys) behind the original design are fully understood. Lack of attention to this guideline leads to the creation of new problems.
• A product development team can use a DSM (design structure matrix) to establish relationships and interdependencies among the design parameters in a system or in a module. A DSM is a table-like chart that lists the parameters of a design in the rows and also in the columns of a square matrix. To show the dependencies among the design parameters, an “X” is put in a box that is at the intersection of the column of a parameter that is an input to the parameter in the intersecting row (Figure 6.1). For example, in Figure 6.1, parameter A is an input to parameters B and D.

A DSM can also be used for project management in product development (see Chapter 8). The tasks of the project are listed instead of the design parameters. Reading across the row of a task (e.g., D), the DSM shows all tasks whose output is required to perform that task (D). In project management, a DSM helps identify and analyze task dependencies. (Note: Project management application software such as MS Project can also create a DSM through PERT charting.)

6.2 DESIGN FOR EXCELLENCE

DFx (design for excellence) is a generic designation for excellence in meeting a multitude of requirements in a design—“x” might stand for manufacturability, serviceability, and maintainability; safety; environmental sustainability; reliability and robustness; etc.
The following sections discuss each of these requirements and recommend design practices for excellence. A more detailed section is devoted to reliability and robustness. The important subject of design for environmental sustainability (DFES) is treated only briefly. A number of references are cited, however, that the reader is encouraged to consult.

### 6.2.1 Design for Manufacturability

DFM (design for manufacturability), design for lean manufacturing, and design for assembly are common (and synonymous) terminologies that are used to indicate “designing a product that can be manufactured most efficiently.” The primary metrics of efficiency are product manufacturing cost, manufacturing defects, and production cycle time.

To achieve the objective of efficiency, a product development team must understand well the manufacturing processes by teaming with manufacturing engineers, value engineers, and supplier engineers during the design process. For example, a DFM necessitates a careful assessment of design tolerances (so they are not made too tight) and a careful selection of product components to maximize usage of commercially available parts (instead of special designs or parts that require special processes to fabricate). Value engineering of a product after the design is complete and released to production is often too late and is the equivalent of a rework of the design.

Lean manufacturing is eliminating waste at all steps of material flow in the production process. Lean manufacturing achieves low overhead, short cycle time, high inventory turns, high labor productivity, low defects, and on-time delivery. Common manufacturing wastes that must be eliminated include:

- Wait time (people waiting for material or machines, machines waiting for material or people, material waiting for people)
- Transportation waste (multiple moves of material due to layout or process design, multiple transactions, and return of unused material)
- Walking around to get parts and tools
- Lack of proper tools and fixtures, inadequate maintenance of tools and machines, long setup time
- Defects in material and assembly at the input to and output of any stage
- Large inventory (incoming, in process, and finished goods) causing excessive material and space cost, obsolescence, extra people and paperwork
- Overproduction and overcapacity

A product that is designed for lean manufacturing facilitates elimination of these wastes through efficient plant design, proper production planning, ergonomic work stations that are safe and efficient, continuous housekeeping, and Kaizen.

A common practice of manufacturing is to employ statistical process control (SPC) methodologies to minimize variability in production. The product design can play a pivotal role in the production process control by making the function of the product insensitive to variability in the manufacturing process. Design engineers must also build poka-yoke into the product design. Poka-yoke, or “error proofing” in Japanese, makes the product difficult to assemble incorrectly and the assembly mistakes obvious.
6.2.2 Design for Serviceability and Maintainability

DFS (design for serviceability and maintainability) is designing a product that has a predictable frequency of maintenance (required) and that can be serviced and put back into operation quickly. DFS ensures minimal unscheduled and unpredictable downtime.

Intelligent systems “alarm” for pending failures before a catastrophic breakdown and notify the operator about an upcoming scheduled maintenance. For example, many modern automobiles have an early warning capability for scheduled maintenance and are instrumented to alarm pending critical failures. Design for ease and speed in maintenance, whether it is scheduled or unscheduled, is an important element of the serviceability specification (if an unscheduled failure occurs, can it be easily diagnosed and its root causes identified?). In other words, the product hardware and software should have adequate instrumentation for serviceability.

An unscheduled failure results in poor predictability in system performance and is highly undesirable and costly in a business operation, including the manufacturing plant operation and the enterprise IT system. An unscheduled failure (or downtime) of equipment in a manufacturing plant causes damage to the customer product in production, backs up the work in progress (WIP) inventory, delays delivery of customer products to the customer’s customers, and lowers customer productivity.

Training service personnel to troubleshoot and maintain the product is also critical in minimizing downtime. Furthermore, training users of the product to operate the product is important to minimize downtime caused by operator error and to make the customer’s experience satisfying. A user-friendly, error-free, and complete product operations and maintenance (O&M) manual is a requirement of serviceability. The Q&M must be delivered with the product.

6.2.3 Design for Safety

Personnel and equipment safety must always be treated as the number one priority in product and process design. DFS (design for safety) means ensuring the safety of all stakeholders of the product, including the user, development engineers, manufacturing and plant personnel, service personnel, and the suppliers, and safety in transportation and in the community at large. The product ERS should call out, in detail, the product and process safety requirements to comply with local, national, and global safety laws, codes, and standards and customer-specific requirements. The firm may have more stringent safety requirements of its own that should be included in the ERS as well. The best DFS practice is to apply the most stringent safety requirements uniformly worldwide—even if certain regions of the global market have less restrictive local regulations.

6.2.4 Design for Environmental Sustainability

DFES (design for environmental sustainability) has become an imperative of business sustainability in the twenty-first century and hence a crucial requirement in product development. Environment refers to air, water, soil, and all other natural resources of the earth (including raw material) that are endowed for the well being of living species (people, animals, and plants) locally, globally, at present, and in the future. Environmental sustainability refers to being in
harmony with the ecological system of the earth, ensuring that manufacturing resource utilization and effluents do not harm the ecosystem equilibrium.

The engineering team must design a product and develop a manufacturing process that meets the environmental laws and standards, global protocols, and the company’s internal safeguards for leadership in environmental protection and sustainability. Designing for maximum efficiency and for minimal waste (in the usage of process consumables, manufacturing material, and packing material) is environmentally and economically sound. The use of reusable packing material and shipping crates should be a standard practice. The product should also be designed for environmentally sound end-of-life management, including an ability to be recycled and a minimal need for disposal in landfills. A sustainable product does not include hazardous material or material that cannot be recycled; is designed for disassembly; has a long life; and can be manufactured by means of a sustainable process.

To meet the DFES requirement, the product design must start with a life cycle analysis (LCA) that assesses the environmental impact of the product throughout its life cycle, starting with raw material extraction, manufacturing, use, and end-of-life disposal. DFES minimizes environmental impact throughout the cycle. Reviews of DFES practices may be found in Klostermann (1998), Manahan (1999), and Graedel and Allenby (1998).

6.3 DESIGN FOR RELIABILITY, PREDICTABILITY, AND ROBUSTNESS

Product reliability, according to the Japanese Industrial Standards (JIS), is the probability that the product satisfies the required functions during the specified time period and under the specified conditions.

Predictability of product performance is the variability (dispersion) in the expected performance (or the output) of one unit from another or of a given unit over a time period. A system is stable when it has a consistent and predictable output over time.

Robustness of a system is the tolerance of its performance (or output) to variability in the specified conditions of the operating environment, including the initial and boundary conditions, environmental state, and system constraints.

When a product is said to be fault tolerant that means its function is not interrupted by faults and that the product has the ability for self-diagnostics and auto-recovery from a fault condition.

Availability is the percentage of time, during the period of operation, that a product is in a condition to perform its required function.

The commonly used metrics of product reliability are mean time between failures (MTBF) and failure rate (FR). FR is the inverse of MTBF. “Shorter” failures are sometimes referred to as “interrupts” and are specified in mean time between interrupts (MTBI). The product reliability goal in MTBF must be specified in the exit criteria of the alpha and beta phases of a PDCP and should include the acceptable confidence level in demonstrating conformance to the goal. The confidence level is the measure of how well the test data conforms to the statistical probability of failure in a real (customer) operating environment.

Reliability of a complex system depends on the reliability of individual components and subassemblies and the interactions between them. Design and process characteristics, manufacturing quality, service quality, and product operability all contribute to the reliability of a system and must be considered in the product design for reliability. The product design must
then be tested for reliability at both the subsystem and system levels. An inadequate design for reliability results in higher cost of quality assurance, warranty, and service. Lower reliability of industrial products also increases the customer’s operating cost.

Availability of a product depends on its reliability and the time to repair should the product fail. The time to repair a failed product is measured in mean time to repair (MTTR) and directly impacts the product’s downtime.

### 6.3.1 Reliability and Robustness—Guidelines

The following guidelines must be followed in the alpha phase of a product development process:

1. Clarify product reliability requirements (MTBF, MTBI, confidence level, availability, predictability, and MTTR) and specify guidelines for design in the ERS (engineering requirement specification) document.
2. Understand well the operating environment of target customers. This is usually the weakest link in design for reliability. Although the reliability requirements (MTBF, availability, etc.) are usually specified, design engineers often do not fully comprehend the customer’s operating environment and its variability. They do not understand how and under what conditions the customer might operate and maintain the product. This situation often occurs when an existing product is modified for use in a different market segment and for a different application. In such a case, a proven, reliable product fails because it does not “match” the new application environment. For example, robotic products and components that had been designed and successfully used in automotive applications over a long time failed when they were introduced into the semiconductor manufacturing environment. Robot suppliers facing this problem learned about the new application environment the hard way—through many redesign cycles of learning. Design engineers should visit the customer’s use environment and familiarize themselves with the customer’s operating scenarios. The engineering team should then review their level of understanding with the customer.
3. Select parts according to their recommended application.
4. Use off-the-shelf proven components when possible.
5. Select suppliers who have a reputation for reliable products.
6. Select a part such that it is operated at less severe stress conditions than the conditions for which it is rated.
7. Add redundancy by using parallel components when possible.
8. Design-in simplicity and minimize the number of parts through combining functionality.
9. Use sensors to detect failure or prevent catastrophic failures (e.g., a thermal switch fuse or a temperature sensor could prevent major damage to the equipment and even the operator).
10. Use automated process control (APC) techniques with feed-forward/feedback control to reduce variability in the product performance.
11. Make a list of reliability problems with similar products in the past and identify design actions that would prevent their recurrence. A library of existing knowledge gained through experience and the corresponding design guidelines should be referenced in the ERS. Include industry standards for reliability.
12. Train a serviceperson who can readily troubleshoot and service products that integrate varieties of technologies and components. Products with integrated technologies and components are often complex and difficult to troubleshoot and maintain. Training a serviceperson who can readily maintain such products will be difficult. To improve maintainability, capabilities that must be designed into the product include:
   - Modularity, in which functions of the modules can be independently tested
   - Fault detection and status monitoring functions
   - Fault diagnostics and rapid fault localization
   - Fault recovery, preferably an auto-fault recovery
   - Alarm indicators and useful help descriptions

13. Evaluate the reliability of new technologies and components as early as possible. New parts are usually the weakest link. Reliability testing of a new technology and a newly designed part must be carried out first at the component level. If successful, the new component should be tested within the entire system to evaluate its interactions with other components.

14. Develop the test tools and methods for measuring and verifying product reliability and robustness and for implementing failure corrective actions.

15. Test subsystem and system reliability at the design point and over the planned range of operational envelope. Furthermore, test the system for robustness in a simulated customer environment over the entire range of input parameters and extreme conditions of the operating environment.

16. Develop a reliability test plan and include:
   - Test objectives for alpha and beta phases
   - Required resources (people, equipment, measurement tools)
   - Sample size, test length, and required confidence level
   - Test environment for robustness
   - Test procedure and schedule
   - Data collection scheme (DOE, IRONMAN, or marathon methods)
Data analysis and modeling methods [Use reliability modeling to predict product reliability and to identify subsystem reliability (budget) requirements.]

A test report and a corrective action project put in place based on the test results

6.3.2 Corrective Action Plan

Based on analysis of the failure data, engineers should develop hypotheses about the failure mechanism, identify the root causes, and verify the hypothesis by reproducing the failure. Corrective actions should follow to improve the design and the manufacturing process. Often engineers rush to implement a corrective action based on the data analysis and a hypothesis for a root cause, bypassing the verification step. This usually results in “fixing” the wrong problem.

Note: If you do not reproduce the failure, you cannot be certain that you have correctly identified the root cause of the failure or that you fully understand the exact failure condition.

6.4 RELIABILITY PROFILE OVER THE PRODUCT LIFE CYCLE

A typical reliability profile over the life cycle of a product is illustrated in Figure 6.2. The initial failure rate (which is typically high) can be eliminated through excellence in design, manufacturing quality, and flawless product installation and start-up. Random failures (past the initial failures and during the product’s useful life) create undesirable downtime and unpredictability. Random failures can be eliminated through designing robustness into the product, improving its maintainability for low MTTR, and an excellent preventive maintenance schedule.

6.5 RELIABILITY ASSURANCE BEYOND THE DESIGN PHASE

Reliability assurance in the manufacturing, quality inspection, and sales and service stages is also important to maximizing product reliability and predictability as experienced by the customer. In high-tech products, often the manufacturing technology is not well understood and the relationship between the manufacturing parameters and the product performance cannot be accurately specified. This situation can result in unacceptable deviations in product performance. In such a case, documenting the best-known manufacturing process conditions precisely and strictly adhering to the process of record might be the only solution.

An example of such case in IC manufacturing was encountered by a supplier of equipment for etching polysilicon in the manufacture of transistors. Polysilicon etching was done in a plasma reactor and was known to be quite sensitive to the properties of the electrode in the reactor. The electrode was made of high-purity aluminum and was coated by a thin layer of aluminum oxide through an anodization process. The etch results were quite sensitive to the anodization process. However, the relationship between the behavior of the electrode in the reactor and the manufacturing process to anodize the aluminum was not understood. The yield in making “good” electrodes was quite low. After a long and painful investigation, the equipment supplier and the anodization shop decided to precisely document the “good anodization” process (that resulted in a “good” electrode) and to strictly adhere to it in the shop.
operation. The documented process of record included all of the people, machines, and materials that came in contact with an electrode. Anodization yield improved drastically.

Sales personnel can contribute to the customer’s experience of product reliability by ensuring that they understand the application environment, sell the product to an appropriate application, and manage the customer’s expectations. The training level and responsiveness of service personnel in installation and maintenance of a product greatly impact the customer’s experience. Knowledge of the product and proficiency in troubleshooting and problem solving by service personnel are highly critical in reducing equipment downtime. Also, timely communication of the field data to the engineering team enables rapid corrective action and resolution of reliability problems.

6.6 RELIABILITY DESIGN—RELIABILITY MODELING AND OTHER TOOLS

Numerous methodologies and tools are available in the literature that can be applied to predict system reliability, to reduce product life cycle failures, and to improve a product’s useful (reliable) life. This section will briefly review some of these tools. (Note: The reader may consult the resources in the Additional Reading section for a comprehensive treatment of the topics in this overview.)

6.6.1 Reliability Modeling

Reliability modeling, as a tool of product development, can be used to:
• Improve understanding of a product by quantifying the effect of variability in a subsystem on the overall system
• Allow evaluation of design alternatives
• Identify critical subsystems, components, and their interactions
• Apportion product system reliability goal into individual subsystem/component budgets
• Assist in planning reliability tests to verify compliance to the ERS

A reliability model is particularly useful in predicting reliability when the system is complex and consists of a large number of interacting subsystems.

6.6.2 Mathematical Methods—Series and Parallel Models

Mathematical methods such as raptor and empirical block models predict system reliability by modeling the system as an assembly of blocks (subsystems and components) that are connected in series or in parallel. A reliability model is usually based on the input from a system reliability block diagram and a fault tree (see Figure 6.4), which depicts the system components and subsystems that affect its reliability and the failure rate of components and subsystems, for every failure mode and distribution. Most reliability models use Monte Carlo methods to generate a large sample of the system in the analysis.

Reliability of a system with independent failure modes is designated as:

\[ R_{\text{system}} = f(R_1, R_2, \ldots, R_n) \]

where,
**R**<sub>i</sub> is the reliability of component or subsystem *i*

\[ R_i = e^{-(\lambda_i)t} \]

where,
- \( \lambda_i \) is the failure rate of component *i*
- *t* is the interval of operation

The failure probability or unreliability of component *i* over time interval *t* is:

\[ F_i = (1 - R_i) \]

The function *f* depends on the interdependence of the components and the system and on the distribution of the failure rates. In a series model, failure of one component results in system failure, while in a parallel model, all components in a group must fail to cause a system failure. The following is the formulation of system reliability for the series and parallel models:

**Series system.** A series system is a system in which all subsystems and components are so interrelated that the entire system will fail if any one of its components fails. The probability that the system will fail is given by the special rule of multiplication for probabilities or the series product law of reliabilities, i.e.,

\[
R_{\text{system}} = \prod R_i 
\quad \text{or} 
\quad R_{\text{system}} = \prod e^{-(\lambda_i)t} = e^{-(\sum \lambda_i)t}
\]

\( \lambda_s \), the failure rate of the entire series system, is equal to the sum of the failure rate of its components:

\[ \lambda_s = \sum (\lambda_i) \]

Since MTBF = 1/\( \lambda \), the series system MTBF is:

\[
\text{MTBF}_{\text{series}} = 1/(1/\text{MTBF}_1 + 1/\text{MTBF}_2 + \ldots + 1/\text{MTBF}_n) 
= 1/(\lambda_1 + \lambda_2 + \ldots + \lambda_n)
\]

**Parallel system.** A parallel system is a system in which all “*n*” subsystems and components are connected in parallel and the system will fail to function if all *n* components fail. The unreliability of component *i* is \( F_i = 1 - R_i \). Applying the special rule of multiplication for probabilities:

\[ F_{\text{parallel}} = \prod F_i = \prod (1 - R_i) \]
Using the product law of unreliability, the system reliability will be:

\[ R_{\text{system}} = 1 - \prod (1 - R_i) \]

The MTBF (\(= 1/\lambda\)) for the parallel system is:

\[ \text{MTBF}_{\text{parallel}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \left( \frac{1}{\lambda_1 + \lambda_2} + \ldots \right) \]

If the failure rates of all \(n\) components are the same, the MTBF of this “redundant system” will be:

\[ \text{MTBF}_{\text{parallel}} = \frac{1}{\lambda} \times \left( 1 + \frac{1}{2} + \ldots + \frac{1}{n} \right) \]

**Example:** Figure 6.3 illustrates a system of semiconductor process equipment that is comprised of three subsystems—a transport module that is in series with a cluster of two process modules that are in parallel. The reliability of the individual subsystems is noted in the figure. The overall system reliability can be computed using the above equations as follows:

\[ \text{MTBF}_{\text{System}} = \frac{1}{(1/500 + 1/ (350 + 350) - (1/ (1/350 + 1/350)))} = 256 \text{ hr} \]

### 6.7 FAULT TREE ANALYSIS

FTA (fault tree analysis) is intended to describe and analyze all failures—their rates, their causes, and the possible design failures of a system. The first step in the FTA process is to list all system failure events. Next is to determine the various ways that a given failure can occur and to identify the potential subsystems and their components whose failure can lead to the system failure.

This methodology results in a tree of subsystems and components in which the fault might initiate and lead to a system failure. Based on the fault tree, an equation for system failure is
constructed as a function of subsystem/component failures. Figure 6.4 depicts an example of a fault tree. Note the designation of the dependency of the system failure to the fault conditions of its subsystems and components. The OR and AND gates (see legend in figure) signify series or parallel dependencies, respectively, in the hierarchy of the “significant” contributors. The tree is constructed downward from the system level failure to the “basic events” at a subsystem or component level.

6.8 FAILURE MODES, EFFECTS, AND CRITICALITY ANALYSIS

FMECA (failure modes, effects, and criticality analysis) examines all of the components of a system to identify how they might fail and the results of these failures; prioritizes the failures; and plans corrective actions. FMECA is best conducted using a table with columns that contain the following information.8

1. Part name (subsystem or component)
2. Part function
3. Potential failure mode
4. Effects of failure, both local and system level
5. Severity (assign a number from 1 to 10, with 10 being the most severe)
6. Potential causes of failure
7. Likelihood of occurrence (assign a number from 1 to 10, with 10 being highly likely)
8. Current design verification
9. Design detection number (assign a number from 1 to 10) (A low number means failure is detected, reduced, or prevented. A high number means the failure is not detected or stopped.)
10. RPI (reliability priority index), calculated as the product of “severity,” “likelihood,” and “detection number” from columns 5, 7, and 9, respectively (The RPI range will be from 1 to 1000.)
11. Root causes and recommended actions (Prioritize and assign resources based on the RPI ranking.)

6.9 DESIGN OF EXPERIMENTS

DOE (design of experiments) is a statistical method for determining the relationship between the factors affecting a process and the output of that process. A factor of an experiment is a controlled independent variable whose “levels” are set by the experimenter.

6.10 PASSIVE DATA COLLECTION

PDC (passive data collection) is a test procedure to establish process stability. PDC accumulates data for a specified time period without any process or equipment adjustment (i.e., under normal operating conditions).
6.11 ACCELERATED TESTING AND SCREENING

Accelerated testing is intended to establish a relationship between environmental factors and system lifetime. These tests include environmental stress screening (ESS) and highly accelerated life testing (HALT).

6.12 WEIBULL ANALYSIS

Weibull analysis uses the following equation to predict the expected number of failures as a function of time:

\[ N(t) = (1 - e^{-(t/\alpha)^\beta}) \times n \]

where,
- \( t \) is time
- \( n \) is the population
- \( \alpha \) and \( \beta \) are Weibull constants corresponding to scale and shape parameters, respectively

Using the experimental data of past failures, one can calculate the Weibull parameters (\( \alpha \) and \( \beta \)) and use the above equation to forecast the expected number of failures in the future.

6.13 THE DUANE GROWTH MODEL

The Duane growth model uses a relationship between the cumulative test time and the cumulative failures to develop a reliability growth profile. The Duane model allows a user to assess the effectiveness of proposed and implemented reliability improvement fixes. A Duane chart is a log-log plot of cumulative MTBF versus cumulative test time.

6.14 RELIABILITY GROWTH TESTING

The reliability growth testing method is the continuous testing of a system to detect failures (under test conditions), to implement corrective actions, and to continue with the test. One such method is called IRONMAN (improving reliability of new machine at night) developed by Motorola Corporation in partnership with semiconductor equipment suppliers.

6.15 ROBUSTNESS AND PREDICTABILITY OF PERFORMANCE

A product must be designed for the “real world” context of the target application, i.e., the conditions of the stakeholders’ environments that it comes into contact with. Variability in the input parameters should not cause undesirable excursions in product performance.

A system or subsystem has two types of input parameters. First are the input parameters at the interface of one subsystem or system to another that are designed to change for achieving the desired performance of the system (or subsystem). These parameters and their operating ranges are usually determined by the product designer and set by either the manufacturer or the user. For example, the interior temperature of a passenger car is set by the driver and the temperature of the engine coolant is set at the factory.
Second are the input parameters from the conditions of the environmental within which the system operates. These parameters are either kept “constant” or are expected to have minimal impact on the performance of the system (subsystem). For example, the temperature and humidity of an office or a hospital operating room are the environmental parameters within which a computer or an X-ray scanner must properly operate.

An example of the first type of parameter or system variable is radio-frequency (RF) electrical power in an etch system in the IC manufacturing process. The RF power level is set at different levels by the user to achieve a higher or lower etching rate. The second type of parameter in an IC fab is the utility AC voltage level (normally 110 or 220 volts). The utility AC power energizes the etcher to generate the user-set RF power level and to operate the etching reactor.

A robust system (or subsystem) has a predictable and controlled response (i.e., not very sensitive) to the variability in the input parameters of either type. In other words, a robust system is tolerant of inaccuracy and imprecision in the input variables. Achieving a higher degree of accuracy and precision in input variables is usually costly and increases the system’s complexity.

The etcher in the above example is not a robust system if a random deviation from the set point (e.g., a fraction of 1%) in the output of the RF generator results in a significant change (e.g., more than 10%) in the reactor etching rate. Moreover, if a random “voltage sag” in the fab utility power caused a catastrophic damage to the etch equipment, the system is not robust.

Predictability of performance of a product is often as important to a user as its reliability and availability. Predictable downtime is undesirable, but manageable; however, unpredictability is disruptive to the user’s operation and could be very costly, which is true for consumer and industrial products. A random crash of a computer operating system or a desktop application software can be catastrophic (or at the least annoying) for a sales person in a conference with a customer.

Predictability of performance of an industrial product in a customer’s production environment is often more critical than its MTBF because predictability of performance impacts the customer’s manufacturing work in progress (WIP) and the overall factory output in an unplanned way. Figure 6.5 illustrates an example of how an IC fab WIP profile is impacted by dispersion in the availability of process equipment (tools) in the fab. (Note: The unbalanced fab line in Figure 6.5 has downstream effects that constrain fab operation and lower fab output.)
**6.16 TERMINOLOGY IN PRODUCT DESIGN AND DEVELOPMENT—DEFINITIONS**

This section defines common terminologies for several key tasks and events in product development to clarify the scope of these tasks and to provide a common communication framework for team members. The definitions in this section are not intended to be universal or precise. They are merely a framework for establishing a common language and for managing the product development project. These definitions should be tailored to the specific needs and preferences of a product development team based on the firm’s established business processes, the nature of the firm’s business and the product, and historical practices.

Important for a product development team is that it has a clear definition and common understanding of the scope of the various tasks and their success criteria. Oftentimes the lack of a common response to questions such as “what is a conceptual design,” “what should be the scope of alpha testing,” “what does a product release entail,” and other similar questions reduces the efficiency of the product development team and causes confusion and frustration among team members.

To elucidate the concepts in this section, the layout in Figure 6.6 of process equipment in semiconductor manufacturing is used as a reference product.

**6.16.1 Design Stages**

The design of a product usually undergoes three stages of evolution—conceptual, preliminary, and detailed design. In general, the conceptual design is carried out in Phase 1 of a PDPC and the preliminary and detailed designs are done in Phase 3 (alpha phase).

Different subsystems and components of a product, however, can be in different stages of design and go through different evolutionary paths during the PDCP. For example, if a new
product incorporates an existing component of another product, that component is already at a detailed design stage (from the beginning of the PDCP). On the other hand, in Phase 1 (E&F), in which alternate concepts for a high-risk component are evaluated, the design must be carried out to the detailed stage in order to fabricate and test the component—although this design might be modified a few times during the same phase or in subsequent phases as new knowledge is generated during the development process and through multiple cycles of learning. A new product, including all its components and subsystems, must reach the detailed design stage before the product can be released for commercialization in Phase 3 (beta phase).

6.16.2 Designs—Scope and Output

The scope and expected output of each design stage are outlined below. Some of the examples of their content are specific to the system in Figure 6.6:

Conceptual Design:
• System architecture (hardware, controls, and software)
• System layout, identifying various modules and their interfaces
• Subsystem arrangement, on-board and off-board of the product
• Controls and software design approach
• Overall system performance modeling and calculations, such as throughput, fluid flow, heat transfer, structural stress, power distribution, signal communication timing and latency, etc.
• Subsystem sizing and performance calculation, such as controllers, robotic arm (reach, speed, and loads), temperature control unit, vacuum pumps, power generators, gas delivery system, and others
• Detailed subsystem and component performance budgets that add up to meet the overall system requirements per MRS (defect contribution, robotic transport overhead, power consumption, reliability, and availability)
• System conceptual cost estimate
• ERS (engineering requirements specification)

Preliminary Design:
• Component sizing
• Component selection and supplier identification (user interface, pumps, mass-flow controllers, robots, control units and microprocessors, application software, software development system, power generators)
• Materials of construction and manufacturing methods for all components and system packaging (Certain manufacturing techniques may have to be determined to meet the performance requirements of a component or subsystem. For example, a high vacuum chamber in Figure 6.6 may have to be machined out of a solid block of aluminum rather than forged to attain a desired “low” leak rate.)
• Layout of the subsystems (For the Figure 6.6 example, the subsystems include reaction chamber module, wafer transfer module, robotic arm assembly, vacuum manifolds, FI module, and various printed circuit boards.)
• ICD (interface control document) for all hardware modules (subsystems) and API (application programming interface) for all software modules
- System-level drawings and documents, including assembly tree, signal list, P&ID (process and instrumentation diagram), and electrical single-line diagram
- System preliminary cost estimate
- Updated ERS (engineering requirements specification)

Detailed Design:
- All drawings, documentation, and specifications of the product and manufacturing tools necessary to manufacture the product
- Software source and executable codes and documentation for installation, use, and troubleshooting instructions
- BOM (bill of materials)
- Fabricated parts drawings and specification
- PCB (printed circuit board) designs, layout, routing, and components
- System frame and packaging design
- Electrical schematics
- Power and signal cable harness routing and terminations
- Specification sheets of all supplier components
- Assembly drawings and procedures
- Updated system documents (assembly tree, signal list, P&ID)
- Facilities installation package, including tooling and software

6.17 PRODUCT DOCUMENTATION

Output of the engineering effort in developing a new product is a set of documents that serves the needs of all stakeholders (internal and external to the firm) and informs them of the product performance characteristics (product specification data sheets). The product stakeholders and their needs include customers who use the product; sales personnel who configure the product and quote a price; manufacturing and supplier organizations who buy parts and build the product; service organizations that install the product, support the customers, and maintain the installed base; engineers who continuously improve the product; and marketing/product management who forecasts demand for the product, manages change throughout the product life cycle, and identifies opportunities for business development and for extending the product’s life.

Product documentation should include the items listed above (in Detailed Design output) and the following items:

- Process recipes
- System and subsystem theory of operation
- Manufacturing sequence of events and method sheets
- Manufacturing parameters and control methodologies for all components and subsystems except for off-the-shelf items (Although external suppliers of components and subsystems might protect such information as proprietary, the product development team must ensure that such information is available and is under revision control.)
- System test plan for manufacturing qualification and for troubleshooting
Subsystem and system test and calibration procedures
Design specification of special tools and equipment
O&M (operation and maintenance) procedures, including tools and diagnostics software
Shipping assembly
Installation instructions, including software
Spares parts list and recommended stock
Product sales documents such as system configuration software
Marketing collaterals and brochures
Training documents for application engineers, customer process engineers, and the Manufacturing, Customer Service, and Marketing and Sales departments
Product specification (specifies the product from the customer’s viewpoint, including product performance, its intended use, interfaces to the customer’s operating environment, such as signal communication protocol, physical dimensions of the product, and facilities interfaces)

Comment: Engineers usually do not like to complete the product documents listed above because the documentation process is considered to be boring and not creative. Yet the completeness, accuracy, and usefulness of product documents are paramount to the product commercialization success, including profitability and customer satisfaction. The best practice is to document the mechanical, electrical, controls, and software designs “as you go.”

6.18 PROTOTYPING

Knowledge generation by experimentation through cycles of learning is a crucial element of new product development. Experimentation can be done via modeling, analysis simulation, and prototyping. The objective of prototyping is to learn the interaction among various modules/subsystems, verify the design, learn design shortcomings, and characterize the performance of subsystems and the system as a whole in applicable use environments.

Prototypes can be built in full scale or in subscale. Usually, a subscale prototype is built to save cost and time. However, experimentation through subscale prototyping is only effective if the scaling laws of design and performance are understood.

Prototyping occurs in all phases of the PDCP. Prototypes can be built for a component, a subsystem, or the entire system. In Phase 1 of the PDCP, in which the objective is to evaluate a new technology and to assess alternative design concepts, building a prototype of only the subsystem (module) under evaluation is generally more economical. This practice is known as building a “bench prototype.” Interaction of the subsystem developed in Phase 1 with the other modules, and its performance within the system as whole, is learned in Phase 3 by testing a prototype of the entire system (known as an “engineering prototype”). Customer testing and a manufacturing evaluation of the product are carried out in Phase 4 by building a “preproduction prototype.”

Descriptions of the different types of prototypes are presented in the following sections. The prototype purpose, characteristics, and timing during a PDCP are highlighted.
6.18.1 Bench Prototype

**Purpose.** The purpose of a bench prototype (BP) is to evaluate and demonstrate the feasibility of proposed technologies and design concepts; to evaluate high-risk components and modules; to perform life cycle testing of high-risk subsystems; and to identify early life reliability and performance issues. A BP mitigates overall project schedule risks. BP test results can be used as a basis for the technology and design “go/no go” decision in Phase 1.

**Characteristics.** A BP usually operates manually; is a realistic (full scale?) representation of the function of the final design; performs a “single” function (as much as possible); is heavily instrumented; and is highly flexible to permit rapid experimentation of ideas and improvements.

**Timing.** A BP should be built as early as possible in Phase 1 of a PDCP. The BP design/build/test should be scheduled into the project plan to allow for timely evaluation and learning. BP evaluation requires resources for the design/build/test and impacts the overall project schedule and cost. Required resources are usually overlooked by project managers, causing schedule and cost variances.

6.18.2 Engineering Prototype

**Purpose.** The purpose of an engineering prototype (EP) is to evaluate the integrated system performance, including hardware, process control, and software; to develop the process; to learn about the interaction between various modules; to identify performance and design integration deficiencies of the subsystems with the system; and to establish the final design of the system packaging (including cable harness routing and piping).

**Characteristics.** An EP should be designed as the “final product” for volume production as if the EP were the team’s last chance. For example, Japanese car manufacturers emphasize that the first EP should be fully functional and in some cases complete in appearance, down to surface finishes, because the EP is the ultimate test of how the entire system fits together. If there is a significant difference between the EP and the later volume-production parts, the alpha-phase test and the refinement of the design will be rendered irrelevant. Unlike a BP, no special design provisions (e.g., one-time instrumentation) should be required for an EP. To accelerate the development schedule, the EP could forego inclusion of “second-order” and low-risk features and capabilities of the product that can be integrated during the subsequent beta phase. Data collection and storage capability in IC process equipment are examples of second-order features.

**Timing.** EPs are built in Phase 3 (the alpha phase) of a PDCP. A development team is often faced with the question of how many EPs to build. The “right” number depends on the nature and complexity of the product and the extent of testing that is called for in the alpha exit criteria. For example, for IC process equipment, a minimum of two EPs is often desirable—one dedicated to developing the process and a second dedicated to verifying the hardware and software performance against the ERS. For a flash-memory card of a digital camera, several hundred EPs might be required to gather statistically valid verification data. Budget and project schedule constraints, however, often play a decisive role in how many EPs can be built.
6.18.3 Beta (Preproduction) Prototype

**Purpose.** The purpose of a beta or preproduction prototype (PPP) is to qualify the product for customer use and for manufacturing before its release for production and commercialization; to characterize the function of the product in-house and at the customer’s environment (under “battlefield” conditions!)

**Characteristics.** A PPP should include the design modifications (for improvement) that were identified in the alpha phase after evaluation of the EP. A PPP should also include all product features and capabilities that are intended for initial product introduction such as packaging and provisions to install the product at the customer’s operating environment. A PPP should not be conceptually different from the EP. If, as a result of the alpha (EP) testing, the system architecture or its design concept was found to be inadequate (in meeting the ERS and MRS), the PDCP has to revert to the beginning of Phase 2 to reassess the viability of the product design, technology, and market timing.

**Timing.** A PPP is shipped to a selected group of beta customers for evaluation during Phase 4 of a PDCP. One or more identical units of the product should be kept in-house for manufacturability verification, finalization of manufacturing process and tooling, and for customer support through rapid resolution of issues identified by beta customers.

6.18.4 First Article Production

**Purpose and timing.** The purpose and timing of a first article production run is to develop volume manufacturing procedures and tooling in the Phase 5 production ramp (gamma phase). The product design and documentation modifications resulting from the beta evaluation should be incorporated in the design before the first article production run.

**Comment:** Depending on the nature of the product and the structure of the PDCP, the first article production run and the beta prototype (PPP) could be synonymous.

6.19 PRODUCT CHARACTERIZATION TESTING

The testing to validate a new design and characterize its performance is a critical task of product development. Testing is required in Phase 1 of a PDCP to select the optimal technology and design concept, in Phase 3 to learn the interactions between the subsystems and components of the product, and in Phase 4 to validate the system performance against the MRS.

In each phase, the tests must be carefully planned, carried out, and their results analyzed. Specifying the objective of a testing program and articulating the planned output and knowledge that the team is expected to learn are important. A detailed test plan, including how to conduct testing, the required tools and instrumentation, and the methodology for data collection and analysis, should be carefully prepared and reviewed before starting testing. After the tests are completed, a test report must be prepared detailing test conditions, test method, collected data, data analysis, and conclusions that are derived from the results and observations stating whether the test objectives have been satisfied.

In Phases 3 and 4, planning a testing program that measures the performance parameters that are pertinent to demonstrating whether the product has satisfied the success criteria of the phase is important. If the product performance falls short of the goal (in any critical
parameter), test engineers must identify the root cause of the problem and, in collaboration with design engineers, implement a corrective action plan.

Usually, too many variables exist, preventing the performance of all of the possible experiments. Therefore a subset of the experiments must be run, with a focus on the most efficient combination of experiments to permit gathering system information. One such approach is the design of experiments by Genichi Taguchi. Refer to Taguchi, Chowdhury, and Wu (2004)\textsuperscript{8} and Taguchi and Clausing (1990)\textsuperscript{10} for a full discussion of this approach.

In Phase 4 of a PDCP, beta customers should participate in setting the test objectives and in preparing the test plan for the phase (see Section 6.20).

\section*{6.20 CUSTOMER PARTICIPATION IN PRODUCT DEVELOPMENT}

In high-tech markets, customer intimacy is critical in all phases of product development, from the onset in preparing the MRS to execution of the beta phase and product launch. Notwithstanding the concern for IP protection and the risk of exposing an immature product and technology to key customers, consulting customers in Phases 0 and 1 and having selected customers participate in the alpha phase as co-development partners are desirable. The beta phase, however, must include active participation by several key customers to qualify the viability of the product in meeting their needs.

The purpose of a customer joint development project (JDP) in the alpha phase is mitigation of development risk through early and deep learning of the customer’s application needs and priorities. A JDP customer might also assist in evaluating the technology through active participation in test planning and execution. The engineers from a JDP customer could reside, at least part time, at the manufacturing company’s premises and provide expertise, the user’s viewpoint (realistic applications and expectations), testing material (such as wafers in the development of IC process equipment), and other resources.

The purpose of customer participation in the beta phase is to assess product performance qualification against the requirements by the customer in his/her operating environment. The goal is to test the product in the “battlefield” environment of the customer, to receive installation and maintenance feedback (including requirements for spare parts), and to assess the product’s user friendliness and robustness.

The desired (or optimal) number of beta customers is highly dependent upon the technology, product, industry, and firm’s resources (in personnel and budget). For example, in the development of process equipment in the semiconductor manufacturing industry, three is the optimal number of beta customers, whereas to qualify new application software, Microsoft Corporation might have several hundred beta customers.

Critical is that beta customers are selected carefully and a formal agreement is signed with them that specifies the objectives and mutual expectations. A successful beta program is also dependent on having a dedicated beta project team. Because beta customers are usually early adopters of the new technology and are interested in making the product successful, supporting beta customers with the best resources during a beta program must be the number one priority of a product development team.
6.20.1 Selection Criteria—Beta Customers

Four criteria should be used in selecting beta customers:

- Customer’s level of interest and excitement for the product in satisfying an unfilled and high priority need—Does the product capture the customer’s imagination about its future possibilities? The firm’s technology and the product should enable the beta customer’s business success and enhance the beta customer’s competitive advantage.
- Competitiveness of the new technology and the product in the beta customer’s application—Is there a compelling differentiating advantage over the customer’s alternative solutions?
- Customer’s strategic significance to the firm, as measured by the potential business opportunity, and the customer’s market position and influence as a reference to assist the firm to successfully penetrate the market
- Resource availability to make the beta project a resounding success—Adequate skilled resources in technology, engineering, support, operations, and project management are essential for success. Doing fewer beta projects well is preferable to doing many poorly.

6.21 QUALITY

The subject of quality is extensively covered in the literature and is beyond the scope of this book. The purpose of this section is to briefly discuss selected definitions and concepts of quality in a product development and commercialization process.

Quality products and services conform exactly to established customer requirements. The established customer requirements could be specified in a documented agreement between a supplier and a customer or they could be a customer’s expectation of what the product or service entails and what value will be delivered. Customer expectations are established based on the supplier’s representation and the customer’s reference product/service such as competitors’ alternative offering.

Quality management entails more than having zero defects in a design or manufacturing process. Quality management is enabling a customer’s experience (in his/her operating environment) that satisfies the customer’s needs and wants. Quality management is having a customer-focused culture in an organization and adopting a broad view of the customer that includes both internal and external customers.

Quality control, according to the Japan Industrial Standards (JIS), is “a system of means to economically produce goods and services which satisfy customer requirements.”

6.21.1 Quality Leverage in PDCP

The cost of fixing a product defect (the cost of poor quality) multiplies as it permeates throughout the value-added sequence of a PDCP (illustrated in Figure 6.7). During the engineering phase for generation and integration of knowledge and during manufacturing when material is formed and assembled into finished goods, a sequence of operations is performed in each “work area” and the output is passed on to the next work area. The “last stop” is at the
customer’s use environment. The cost of fixing a problem that occurs in a work area rises exponentially the further down the sequence the error is caught.

Experiencing a 100-times increase in the cost of fixing a design problem if it is caught by an end user versus finding the problem in the design “work area” is not uncommon. In the late 1990s, the seemingly minor, but undetected design problem with the Pentium chip cost Intel hundreds of millions of dollars when it was caught by the end users. Intel had to implement a global customer damage control program to reestablish consumer confidence.

### 6.21.2 Precision and Accuracy

The *Merriam-Webster*’s dictionary gives the following definitions:

- **Precision**—"The degree of refinement with which an operation is performed or a measurement stated"
- **Accuracy**—"Conformity to truth or to a standard or model"

For a product or a process, *precision* is an indication of the reproducibility of the performance and *accuracy* is the distance of the performance from the “target.” The concepts of precision and accuracy in product performance are illustrated in Figure 6.8.

In Figure 6.8 the consistent and predictable performance on the left side is preferable because the user can manage the situation. For example, with a small adjustment, performance of the product might be shifted on the target or the customer might be able to make adjustments to other parts of the operation. The performance on the right side of Figure 6.8, however, is unmanageable and undesirable.
Minimum variability in performance (i.e., high precision) must be the primary goal of product development. Product designers must achieve a design that can be produced and function consistently under all customer-use conditions. Taguchi and Clausing (1990) point out that “catastrophic stack-up is more likely from scattered deviation within specifications than from consistent deviation outside.”

REFERENCES

ADDITIONAL READING