

**Wiley Series in
Systems Engineering and Management**

Andrew P. Sage, Series Editor

Reliability Engineering



Kailash C. Kapur Michael Pecht

WILEY

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AND MANAGEMENT**

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A complete list of the titles in this series appears at the end of this volume.

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Kailash C. Kapur
Michael Pecht

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Preface

Humans have come to depend on engineered systems to perform their daily tasks. From homes and offices to cars and cell phones, the context in which we live our lives has been largely constructed by engineers who have designed systems and brought their ideas to the marketplace.

While engineered systems have many benefits, they also present risks. How do we know that a building is safe and reliable? How do we know that a sensor in a train will work? How do we know that airbags and brakes will function in an emergency? No matter how many experts were involved in designing systems, the chance for failure always lingers. Thus, all engineering disciplines need reliability.

Today, reliability engineering is a sophisticated and demanding interdisciplinary field. All engineers must ensure the reliability of their designs and products. Moreover, they must be able to analyze a product and assess which parts of the system might be prone to failure. This requires a wide-ranging body of knowledge in the basic sciences, including physics, chemistry, and biology, and an understanding of broader issues within system integration and engineering, while at the same time considering costs and schedules.

The purpose of this book is to present an integrated approach for the design, engineering, and management of reliability activities throughout the life cycle of a product. This book is for those who are interested in gaining fundamental knowledge of the practical aspects of reliability to design, manufacture, and implement tests to ensure product reliability. It is equally helpful for those interested in pursuing a career in reliability, as well as for maintainability, safety, and supportability teams. We have thus written this book to provide students and practitioners with a comprehensive understanding of reliability engineering.

The book is organized into 19 chapters. Each chapter consists of a number of numerical examples and homework problems. References on the topics covered are presented to help the reader delve into more detail.

Chapter 1 provides an overview and discussion of the relevance of reliability engineering for the twenty-first century. This chapter presents a definition of reliability and describes the relationship between reliability, quality, and performance. The consequences of having an unreliable product, that is, a product that fails, are presented with examples. The chapter concludes with a discussion of supplier–customer reliability objectives and responsibilities. It also discusses various stakeholders in product reliability. Principles for designing and managing a reliability program for the twenty-first century are presented.

Chapter 2 presents the fundamental mathematical theory for reliability. Useful reliability measures for communicating reliability are presented. The focus is on reliability and unreliability functions, the probability density function, the hazard rate, the conditional reliability function, and key time-to-failure metrics, such as mean time to failure, median time to failure, percentiles of life, various moments of a random variable, and their usefulness in quantifying and assessing reliability. The bathtub curve and its characteristics and applications in reliability are discussed.

Chapter 3 covers basic concepts in probability related to reliability, including statistical distributions and their applications in reliability analysis. Two discrete distributions (binomial and Poisson) and five continuous distributions (exponential, normal, lognormal, gamma, and Weibull) that are commonly used in reliability modeling and hazard rate assessments are presented. The concepts of probability plotting and the graphical method for reliability estimation are also presented with examples.

Chapter 4 gives a comprehensive review of the Six Sigma methodology, including Design for Six Sigma. Six Sigma provides a set of tools to use when a focused technical breakthrough approach is required to resolve complicated technical issues, including reliability in design and manufacturing. In this chapter, an introduction to Six Sigma is provided, and the effect of process shift on long-term and short-term capabilities and process yield is explained. A historical overview of Six Sigma is provided, including a thorough discussion of the phases of quality improvement and the process of Six Sigma implementation. Optimization problems in Six Sigma quality improvement, transfer function, variance transmission, and tolerance design are presented. The chapter concludes with a discussion of the implementation of Design for Six Sigma.

Chapter 5 discusses the role of reliability engineering in product development. Product development is a process in which the perceived need for a product leads to the definition of requirements, which are then translated into a design. The chapter introduces a wide range of essential topics, including product life-cycle concepts; organizational reliability capability assessment; parts and materials selection; product qualification methods; and design improvement through root cause analysis methods such as failure modes effects and criticality analysis, fault tree analysis, and the physics-of-failure approach.

Chapter 6 covers methods for preparing and documenting the product requirements for meeting reliability targets and the associated constraints. The definition of requirements is directly derived from the needs of the market and the possible constraints in producing the product. This chapter discusses requirements, specifications, and risk tracking. The discussion also includes methods of developing qualified component suppliers and effective supply chains, product requirement specifications, and requirements tracking to achieve the reliability targets.

Chapter 7 discusses the characteristics of the life-cycle environment, definition of the life-cycle environmental profile (LCEP), steps in developing an LCEP, life-cycle phases, environmental loads and their effects, considerations and recommendations for LCEP development, and methods for developing product life-cycle profiles, based on the possible events, environmental conditions, and various types of loads on the product during its life cycle. Methods for estimating life-cycle loads and their effects on product performance are also presented.

Chapter 8 provides a discussion on the reliability capability of organizations. Capability maturity models and the eight key reliability practices, namely reliability requirements and planning, training and development, reliability analysis, reliability testing,

supply chain management, failure data tracking and analysis, verification and validation, and reliability improvement, are presented.

Chapter 9 discusses parts selection and management. The key elements to a practical selection process, such as performance analysis of parts for functional adequacy, quality analysis of the production process through process capability, and average outgoing quality assessment, are presented. Then, the practices necessary to ensure continued acceptability over the product life cycle, such as the supply chain, parts change, industry change, control policies, and the concepts of risk management, are discussed.

Chapter 10 presents a new methodology called failure modes, mechanisms, and effects analysis (FMMEA) which is used to identify the potential failure mechanisms and models for all potential failures modes and prioritize the failure mechanisms. Knowledge of failure mechanisms that cause product failure is essential for the implementation of appropriate design practices for the design and development of reliable products. FMMEA enhances the value of failure mode and effects analysis (FMEA) and failure mode, effects, and criticality analysis (FMECA) by identifying the “high priority failure mechanisms” to help create an action plan to mitigate their effects. Knowledge of the causes and consequences of mechanisms found through FMMEA helps to make product development efficient and cost effective. A case study describing the FMMEA process for a simple electronic circuit board assembly is presented. Methods for the identification of failure mechanisms, their prioritization for improvement and risk analysis, and a procedure for documentation are discussed. The FMMEA procedure is illustrated by a case study.

Chapter 11 covers basic models and principles to quantify and evaluate reliability during the design stage. Based on the physics of failure, the designer can understand the underlying stress and strength variables, which are random variables. This leads us to consider the increasingly popular probabilistic approach to design. Thus, we can develop the relationships between reliability and different types of safety factors. This chapter provides a review of statistical tolerances, and develops the relationship between tolerances and the characteristics of the parts and reliability.

Chapter 12 discusses the concepts of derating and uprating. This chapter demonstrates that the way in which a part is used (i.e., the part’s stress level) has a direct impact on the performance and reliability of parts. This chapter introduces how users can modify the usage environment of parts based on ratings from the manufacturer, derating, and uprating. The discussion includes factors considered for determining part rating, and the methods and limitations of derating. Stress balancing is also presented.

Chapter 13 covers reliability estimation techniques. The purpose of reliability demonstration and testing is to determine the reliability levels of a product. We have to design tests in such a manner that the maximum amount of information can be obtained from the minimum amount of testing. For this, various statistical techniques are used. A major problem for the design of adequate tests is simulating the real-world environment. The product is subjected to many environmental factors during its lifetime, such as temperature, vibrations and shock, and rough handling. These stresses may be encountered individually, simultaneously, or sequentially, and there are other random factors. Methods to determine the sample size required for testing and its relationship to confidence levels are presented. Reliability estimation and the confidence intervals for success-failure tests and when the time to failure is an exponential distribution are also discussed with numerical examples. A case study is also presented for reliability test qualification.

Chapter 14 describes statistical process control and process capability. Quality in manufacturing is a measure of a product's ability to meet the design specifications and workmanship criteria of the manufacturer. Process control systems, sources of variation, and attributes that define control charts used in industry for process control are introduced. Several numerical examples are provided.

Chapter 15 discusses methods for product screening and burn-in strategies. If the manufacturing or assembly processes cannot be improved, screening and burn-in strategies are used to eliminate the weak items in the population. The chapter demonstrates the analysis of burn-in data and discusses the pros and cons of implementing burn-in tests. A case study demonstrates that having a better manufacturing process and quality control system is preferable to 100% burn-in of products.

Chapter 16 discusses root cause analysis and product failure mechanisms, presents a methodology for root cause analysis, and provides guidance for decision-making. A root cause is the most basic causal factor (or factors) that, if corrected or removed, will prevent the recurrence of a problem. It is generally understood that problem identification and correction requires the identification of the root cause. This chapter presents what exactly a root cause analysis is, what it entails, and at what point in the investigation one should stop. This chapter also reviews the possible causes and effects for no-fault-found observations and intermittent failures, and summarizes them into cause-and-effect diagrams. The relationships between several techniques for root-cause identification, such as Ishikawa diagrams, fault tree analysis, and failure mode, mechanisms, and effects analysis, are covered.

Chapter 17 describes how to combine reliability information from the system architecture to compute system-level reliability. Reliability block diagrams are preferred as a means to represent the logical system architecture and develop system reliability models. Both static and dynamic models for system reliability and their applications are presented in this chapter. Reliability block diagrams, series, parallel, stand-by, k -out-of- n , and complex system reliability models are discussed. Methods of enumeration, conditional probability, and the concepts of coherent structures are also presented.

Chapter 18 highlights the significance of health monitoring and prognostics. For many products and systems, especially those with long life-cycle reliability requirements, high in-service reliability can be a means to ensure customer satisfaction and remain competitive. Achieving higher field reliability and operational availability requires knowledge of in-service use and life-cycle operational and environmental conditions. In particular, many data collection and reliability prediction schemes are designed before in-service operational and environmental aspects of the system are entirely understood. This chapter discusses conceptual models for prognostics, the relationship between reliability and prognostics, the framework for prognostics and health management (PHM) for electronics, monitoring and reasoning of failure precursors, the application of fuses and canaries, monitoring usage profiles for damage modeling, estimation of remaining useful life, uncertainties associated with PHM, and the implementation of these concepts in complex systems.

Chapter 19 discusses warranty analysis and its relationship to reliability. A warranty is a guarantee from a manufacturer defining a responsibility with respect to the product or service provided. A warranty is a commitment to repair or replace a product or re-perform that service in a commercially acceptable manner if it fails to meet certain standards in the marketplace. Customers value a good warranty as economic protection, but a product is generally not considered good if it fails during the

product's useful life (as perceived by the customer), regardless of the warranty. The chapter covers warranty return information, types of warranty policies and cost analyses, the effect of burn-in on warranty, simplified system characterization, and managerial issues with regard to warranty.

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Michael Pecht



1 Reliability Engineering in the Twenty-First Century

Institutional and individual customers have increasingly better and broader awareness of products (and services) and are increasingly making smarter choices in their purchases. In fact, because society as a whole continues to become more knowledgeable of product performance, quality, reliability, and cost, these attributes are considered to be market differentiators.

People are responsible for designing, manufacturing, testing, maintaining, and disposing of the products that we use in daily life. Perhaps you may agree with Neville Lewis, who wrote, “Systems do not fail, parts and materials do not fail—people fail!” (Lewis 2003) It is the responsibility of people to have the knowledge and skills to develop products that function in an acceptably reliable manner. These concepts highlight the purpose of this book: to provide the understanding and methodologies to efficiently and cost effectively develop reliable products and to assess and manage the operational availability of complex products, processes, and systems.

This chapter presents the basic definitions of reliability and discusses the relationship between quality, reliability, and performance. Consequences of having an unreliable product are then presented. The chapter concludes with a discussion of supplier–customer reliability objectives and responsibilities.

1.1 What Is Quality?

The word *quality* comes from the Latin *qualis*, meaning “how constituted.” Dictionaries define *quality* as the essential character or nature of something, and as an inherent characteristic or attribute. Thus, a product has certain qualities or characteristics, and a product’s overall performance, or its effectiveness, is a function of these qualities.

Juran and Gryna (1980) looked at multiple elements of fitness for use and evaluated various quality characteristics (or “qualities”), such as technological characteristics (strength, weight, and voltage), psychological characteristics (sensory characteristics, aesthetic appeal, and preference), and time-oriented characteristics (reliability and

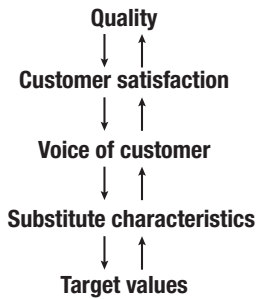


Figure 1.1 The relationship of quality, customer satisfaction, and target values.

maintainability). Deming (1982) also investigated several facets of quality, focusing on quality from the viewpoint of the customer.

The American Society for Quality (ASQC Glossary and Tables for Statistical Quality Control 1983) defines *quality* as the “totality of features and characteristics of a product or service that bear on its ability to satisfy a user’s given needs.” Shewhart (1931) stated it this way:

The first step of the engineer in trying to satisfy these wants is, therefore, that of translating as nearly as possible these wants into the physical characteristics of the thing manufactured to satisfy these wants. In taking this step, intuition and judgment play an important role, as well as a broad knowledge of the human element involved in the wants of individuals. The second step of the engineer is to set up ways and means of obtaining a product which will differ from the arbitrary set standards for these quality characteristics by no more than may be left to chance.

One of the objectives of quality function deployment (QFD) is to achieve the first step proposed by Shewhart. QFD is a means of translating the “voice of the customer” into substitute quality characteristics, design configurations, design parameters, and technological characteristics that can be deployed (horizontally) through the whole organization: marketing, product planning, design, engineering, purchasing, manufacturing, assembly, sales, and service.

Products have several characteristics, and the “ideal” state or value of these characteristics is called the target value (Figure 1.1). QFD (Figure 1.2) is a methodology to develop target values for substitute quality characteristics that satisfy the requirements of the customer. Mizuno and Akao (Shewhart 1931) have developed the necessary philosophy, system, and methodology to achieve this step.

1.2 What Is Reliability?

Although there is a consensus that reliability is an important attribute of a product, there is no universally accepted definition of *reliability*. Dictionaries define *reliability* (noun) as the state of being reliable, and *reliable* (adjective) as something that can be relied upon or is dependable.

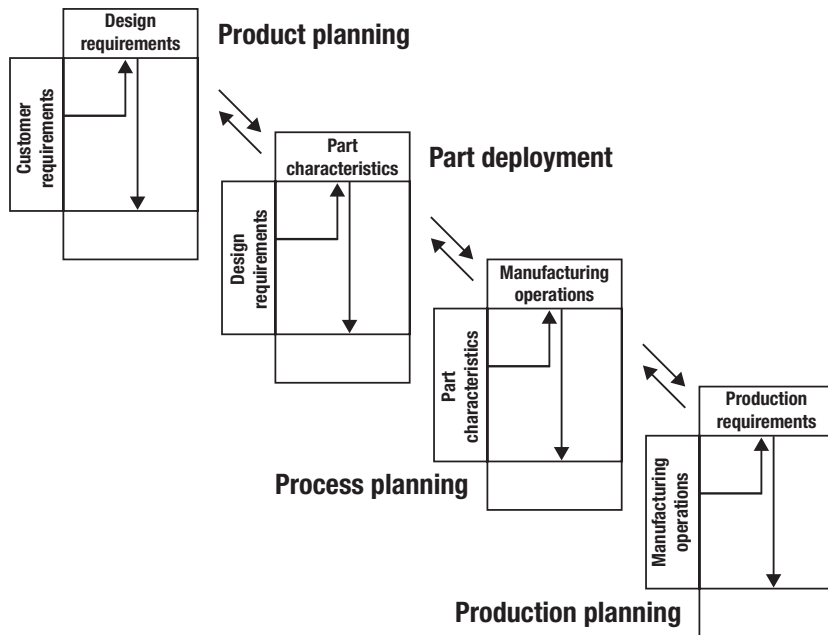


Figure 1.2 Illustration of the steps in QFD.

When we talk about reliability, we are talking about the future performance or behavior of the product. Will the product be dependable in the future? Thus, reliability has been considered a time-oriented quality (Kapur 1986; O’Conner 2000). Some other definitions for reliability that have been used in the past include:

- Reduction of things gone wrong (Johnson and Nilsson 2003).
- An attribute of a product that describes whether the product does what the user wants it to do, when the user wants it to do so (Condra 2001).
- The capability of a product to meet customer expectations of product performance over time (Stracener 1997).
- The probability that a device, product, or system will not fail for a given period of time under specified operating conditions (Shishko 1995).

As evident from the listing, various interpretations of the term *reliability* exist and usually depend on the context of the discussion. However, in any profession, we need an operational definition for reliability, because for improvement and management purposes, reliability must be precisely defined, measured, evaluated, computed, tested, verified, controlled, and sustained in the field.

Since there is always uncertainty about the future performance of a product, the future performance of a product is a random variable, and the mathematical theory of probability can be used to qualify the uncertainty about the future performance of a product. Probability can be estimated using statistics, and thus reliability needs both probability and statistics. Phrases such as “perform satisfactorily” and “function normally” suggest that a product must function within certain performance limits in order to be reliable. Phrases such as “under specified operating conditions” and “when

used according to specified conditions” imply that reliability is dependent upon the environmental and application conditions in which a product is used. Finally, the terms “given period of time” and “expected lifetime” suggest that a product must properly function for a certain period of time.

In this book, reliability is defined as follows:

Reliability is the ability of a product or system to perform as intended (i.e., without failure and within specified performance limits) for a specified time, in its life cycle conditions.

This definition encompasses the key concepts necessary for designing, assessing, and managing product reliability. This definition will now be analyzed and discussed further.

1.2.1 The Ability to Perform as Intended

When a product is purchased, there is an expectation that it will perform as intended. The intention is usually stated by the manufacturer of the product in the form of product specifications, datasheets, and operations documents. For example, the product specifications for a cellular phone inform the user that the cell phone will be able to place a call so long as the user follows the instructions and uses the product within the stated specifications.¹ If, for some reason, the cell phone cannot place a call when turned on, it is regarded as not having the ability to perform as intended, or as having “failed” to perform as intended.

In some cases, a product might “work,” but do so poorly enough to be considered unreliable. For example, the cell phone may be able to place a call, but if the cell phone speaker distorts the conversation and inhibits understandable communication, then the phone will be considered unreliable. Or consider the signal problems reported for Apple’s iPhone 4 in 2010. The metal bands on the sides of the iPhone 4 also acted as antennas for the device. Some users reported diminished signal quality when gripping the phone in their hands and covering the black strip on the lower left side of the phone. The controversy caused Apple to issue free protective cases for the iPhone 4 for a limited time to quell consumer complaints (Daniel Ionescu 2010).

1.2.2 For a Specified Time

When a product is purchased, it is expected that it will operate for a certain period of time.² Generally, a manufacturer offers a warranty, which states the amount of time during which the product should not fail, and if it does fail, the customer is guaranteed a replacement. For a cell phone, the warranty period might be 6 months, but customer expectations might be 2 years or more. A manufacturer that only designs

¹The specifications for a product may also state conditions that must be satisfied to guarantee that the product will operate in a reliable manner. These conditions can include mechanical, electrical, and chemical limits. For example, a product might have voltage or temperature limits that should not be exceeded to guarantee the reliable operation of the product. The specifications usually depend on the design, materials, and processes used to make the product and the expected conditions of use.

²Time may be expressed as the total age of a product, the number of hours of operation, the number of miles, or some other metric of use or age.

for the warranty can have many unhappy customers if the expectations are not met. For example, most customers expect their car to be able to operate at least 10 years with proper maintenance.

1.2.3 Life-Cycle Conditions

The reliability of a product depends on the conditions (environmental and usage loads) that are imposed on the product. These conditions arise throughout the life cycle of the product, including in manufacture, transport, storage, and operational use.³ If the conditions are severe enough, they can cause an immediate failure. For example, if we drop or sit on a cell phone, we may break the display. In some cases, the conditions may only cause a weakening of the product, such as a loosening of a screw, the initiation of a crack, or an increase in electrical resistance. However, with subsequent conditions (loads), this may result in the product not functioning as intended. For example, the product falls apart due to a missing screw, causing a connection to separate; cracking results in the separation of joined parts; and a change in electrical resistance causes a switch to operate intermittently or a button to fail to send a signal.

1.2.4 Reliability as a Relative Measure

Reliability is a relative measure of the performance of a product. In particular, it is relative to the following:

- Definition of function from the viewpoint of the customer
- Definition of unsatisfactory performance or failure from the viewpoint of the customer
- Definition of intended or specified life
- Customer's operating and environmental conditions during the product life cycle.

Furthermore, the reliability of a product will be dependent, as a probability, on the following:

- Intended definition of function (which may be different for different applications)
- Usage and environmental conditions
- Definition of satisfactory performance
- Time.

Many organizations have a document called "Failure Definitions and Scoring Criteria." Such a document delineates how each incident or call for attention in a product will be handled with regard to reliability, maintainability, or safety.

³A good analogy to products is people. A person's physical reliability will depend on the conditions (loads and stresses) "imposed" on him/her, starting from birth. These conditions can include, but are not limited to, diseases, lifestyle, and accidents. Such conditions can cause the body to wear out or fail in a catastrophic manner.

1.3 Quality, Customer Satisfaction, and System Effectiveness

For consumer products, quality has been traditionally associated with customer satisfaction or happiness. This interpretation of quality focuses on the total value or the utility that the customer derives from the product. This concept has also been used by the U.S. Department of Defense, focusing on system effectiveness as the overall ability of a product to accomplish its mission under specified operating conditions.

There are various characteristics (e.g., engineering, technological, psychological, cost, and delivery) that impact customer satisfaction. Thus, quality (Q) may be modeled as:

$$Q = \text{Customer Satisfaction} = \phi(x_1, x_2, \dots, x_i, \dots, x_n, \dots), \tag{1.1}$$

where x_i is the i th characteristic ($i = 1, 2, \dots, n, \dots$).

These qualities will impact the overall value perceived by the customer, as shown in Figure 1.3. In the beginning, we have ideal or target values of the characteristics $x_1, x_2, \dots, x_i, \dots, x_n, \dots$. These values result in some measure of customer satisfaction. With time, changes in these qualities will impact customer satisfaction. Reliability as a “time-oriented” quality impacts customer satisfaction.

The undesirable and uncontrollable factors that cause a functional characteristic to deviate from its target value are called *noise factors*. Some examples of noise factors are:

- Outer noise: environmental conditions, such as temperature, humidity, dust, and different customer usage conditions.
- Inner noise: changes in the inherent properties of the product, such as deterioration, wear, fatigue, and corrosion—all of which may be a result of the outer noise condition.
- Product noise: piece-to-piece variation due to manufacturing variation and imperfections.

A reliable product must be robust over time, as demonstrated in Figure 1.4.

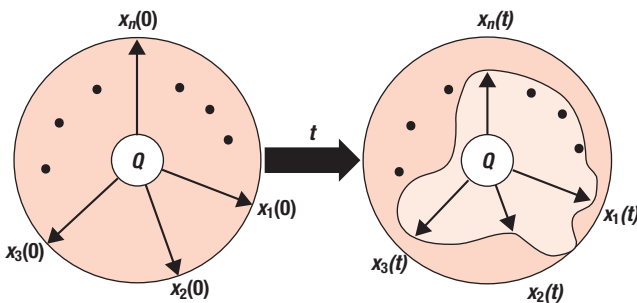


Figure 1.3 Time-oriented qualities and customer satisfaction.

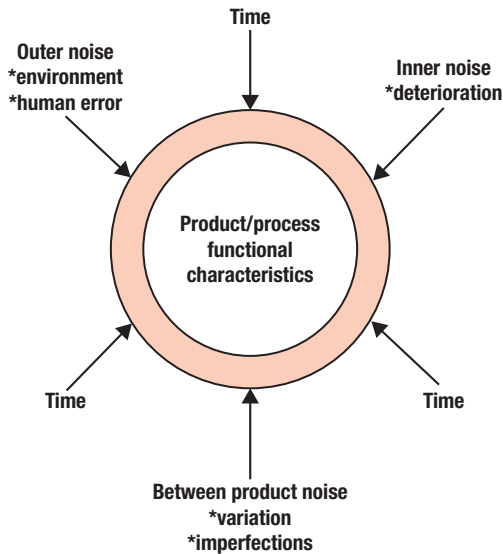


Figure 1.4 A reliable product/process is robust over time.

1.4 Performance, Quality, and Reliability

Performance is usually associated with the functionality of a product—what the product can do and how well it can do it. For example, the functionality of a camera involves taking pictures. How well it can take pictures and the quality of the pictures involves performance parameters such as pixel density, color clarity, contrast, and shutter speed.

Performance is related to the question, “How well does a product work?” For example, for a race car, speed and handling are key performance requirements. The car will not win a race if its speed is not fast enough. Of course, the car must finish the race, and needs sufficiently high reliability to finish the race. After the race, the car can be maintained and even replaced, but winning is everything.⁴

For commercial aircraft, the safe transportation of humans is the primary concern. To achieve the necessary safety, the airplane must be reliable, even if its speed is not the fastest. In fact, other than cost, reliability is the driving force for most commercial aircraft design and maintenance decisions, and is generally more important than performance parameters, which may be sacrificed to achieve the required reliability.

Improving the performance of products usually requires adding technology and complexity. This can make the required reliability more difficult to achieve.

Quality is associated with the workmanship of the product. For example, the quality metrics of a camera might include defects in its appearance or operation, and the camera’s ability to meet the specified performance parameters when the customer first receives the product. Quality defects can result in premature failures of the product.

⁴If the racing car were only used in normal commuter conditions, its miles to failure (reliability) might be higher since the subsystems (e.g., motor and tires) would be less “stressed.”

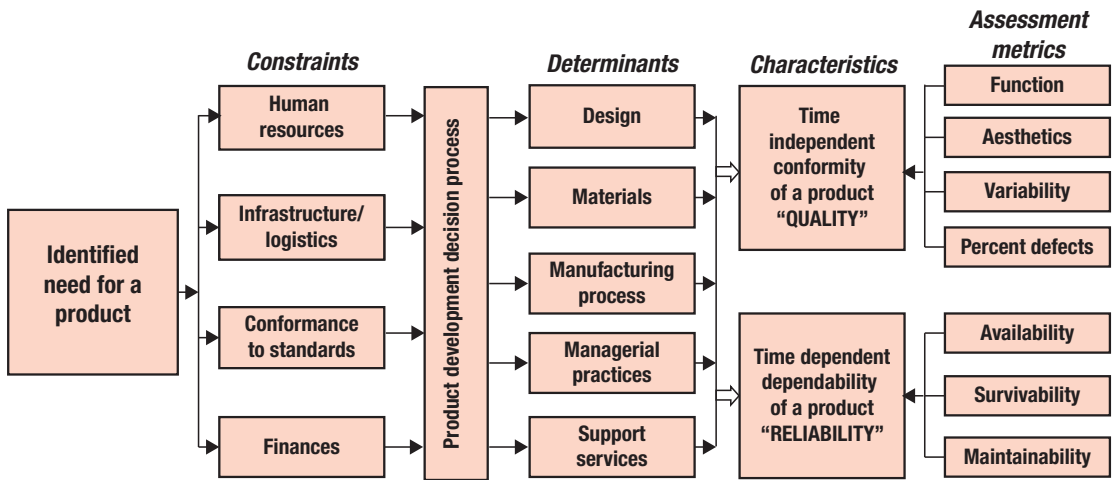


Figure 1.5 Quality and reliability inputs and outputs during product development.

Reliability is associated with the ability of a product to perform as intended (i.e., without failure and within specified performance limits) for a specified time in its life cycle. In the case of the camera, the customer expects the camera to operate properly for some specified period of time beyond its purchase, which usually depends on the purpose and cost of the camera. A low-cost, throwaway camera may be used just to take one set of pictures. A professional camera may be expected to last (be reliable) for decades, if properly maintained.

“To measure quality, we make a judgment about a product today. To measure reliability, we make judgments about what the product will be like in the future” (Condra 2001). Quality in this way of thinking is associated primarily with manufacturing, and reliability is associated mostly with design and product operation. Figure 1.5 shows the role of quality and reliability in product development.

Product quality can impact product reliability. For example, if the material strength of a product is decreased due to defects, the product reliability may also be decreased, because lower than expected life-cycle conditions could cause failures. On the other hand, a high-quality product may not be reliable, even though it conforms to workmanship specifications. For example, a product may be unable to withstand environmental or operational conditions over time due to the poor selection of materials, even though the materials meet workmanship specifications. It is also possible that the workmanship specifications were not properly selected for the usage requirements.

1.5 Reliability and the System Life Cycle

Reliability activities should span the entire life cycle of the system. Figure 1.6 shows the major points of reliability practices and activities for the life cycle of a typical system. The activities presented in Figure 1.6 are briefly explained in the following sections.