Reliability Performance and Specifications in New Product Development

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Preface

The establishment of a framework for Reliability Performance and Specifications in New Product Development is the objective of a joint research project between University of Queensland and the Norwegian University of Science and Technology. The project is divided into three parts:

- **Part I:** Establish a conceptual framework for determining reliability specifications and assessing reliability performance in new product development.
- **Part II:** Discuss briefly the tools and techniques needed in the above framework.
- **Part III:** Conduct case studies.

This report documents the results from Parts I and II of the research project. The conceptual framework presented in Part I provides the basis for Part II of the research project which deals with the tools and techniques needed.

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Part I:

A Conceptual Framework

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1 Introduction

Technological advances and increasing customer expectations have resulted in new products appearing on the market at an ever increasing pace. The products are becoming more complex and the product life cycles are getting shorter. Better, faster, and cheaper are key words for companies to survive in a dynamic environment with the markets getting global and the competition more intense. To survive, manufacturers need to bring new products to the market on a continuous basis with better product performance and at a cheaper price. This requires the process of designing and developing new products to be managed efficiently.

In this competitive environment product reliability, as a quality parameter, is a key issue. The increasing product complexity and the use of new materials increase the risk of product failure, and the possible damage that may result. From a customer viewpoint, product failures are undesirable, but for manufacturers it is also increasingly so; manufacturers are now, to an ever increasing degree, required to provide compensation for any damage resulting from failures of a product. However, there is no way that failures may be totally eliminated from a product. Therefore, when developing new products, the challenge is to effectively reduce the chance of product failures, such that an acceptable reliability performance may be achieved within given time and cost constraints.

Reliability degrades with age and/or usage and can be controlled through effective maintenance. Reliability specification and product reliability performance are both important issues. Well-defined reliability specifications are necessary to ensure desired reliability performance throughout the life of the product. There is a need to evaluate reliability performance from a product life cycle perspective, and to relate the reliability performance to research and development (R&D), design, manufacturing, marketing, and post-sale issues. A framework for handling reliability specifications and performance is necessary to ensure that reliability performance is treated in a holistic manner throughout new product development. One needs to use a variety of models and tools to assist in determining the reliability specifications and to predict reliability performance during the development process.

The establishment of such a framework is the objective of a joint research project between University of Queensland and the Norwegian University of Science and Technology. The project is divided into three parts:

- **Part I:** Establish a conceptual framework for determining reliability specifications and assessing reliability performance in new product development.
- **Part II:** Discuss briefly the tools and techniques needed.
- **Part III:** Conduct case studies.

The outline of Part I is as follows. Section 2 is concerned with the definition and categorisation of products, description of product hierarchies and product life cycles. Section 3 discusses product performance in a general sense, and Section 4 provides a description of new product development processes. Section 5 contains a discussion on product specifications, followed by a description of the factors influencing product performance in different product life phases, presented in Section 6. In Section 7, product reliability issues are discussed in more detail. These sections form the basis for the conceptual framework for reliability specifications and performance finally presented in Section 8. This conceptual framework is the basis for Part II of the research project which deals with the tools and techniques needed.

2 Products

Products are part of our living – we use them, wear them and even eat them. A narrow definition of products is that they are physical and tangible. This is in contrast to services that are intangible. The distinction between products (as defined above) and services is getting blurred and a more commonly accepted definition is that a product generally involves combinations of the tangible and the intangible as indicated below.

> *"A product can be tangible (e.g. assemblies or processed materials) or intangible (e.g., knowledge or concepts), or a combination thereof. A product can be either intended (e.g., offering to customers) or unintended (e.g., pollutant or unwanted effects*)" (ISO 8402, 1994).

In this report, we will focus on physical products, and exclude software.

2.1 Product Classification

Products may be categorised into four groups:

1. **Consumer nondurables**: These are bought by individuals for consumption. They include food items, cosmetics, and clothes. They differ from consumer durables in the sense that the life of an item is relatively short.
2. **Consumer durables:** Society at large, as well as commercial users and government agencies all consume these types of products (e.g., computers, television sets, appliances, automobiles). They are characterized by a large number of consumers for the product. The complexity of the product can vary considerably.
3. **Industrial and commercial products:** Industrial and commercial products (e.g., large-scale computers, cutting tools, pumps, X-ray machines, commercial aircraft, and hydraulic presses) are characterised by a relatively small number of consumers and manufacturers. The technical complexity of such products and the mode of usage can vary considerably. The products can be either complete units such as cars, trucks, pumps and so forth, or product components needed by a manufacturer, such as batteries, drill bits, electronic modules, and turbines.

4. **Specialised defence-related or industrial products:** Specialised products (e.g., military aircraft, ships, and rockets) are usually complex and expensive and involve "state-of-the-art" technology with considerable R&D effort required of the manufacturers. Customers are typically one or few governments or industrial businesses, and there is a relatively small number of manufacturers. These products are usually designed and built to consumer specifications. Still more complex are large systems (for example, power stations, computer networks, communication networks, and chemical plants) that are collections of several inter-linked products. These are specialised industrial products which are also custom built.

This is the classification we use in this report, and we focus on products in the categories 2, 3 and 4. Examples of other classifications are given below:

1. **Standard products:** These are manufactured in anticipation of a subsequent demand. As such, these products are manufactured based on market surveys. These include all consumer nondurables and durables and, most commercial and industrial products.
2. **Custom-built products:** These are manufactured in response to a specific request from a customer. These include specialised defence and industrial products.

The classifications above are related to the type of product. Note that some products will be in a grey zone between these categories. It is also worthwhile noting that products can be classified according to their novelty in terms of technological innovation. Hamid et al (1993) suggest the following classification based on the nature of the design process involved:

1. **Creative designs:** Creative design is an abstract decomposition of the design problem into a set of levels that represent choices for the problem. An *a priori* plan for the problem does not exist.
2. **Innovative designs:** The decomposition of the problem is known, but the alternatives for each of its subparts do not exist, and must be synthesised. Design might be an original or unique combination of existing

components. A certain amount of creativity comes into play in the innovative design process.

3. **Redesigns:** An existing design is modified to meet the required changes in the original functional requirements.
4. **Routine designs:** An *a priori* plan of the solution exists. The subparts and alternatives are known in advance, perhaps as the result of either a creative or innovative design process. Routine design involves finding the appropriate alternatives for each subpart that satisfies the given constraints.

Hubka and Eder (1988) suggest a broader classification for products. This classification refers to complexity, usage, appearance, and methods for designing the product. The products range from artistic work to industrial plant as indicated below:

1. Artistic works
2. Consumer durables
3. Bulk or continuous engineering products
4. Industry products
5. Industrial products
6. Industrial equipment products
7. Special purpose equipment
8. Industrial plant

Product appearance is more important for products at the top of the list, while methods for designing and use of scientific knowledge are important for products at the bottom of the list. For artistic works, the artist is usually both the designer and manufacturer. Industrial plant is the extreme case of products incorporating other products, and consists of collections of industrial equipment products and devices to provide control and/or connections among them.

Yet another classification is new versus used (or second-hand) products.

In this report we will focus our attention on consumer durables, industrial and commercial products, and specialised defence-related or industrial products, using the following products as illustrative examples:

Example 1 – Computer [Consumer durable / Industrial]

Computers are used extensively, and an increasing number of households have them. Industrial and commercial businesses also use computers for different purposes. As a result, most manufacturers produce several different types of computer which differ in performance and price. There are several competing brands on the market, and the competition among manufacturers is fierce. The trends are (i) the prices are coming down, (ii) the performance levels are increasing and, (iii) new computers are appearing at an ever increasing rate due to technology advances. As a result, manufacturers face continuous pressure to bring new computers with better performance and/or lower price and the lifespan of a computer is typically about two years. Sale price, reliability, noise level, memory size, storage capacity and processor speed, and to an increasing degree, appearance are some of the variables that manufacturers compete with each other to retain existing customers and to attract new customers. ■

Example 2 – Pump [Industrial product]

Pumps are part of many consumer durables (e.g., refrigerators and air-conditioners), and are extensively used in processing industries, water and sewerage networks and in aquariums to keep fish. We confine our attention to pumps used in the industrial context. A range of pumps have been developed for different usage needs and there are several pump manufacturers. The lifespan of pumps can vary significantly and depends on the operating environment and the materials used in the pump. The economic impact of a product breakdown is significant and customers are therefore concerned about product reliability and manufacturer's post-sale support (e.g., time to deliver spares, price of spares, and service personnel availability). Manufacturers compete on pump efficiency, durability and sales price. Appearance is not an issue of any significance. ■

Example 3 –Military aircraft [Specialised Product]

An aircraft may be developed to meet the need of an air force, either in response to potential enemies' improved aircrafts or to technological advances (e.g., new composite materials, laser technology, and computers), which allows for more efficient air warfare. Such aircrafts typically incorporate state-of-the-art technologies, and involve many years of research and development. Development cost and product price are high with the price of a new aircraft typically around USD 20 - 30 million and flying 10,000 hours over a life span of 30 years (for an F-16D). ■

Example 4 – Subsea Separator [Specialised Product]

A subsea separator is an oil/water separator that is placed on the sea bottom close to a subsea oil wellhead. A subsea separator is a rather novel product that will have a lot of benefits if it can be made sufficiently reliable. By separating the water from the oil at the sea bottom, the main offshore platforms can be made smaller and cheaper, the oil production will increase since the water does not have to be lifted up to the platform, and economic and environmental benefits can be obtained since the produced water can be re-injected into a reservoir from the sea bottom. So far, only few subsea separators have been installed, and the information regarding field performance is still very scarce. To be economically feasible, the subsea separator system has to have very few failures and high availability. A semi-submersible rig will be required to correct most of the separator failures. Renting such a rig costs in the order of US$200.000 per day and the repair of a single failure may take several weeks. In addition comes the cost of lost oil production. It is therefore obvious that the reliability is a main aspect in the development of the new product. The manufacturers of the separators have to integrate reliability activities into all phases of the design process, and also to document (prove) that the reliability will be sufficiently high during the entire intended life length (10-15 years) of the separator. In Norway, part of this documentation is done in accordance with the DNV-RP-A-203 guideline. ■

Note that some products are more difficult to categorize. For example, a car may, to a large extent, be tailored to a particular customer's demands. This is also valid for, say, kitchens. This is the effect of so-called modular design that aims to enable manufacturers to provide customers with tailor-made products. Thus, many will conceive these products as specialized products rather than a consumer durable. However, we choose to group such products into the latter category.

2.2 Product Decomposition

A product can be viewed as a system comprising several elements and can be decomposed into a hierarchy of levels, with the system at the top level and parts at the lowest level. There are many ways of describing this hierarchy and the following seven-level description is from Blischke and Murthy (2000):

Level	Characterisation
0	System
1	Sub-System
2	Major Assembly
3	Assembly
4	Sub-Assembly
5	Component
6	Part

Below, a few examples of product decomposition are illustrated:

Example 1[Continued]

A computer typically consists of the following subsystems: the case, motherboard, CPU, fan (or CPU cooler), disk drives, power supply and peripherals (e.g., screen, keyboard, and mouse). The disk drive, in turn, would consist of motor, reading and writing facilities, and control system. ■

Example 2[Continued]

A pump usually consists of a mounting, motor, transmission, pump unit, and a control system. The pump unit would again typically consist of an impeller, an impeller house and a number of seals. ■

Example 3 [Continued]

An aircraft is a complex system consisting of a several subsystems, such as the body, propulsion system, weapon system, navigation system, communication system, and control system. The propulsion system would again consist of engines, fuel tanks, fuel supply systems and propulsion control systems. Engines can further be divided into major assemblies and so on. ■

The complexity of products has been increasing with technological advances. The following example of a farm tractor is from Kececioglu (1991). The numbers of components are as follows:

Model Year	1935	1960	1970	1980	1990
Number of components	1200	1250	2400	2600	2900

For more complex products, the number of parts may be orders of magnitude larger. For example, a Boeing 747 air plane has 4.5 million parts (Appel, 1970).

The number of levels needed to describe a product from system level down to part level depends on product complexity. Many more levels are needed to break down an aircraft than a pump. Tag numbers are frequently used for this purpose.

2.3 Product Life Cycle

There are a number of approaches to the concept of a product life cycle. The concept is quite different in meaning, intent and importance for buyer and manufacturer. For each there are different life cycles that may be of interest. Note that the product life cycle can be viewed in a larger overall context, with important strategic implications (Betz, 1993). In this structure, the product life cycle is seen as embedded in the product line life cycle, which, in turn, is embedded in the technology life cycle. Note that the discussion below is applicable for consumer durables and partly industrial products, as specialized products display a different life cycle characteristic.

2.3.1 Manufacturer's Point of View

There are two different approaches based on marketing perspective and on production perspective. From the marketing perspective, the product life cycle characterises sales over time from the instant the product is launched on the market to the time when it is withdrawn from the market (Rink and Swan, 1979). The life cycle involves the following four phases:

1. Introduction phase (with low sales),
2. Growth phase (with rapid increase in sales),
3. Maturity phase (with near constant sales), and
4. Decline phase (with decreasing sales)

From the production perspective, the product life cycle is the time from the initial conception of the product to the final withdrawal of the product from the marketplace. It can be broken into two stages – pre-launch and post-launch. As the name implies the pre-launch stage deals with activities undertaken by the manufacturer prior to the release of the product in the marketplace. It consists of the following phases:

1. Front-end, involving initial product idea, the identification of target characteristics and pricing, as well as a feasibility study with go/no-go decision.
2. Design, involving the development of non-physical product solutions.
3. Development and production, including physical embodiment of solutions, and encompassing research and prototype development/testing, as well as production.
4. Pre-sale assurance.

These phases are discussed in more detail in Section 4. The post-launch stage consists of the following two phases:

5. Marketing and sales.
6. Post-sale servicing.

The marketing phase can be divided into several sub-phases as indicated earlier.

2.3.2 Buyers' Point of View

From the buyer's viewpoint, the product life cycle is the time from the purchase of an item to its discarding when it reaches the end of its useful life, it being replaced due to technological obsolescence, or the product is no longer of any use. The life cycle involves the following three phases:

1. Acquisition
2. Operation and maintenance
3. Discard, and in many cases replacement by new one.

3 Product Properties and Performance

3.1 Definitions

We first define some terms so as to facilitate the discussions later in the section.

3.1.1 Product Properties

Hubka and Eder (1988) provide an extensive discussion on product properties, and define several different property categories, as indicated below.

- **Design properties:** The means by which a designer achieves all other properties. Examples are function, form, tolerance, surface, materials and dimensions. The design properties are under the direct control of the designer, and are used to create the desired internal and external product properties.
- **Internal properties:** These may differ from one engineering field to another. In mechanical engineering, it is done in terms of variables such as strength, stiffness, hardness, elasticity, corrosion resistance etc. They are a result of the designer's choice of design properties.
- **External properties:** These are product properties of great significance and interest to the end users of the product. They result from the design properties and the internal properties. Examples of external properties are ergonomic, aesthetic, economy of operation, reliability, maintainability and safety.

According to Hubka and Eder (1988), every technical product has several properties which can be grouped into three groups as shown in Figure 3-1. Products differ in terms of the specific properties they embody.

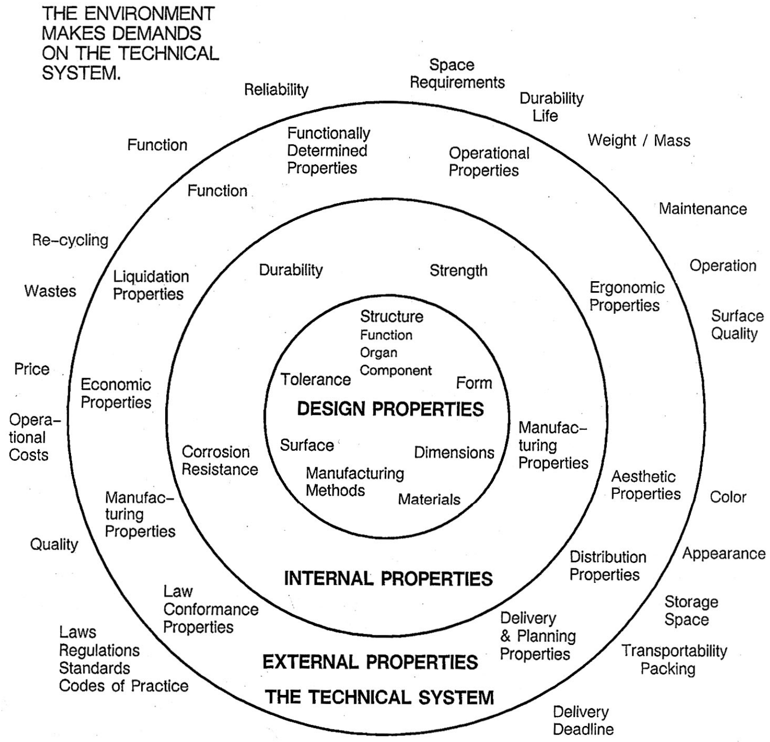


Figure 3-1: Relationship between Classes of Properties (Hubka and Eder (1988)).

One of the greatest challenges that designers face, is to perceive the demand for products (or technical systems) from potential customers, and then choose design properties that transforms to acceptable external properties that meet the customers' demand. The link between them is often difficult to establish. For example, which design properties result in the desired reliability, and what must be their numerical value?

Terms such as product features, characteristics and/or attributes are often used instead of product properties. Tarasewich and Nair (2000), however, provide a clear distinction between characteristics and attributes:

> *"A distinction can be made between product characteristics and attributes. Product characteristics physically define the product and influence the formation of product attributes; product attributes define consumer perceptions and are more abstract than characteristics."*

According to this definition, design and internal properties correspond to product characteristics, whereas the external properties correspond to product attributes.

Example 2 [Continued]

The design properties of the pump would typically be the material choice in the pump housing and the impeller, and this will in turn determine the internal properties, such as corrosion resistance. This would in turn influence the external properties, such as durability. ■

3.1.2 Product Performance

The term product performance is closely linked to product properties, and is important when dealing with specifications. According to the Oxford English Dictionary performance is:

> *"The accomplishment, execution, carrying out, working out of anything ordered or undertaken; the doing of any action or work; working, action (personal or mechanical); spec. the capabilities of a machine or device, now esp. those of a motor vehicle or aircraft measured under test and expressed in a specification. Also used attrib. to designate a motor vehicle with very good performance."*

Many different definitions of performance can be found in the technical literature as illustrated by the sample given below.

Ullman (1997) defines performance as follows:

> *"Performance is the measure of function and behaviour-how well the device does what it is designed to do."*

Ulrich and Eppinger (1995) define product performance as:

> *"How well a product implements its intended functions. Typical product performance characteristics are speed, efficiency, life, accuracy, and noise."*

Finally, according to Zeng and Gu (1999):

> "*Product performance is described as the response of a product to external actions in its working environment. The performance of a product is realised through the performance of its constituent components."*

Many of the above definitions imply that product performance is a measure of the functional aspects of the product. When talking about product performance one must also bring in properties like form, durability, and price. We define product performance as *a vector of variables*, where each variable is *a measurable property of the product or its elements*. The performance variables are concerned with design, internal and/or external properties. The manufacturer is concerned with all three, but the customer is mainly concerned with the external product properties. The performance variables may be:

- Functional properties (e.g., power, throughput, and fuel consumption)
- Form (e.g., dimensions, shape, and weight).
- Durability (defined in terms of failure frequency, mean time to failure (MTTF), survival probability etc).
- Price and market

As indicated in Section 2.2 a product can be decomposed into several levels starting from sub-system level down to component level. One can define performance at each level and Zeng and Gu (1999) state that the performance of a product is realised through the performance of its constituent components.

The performance of a product depends on several factors. These include usage mode, usage intensity, usage environment, skills of the operator involved, and so on.

Example 1 [Continued]

For a computer, the performance variables can include one or more of the following: noise level, CPU frequency, internal memory size, and speed (e.g., 128 MB 133MHz RAM), video card internal memory and speed, hard drive storage capacity and speed, DVD ROM speed, monitor size and resolution. ■

Example 2 [Continued]

For a pump, the performance variables can include the flow rate, head, pump frequency, power consumption, etc. The performance of a pump is dependent on the skills of the operator to prevent potential overloading of the pump, or not conducting proper maintenance. ■

Example 3 [Continued]

For a military aircraft, some of the performance variables are the thrust, speed, range, maximum take-off weight, maximum flying altitude (ceiling) and manoeuvrability. Aircraft performance in battle is heavily dependent on the pilot’s skills to exploit the technology to its maximum limits. ■

3.2 Product Performance: Different Perspectives

Manufacturers and customers focus on different performance variables and there are different notions of performance in the context of product life cycle as will be discussed later in this section. As a result, there are three different perspectives on product performance.

3.2.1 Buyer's Perspective

Buyers can be divided into three categories – individuals (buyers of consumer durables), businesses (buyers of commercial and industrial products/systems as well as consumer durables), government agencies (buyers of the above plus specialised products/systems) and industrial businesses, e.g., within the oil industry (buyers of the same type of products as government agencies).

Individuals buy products either for obtaining certain benefits (a refrigerator for extending the life of perishable products, a washing machine to reduce the effort needed to wash clothes, tools for various purposes, etc.), for pleasure (television, stereo, recreational vehicle) or both (cars, personal computers, sports equipment). The performance of the product has a major impact on consumer satisfaction. The decision to buy a product is influenced by this factor. Product performance is in turn affected by usage pattern and operating environment.

In order to function, businesses require equipment of many types – computers and related items; photocopiers; lathes and power tools in a factory; extractors and pumps in a processing plant; tractors and other machines on a farm; engines and vehicles for transport. The performance of such equipment depends on usage intensity and maintenance. In this context when a product fails to perform satisfactorily (or as expected) the impact can be significant. It not only causes economic loss but can also result in damage to property, persons and environment.

Government agencies, especially the defence organisation, regularly buy specialised products – ships, planes, radar equipment, armaments, and so forth. This is also the typical within the energy sector (e.g., oil/gas industry and power industry). Specialized products often involve new technologies and must meet very demanding performance criteria. Such systems are not only very expensive to purchase, they are also expensive to operate and to maintain. (Government agencies, of course, purchase a great deal of more mundane items as well – tires, uniforms, paper goods, copy machines, and other typical consumer and commercial goods, which do not require special design, development, maintenance and operation.) Usually, bids are invited from a small group of manufacturers (e.g., prequalified through an invitation to tender) when a decision is made to build a new product (e.g., a fleet of aeroplanes). Based on an evaluation of the predicted performance and cost a decision is made to award the contract to the successful bidder.

3.2.2 Manufacturer's Perspective

From a manufacturer's point of view, product performance is influenced by several technical factors – design, materials, manufacturing, distribution, and so forth. These in turn affect the commercial side of the business – sales, warranty costs, profits etc. Poor product performance results in low buyer satisfaction and this in turn affects sales. This implies that a manufacturer needs to find solutions to a range of problems in order to manage the product properties during the design and manufacturing stages from an overall business point of view taking into account customer satisfaction.

Example 1 [Continued]

An typical customer (for home use) may focus on price and performance variables such as, the CPU speed, hard drive storage capacity, as well as reliability which affects the operating cost over the life of the item. The manufacturer’s focus is on making profit. This is influenced by the reliability of the product as this impacts on warranty costs, customer satisfaction, sales etc. The reliability in turn depends on the design and development and, on manufacturing. As may be seen, reliability is an important performance variable for both the buyer and the manufacturer but for different reasons. ■

3.2.3 Product Life Cycle (PLC) Perspective

The performance of a product is dependent on the performance of its constituent components. As a result, one needs to define the performance for the product as a whole and also for its subsystems and components. Therefore we use the term "object" to denote *the product or an element of the product*. For example, an object may be a car, or some subsystem of the car, like the engine, or the transmission.

Three different notions of product performance in the PLC context are used:

- **Desired performance** may be defined as *"a statement about which performance is desired from an object, that is, stating what performance an object should have"*. For manufacturers, the desired performance forms the basis for a new product development that will achieve their business goals. For customers, the desired performance defines the expectations in their purchase decisions. Manufacturers' main challenge lies in realizing a product that is as much in accordance with the customers' desired performance as possible, but that also meets the manufacturer's business goals (e.g., total sales and profits). The degree to which the manufacturer succeeds in fulfilling these expectations determines the customer satisfaction as will be discussed in a later section. The desired performance may be defined as a range, a minimum or maximum value, or an absolute value.

Example 1 [Continued]

Desired performance statements regarding the hard-disk storage capacity for a computer can be stated as one of following:

- *Range*: Between 10 and 20 GB
- *Minimum value*; Should be at least 10 GB
- *Maximum value*: Should not exceed 20 GB
- *Absolute value*: Should be 15 GB ■

- **Predicted performance** may be defined as *"an estimate of an object's performance, attained through analyses, simulation, testing etc."* The manufacturer uses predicted performance throughout design, development and production, to evaluate whether a product will meet the desired performance, and thus forms the basis for his decisions during the different phases of the product life cycle.

- **Actual performance** may be defined as *"observed performance of a prototype of an object during development or of a manufactured object over its operating life"*. The actual performance will differ from the desired performance. The more the actual performance deviates from both the manufacturer's and customers' desired performance, the greater is the probability that the object will not satisfy the manufacturer and/or or customers' expectations.

The three different notions are sequentially linked through the two stages (pre- and post-launch) of the PLC as illustrated in Figure 3-2.

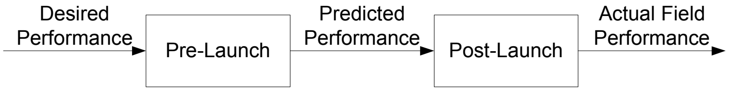


Figure 3-2: Different Performance Notions over Product Life Cycle.

Example 2 [Continued]

In response to a customer request the manufacturer might develop a new pump with the following desired performance characteristics -- maximum flow rate of 120 litres/minute and head 7 metres, and consuming 10% lower power than the existing pump. The flow and head are dependent on the motor and impeller design.

Throughout design and development of the pump, theoretical models are used to predict performance of alternative designs. Suppose that the predicted performance based on the design is as follows: maximum flow rate of 115 litres/minute at 7 metres head with 10% less power consumption. Note that this differs from the desired performance. Suppose that the actual flow rate of the built unit is 110 litres/minute. The difference between the predicted performance and actual performance can be either due to limitations in theoretical models used for prediction or variability in manufacturing. The end result is that the customer's needs are not met. ■

3.3 Product Quality and Customer Satisfaction

3.3.1 Product Quality

The ability of the external properties of a product (see Figure 3-1) to meet customer needs can be viewed as an indicator of *product quality*. Garvin (1988) defines eight dimensions of product quality and they are as follows.

1. Performance
2. Features
3. Reliability
4. Conformance
5. Durability
6. Serviceability
7. Aesthetics
8. Perceived quality

According to Juran and Gryna (1980), the quality properties that describe the fitness for use are the following:

1. Technological characteristics (e.g., strength, weight, efficiency, output)
2. Psychological characteristics (e.g., sensory, beauty, aesthetics)
3. Time-oriented characteristics (e.g., reliability, durability)

This is also in accordance with ISO 8402 (1994), which defines quality as:

> *"The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs"*.

3.3.2 Customer Satisfaction

For a customer, the product's external properties play a critical role in the customer's decision to buy the product and, this in turn determines the degree of customer satisfaction. One of the main reasons for new product failure in the market is due to product performance not meeting the expectations of customers. This fact is well recognised and given due importance by manufacturers of all kinds of products. Customer satisfaction is a topic that has received a lot of attention in the marketing and quality literature.

For consumer durables, customer satisfaction and customers perception of product quality are complicated issues as different individuals may have different views on product's quality for the same product. The upper part of Figure 3-3 shows that customers' perception of a product's quality is based on a combination of the customers' perception basis and the actual product characteristics. A customer's perception of a product's external properties may be the result of cultural background (e.g., different cultures have different views on aesthetics), on physical and cognitive capabilities (cognitive capabilities for example determine how easy it is for a customer to operate a product), an individual's experiences and preferences (a customer having had bad experience with a manufacturers' product will consider another manufacturer), and basic functional needs (which can vary from one person to another).

Example 1 [Continued]

Customers may perceive the noise generated by a computer differently. A customer working in a noisy environment will not mind the additional noise from the computer, whereas others would be extremely sensitive to noise. Equally, the aesthetic appearance of an Apple iMac attracts some customers, and others not, due to differences in their perceptions. ■

In order to produce a product that meets customer expectations, the manufacturer needs to ensure that customer expectations are well understood and properly defined. Often, customer expectations are expressed as vague statements. This is particularly true for consumer durables as illustrated by the following comments on a reliable automobile (Wang, 1990):

- Last for a long time
- Starts every morning
- A well-made car
- No breakdown
- Consistent performance

- Hassle-free during ownership
- Dependable
- Maintenance free

Having identified customer expectations, the challenge lies in transforming these into technical performance variables (using techniques such as quality function deployment [QFD]) and that the product development process ensures that the final product performance meets the desired performance. This is shown schematically in the lower part of Figure 3-3.

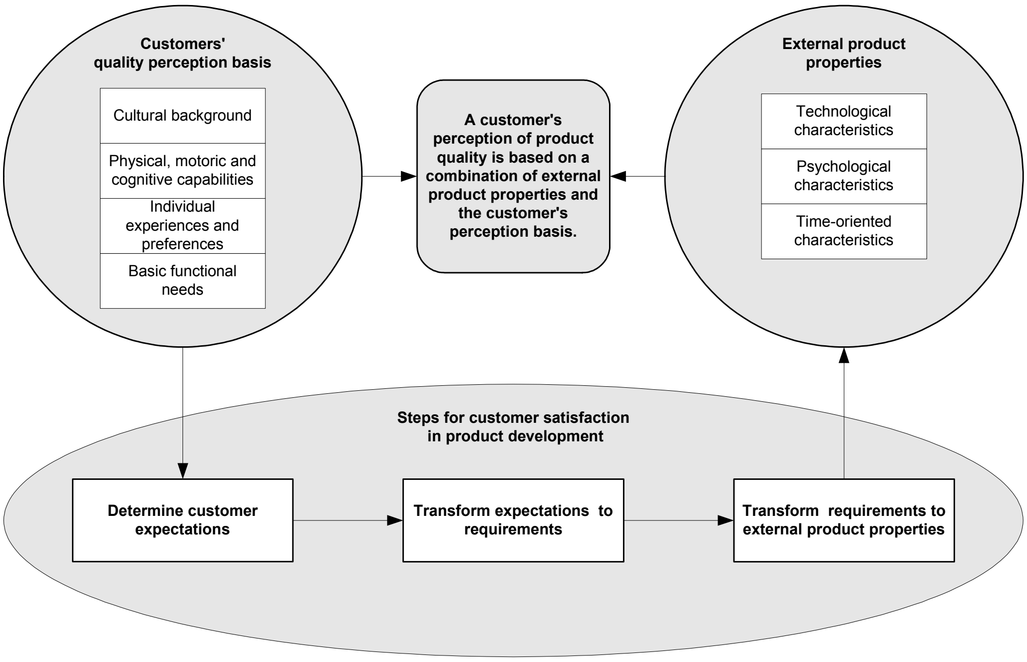


Figure 3-3: Transformation of Customer Expectations to Product Properties.

Once a new product is released into the market, customer feedback allows to assess how well the product meets the needs and expectations of customers. This kind of information is usually obtained from many different sources. These include:

1. Customer surveys
2. Customer complaints
3. Warranty claim reports
4. Magazines (e.g., PC-World)
5. Organizations representing consumer interests

6. Consumer ombudsmann

According to Knowles, et al (1995), the manufacturer needs to answer the following questions in order to produce a product that will satisfy the buyer's expectations:

1. **Does the manufacturer understand the buyer's needs?** This involves defining product requirements in terms of buyer's needs and manufacturer's capabilities to meet those needs. To do this requires understanding the buyer's needs and translating them into product development constraints, goals and requirements.
2. **Can the manufacturer develop the product to meet the buyer's needs?** This involves designing a product to meet the requirements defined in the first question. For example, determining the reliability requirements requires identifying potential problems, their impact on product performance, and approaches to overcoming the problems.
3. **Can the manufacturer assure the buyer that the needs will be met?** This is achieved through the use of TQM practices that ensure that the items produced always meet the buyer's needs. One of these is Quality Assurance. Use of warranties and other post-sale services to assure buyers of appropriate actions when an item fails to perform as expected are important in this context. In addition, setting up procedures to collect feedback from buyers to determine root causes and initiating corrective actions also leads to increased buyer assurance.

It is worth noting that customer satisfaction requires meeting *valid* customer expectations. Advertising and promotion can influence the expectations of customers and this is an important topic in new product management.

Customer satisfaction has received considerable attention. Ishikawa (1985) states

> *"... customer satisfaction. Of course, the product must not be flawed or defective, but this alone is not sufficient. It is necessary to ensure quality of design, making certain that the product is fully functional in the way the consumer expects."*

Wang (1990) states

> *"Customer satisfaction is definitely essential to survival in today's global dynamic competition and everybody knows that the ultimate proof of a product design is the acceptance by the customer. As a result of open market place, only those companies that listen to what the customer wants and provide high-quality and reliable products, which meet customer expectations, over the product useful life period with minimum cost in a timely fashion will eventually survive."*

3.4 Product Cost

3.4.1 Manufacturers' versus Buyers' Perspective

From the manufacturer's perspective, important costs in the design of a new product are *design to cost* (DTC) and *life cycle cost* (LCC). Note that there are some exceptions for manufacturers that sell an image rather than a product (e.g., Morgan cars).

In the DTC methodology, the aim is to produce a product such that the unit manufacturing cost does not exceed some specified value. This cost includes the cost of design and development, testing, and manufacturing. DTC is used to achieve the business strategy of a higher market share through increased sales. It is used for most consumer durables and many industrial and commercial products.

In the LCC methodology, the cost under consideration includes the total cost of acquisition, operation, and maintenance over the life of the item as well as the cost associated with discarding the item at the end of its useful life. LCC is used for expensive defence and industrial products. Buyers of such products often require a cost analysis from the manufacturer as a part of the acquisition process.

From the buyer's perspective, the important costs are the initial acquisition cost, the average operating cost per unit time, and the life cycle cost.

Product performance and cost are closely linked. The value-based notion of quality defined by Garvin (1988) deals with this issue.

3.4.2 Operating Cost versus Product Performance

The operating cost per unit time and the performance of the item change as the item ages. Figure 3-4 is a two-dimensional plot with product performance along one axis and operating cost per unit time along the other. Point *O* corresponds to a new item when put in use. Note that it can be either close to or below the limits (shown by curve Γ_1) possible with the existing technology. As the item ages, the point moves in the southeast direction, implying a degradation in the performance and an increase in the operating cost. When it crosses the minimum acceptable curve then the item needs to be replaced as the degraded performance and increased operating costs make it unacceptable. This implies restarting from point *O* with a new item if there is no product development.

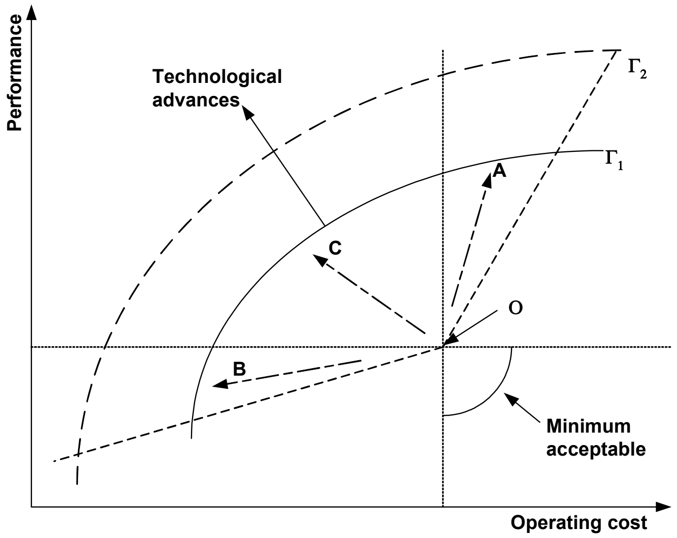


Figure 3-4: Product Performance versus Operating Cost.

With product development based on existing technology, point *O* gets shifted either to point *A* (improved performance but with higher operating cost), point *B* (reduced performance but with a significant reduction in operating cost) or point *C* (with improved performance and lower operating cost). With technological advances, the curve Γ_1 moves northwest to become Γ_2 (implying same performance with lower cost and/or higher performance for the same cost). In this case, points *A* – *C* can move beyond Γ_1 but are always below Γ_2.

New product development objectives determine the shift. The shift from point *O* to point *B* is influenced by the desire for a higher market share (due to lower price) whereas the shift to point *A* is influenced by desire to be market leaders in coming up with innovations that improve product performance.

The shift from point *O* marks the end of the product life cycle for the current product and start of the life cycle (from the marketing perspective) for the new product.

4 New Product Development (NPD) Processes

Companies that are able to bring new products, that satisfy the expectations of the customer fast and efficient to the market, will manage to succeed in the intense and dynamic global environment in which it operates (Wheelwright and Clark, 1992). The US based Product Development & Management Association (PDMA) defines New Product Development as *"a disciplined and defined set of tasks and steps that describe the normal means by which a company repetitively converts embryonic ideas into saleable products or services"* (Belliveau et al, 2002).

4.1 Drivers for NPD

The NPD process is driven by one or more of the following three factors:

1. **Technology:** Advances in technology (either in-house or outside) provide an opportunity for the improvements to an existing product.
2. **Market:** The firm has to improve its existing product in response to (i) to competitors' actions (such as lowering of their price or an improvement to their product) and/or, (ii) feedback from customers through complaints about product performance.
3. **Management:** The motivation for improvement could be (i) internal (e.g., to increase market share, or improve profits by reducing warranty cost) and, (ii) external (e.g., new legislation with regards product performance).

Example 1 [Continued]

The development of computers can be (i) technology driven (for example through advances in CPU technology), (ii) market driven (competitors launching products with better performance all the time), and (iii) management driven (to increase market share). ■

Example 2 [Continued]

The development of a new pump may also be driven by all the factors above. From the technology perspective, a new composite material may for example reduce impeller cavitation. New development may be required due to customer complaining about leakages, and finally, management may like to reduce the high warranty costs associated with the existing pump. ■

Example 3 [Continued]

The development of a new fighter aircraft is mainly technology driven. For example, advances in materials and computer technology allow for improvement in aircraft performance. ■

4.2 NPD Phases

The literature on NPD contains several alternative NPD process models (e.g., Wesner et al, 1995, Wind, 1982, Sounder, 1987, Pugh, 1991, Pahl and Beitz, 1988, Belliveau et al, 2002, and IEC 60300-1, 1991). It is possible to recognize the similarities between the different models. What they have in common is that the NPD process begins with an idea to build a product that meets specific needs (or create new needs for radically innovative products) defined by customers and/or the manufacturer, and ends when the product is launched on the market. This involves six phases as illustrated in Figure 4-1.

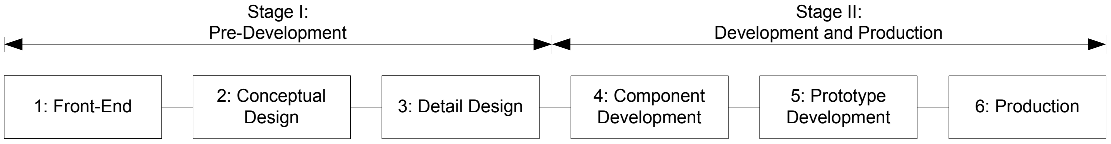


Figure 4-1: Six phases of NPD.

These six phases can be grouped into two stages (Stages I and II). Stage I, the *pre-development stage* consists of the three first phases and is concerned with a *non-physical* (or abstract) conceptualization of the product with increasing levels of detail. Stage II, the *development and production stage,* consists of the next three phases and deals with the *physical* embodiment of the product resulting from the transformation of the conceptual product into a physical entity.

The activities of each phase are briefly described in the remainder of the section along with some definitions and terminology.

4.2.1 Front-End [Phase 1]

The initial activity in the Front-end phase (also known as the pre-design phase) is to identify the needs. For consumer durables and commercial/industrial products, the manufacturer identifies the needs through market studies that also predict the potential demand for the product. In the case of consumer durables, customers often state the needs in a vague manner. This represents a great challenge when conducting market studies and, subsequently, when translating the vague needs into specific product characteristics. For specialised products, the customer usually defines the needs in reasonable detail.

From the need statements, the manufacturer establishes an overall, business level objective for the NPD process. The business level objective may be defined as "*the overall business goal for the NPD process*". The next task is to deduce the desired performance for the product. The desired performance is, in general, more specific and can overlap with the objective.

The next step is to carry out a feasibility study. This involves evaluating whether it is possible to achieve the desired performance within the specified constraints. A constraint may be defined as "*a restriction on the characteristics and attributes of a product*". There could be other constraints such as resources available, time, etc.

The final outcome of the Front-end phase results in a "go/no-go" decision with regards the product, based on the feasibility study. This is a topic of great importance and is an area of active research; see, for example, Khurana and Rosenthal (1998). In the case of a go-decision, the front-end is also concerned with planning the remainder of the NPD project (e.g., time and resource allocations, and scheduling of tasks).

4.2.2 Design [Phases 2 and 3]

If the outcome of the Front-end phase indicates that the project is feasible, an initial product design is undertaken. The design activity evolves with an increasing level of detail, starting at system level and ending at component level. They can be grouped into two different groups. The first is called the conceptual design and the second the detail design. Following Roozenburg and Eekels (1995) we have:

- **Conceptual Design:** [*Phase 2*] Establishing means for performing each major function, and fixing the spatial and structural relationships of the principal product components.

- **Detail Design:** **[***Phase 3***]** Elaborating the concept up to the point where all major decisions about the layout and form of the product have been taken, and tests of the product's functionality, operation and use, appearance, consumer preference etc. can be carried out.

4.2.3 Development [Phases 4 and 5]

Product development deals with the conversion of the design into a physical entity that meets the stated needs, and can be produced in a manner that meets the stated technology and cost limitations. The two phases of development are as follows:

- **Component Development:** [*Phase 4*] Components are physically developed and tested.
- **Prototype Development:** [*Phase 5*] Components from the earlier phase of the NPD process are assembled to develop a prototype of the product.

It is not unusual during these phases to encounter problems where the object (component or higher level assembly) performance does not meet the desired performance and/or violates the given constraints (typical constraints are development time and cost). In this case, one or more aspects of the design need to be modified to overcome the problem. The effort required in these two phases is dependent on the novelty of the technology and/or its application.

The design and development activities are strongly interlinked. Many books on design engineering do not distinguish between design and development, but collectively group them under the heading "design activity" (Pahl and Beitz, 1988).

4.2.4 Production [Phase 6]

The production phase deals with the processes needed to produce items in an economical manner and ensuring that the items conform to the stated design performance specifications.

This starts with pre-production runs. These are required because the manufacturing process must be fine-tuned and quality control procedures established to ensure that the items produced have the same performance as those of the final prototype.

Due to variability in manufacturing not all items produced will meet the design specification. The occurrence of such items is controlled through process control (based on control charts), quality of input material and through regular inspections of the output. These are all part of the quality control paradigm.

Production continues until the product is removed from the market because of obsolescence and/or the launch of a new product.

4.2.5 Testing

Testing is very important during the development and production phases. In the development phases, testing is carried out at component and higher levels to assess the capabilities of the design to meet the stated needs. During the production phase a small number are tested on a regular basis to detect product non-conformance as part of the overall quality management.

In some cases, products are also tested prior to being released to customers as part of product assurance. For complex, expensive products involving new technologies and custom built products, this testing is very important and often explicitly addressed in a negotiated contract between the manufacturer and the buyer. For such products, each item produced is subjected to a well-defined testing procedure to evaluate its performance. For consumer durables and many other standard industrial or commercial products, not every item produced goes through such testing. A more common practice is to test a fraction of the items produced, selected according to some specified sampling rule, to evaluate product performance.

4.3 An Alternative Multilevel Characterisation

Stage I (comprising the first three phases of the NPD process) can be viewed as a multilevel process involving three levels.

- **Level I (Business Level):** Front-End
- **Level II (System Level):** Conceptual Design
- **Level III (Component Level):** Detail Design

Similarly, Stage II (comprising the last three phases of the NPD process) can also be viewed in terms of the three levels indicated above except that the order is reversed so that we have the following:

- **Level III (Component Level):** Component Development
- **Level II (System Level):** Prototype Development
- **Level I (Business Level):** Production

This leads to a matrix characterisation of the NPD process in terms of three levels (business, system and component) and two stages (Stages I and II) as illustrated in Figure 4-2. Note that the phases in Levels II and III may consist of a number of sub-phases depending on the type of product.

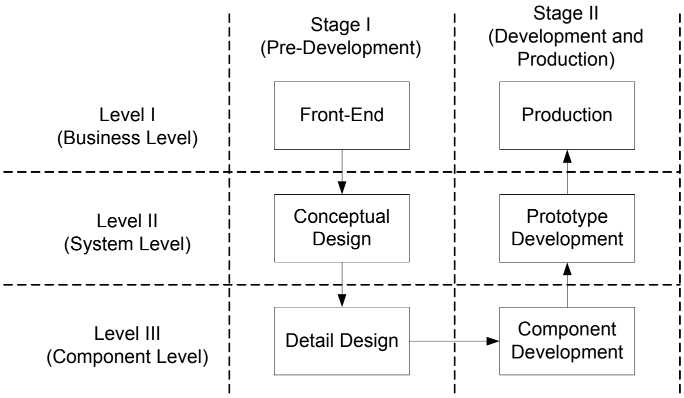


Figure 4-2: Matrix Representation of NPD Process.

4.4 Evaluations and Iterations

At the end of each phase, there is an evaluation of the outcomes to assess whether the desired performance is achieved without violating the stated constraints. In Stage I, the evaluation is based on comparing the predicted performance (based on abstract models) with the desired performance. In Stage II, the performance of the physical object is assessed (through prediction and/or testing) and compared with the desired performance for the corresponding level in Stage I as indicated in Figure 4-3.

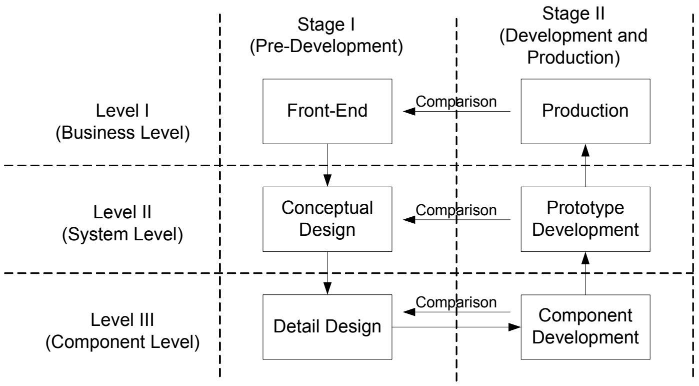


Figure 4-3: Performance Comparisons during the NPD Process.

The above decomposition of specifications in Stage I, followed by comparison/verification in Stage II, is similar to the philosophy outlined in the "V" model proposed by Clausing (1994) and Forsberg et al (2000).

The evaluation of the outcomes at the end of each phase forms the basis for *decision making* in the NPD process (see Section 4.5). Each decision results in one of two outcomes: (1) continue forward if there is no problem, or (2) iterate back to make changes if there is a problem. By a problem, we mean the mismatch between the predicted (or actual) performance and the desired performance.

The iteration patterns are different for Stages I and II and these are discussed in the remainder of this section. In Stage I, if the evaluation reveals a mismatch, or the constraints being violated, during detail design (Component Level), a solution to the problem is first attempted through iterations at the Component Level. If the problem cannot be solved at this level, the problem is examined at the System Level (conceptual design) for possible solution. If the problem cannot be solved at the System Level, it iterates back to the Business Level. These iterations are illustrated in Figure 4-4 along with project termination should the problem be insurmountable.

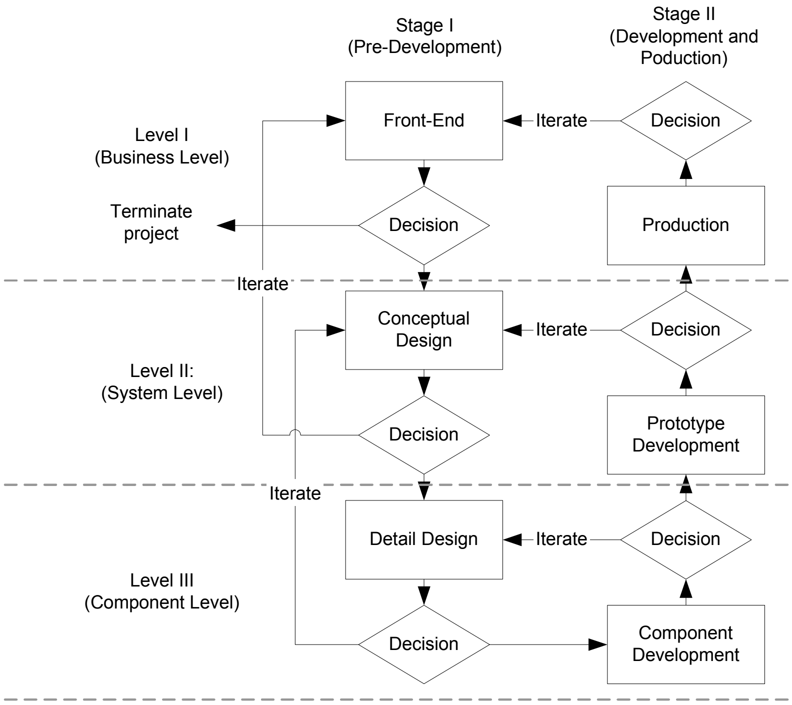


Figure 4-4: Decision Points and Iteration in the NPD Process.

Example 2 [Continued]

Suppose that the desired performance of the pump is as follows: a maximum flow of 120 litre/minute, head 7 meters, and a 10% reduction in power consumption. If, in Phase 3 (Detail Design), the maximum flow at that particular head and power consumption is predicted to not exceed 100 litre/minute, a different concept needs to be explored, i.e., iterating back to Phase 2 (Conceptual Design) is necessary. If no concept can be found meeting this performance, the desired performance must be revised, or the project terminated. This corresponds to iterating back to Phase 1 (Front-end). ■

In Stage II, if a problem is detected, the iteration involves going back to the corresponding phase at the same level in Stage I as indicated in Figure 4-4. A problem detected during Phase 4 (Component Development) results in an iteration back to Phase 3 (Detail Design) as Phase 3 is concerned with component level specifications. If the problem cannot be resolved at this level, it iterates further back to Phase 2 (Conceptual Design). Similarly, if a problem is detected when evaluating the product prototype in Phase 5, the iteration is first to Phase 2 (Conceptual Design).

It is worth noting that iterations from the phases in Stage II are more costly than from the phases in Stage I.

Example 2 [Continued]

If testing the prototype in Phase 5 shows a performance of 100 litre/minute at a head of 7 metres, with the given limitation to power consumption, then iterating back to Phase 2 (the corresponding level in Stage I) is required. If the pump's components are found to perform according to the desired performance in Phase 3, then the problem probably lies with the choice of the concept. ■

In the NPD process, iterations within a phase is normal according to the Design for X-philosophy, i.e., assessing and improving solutions with respect to one or more of the product characteristics (e.g., reliability, manufacturability, and ergonomics) – see, for example, Meerkamm (1990) and Huang (1996).

4.5 Decision-Making

The iteration process illustrated in Figure 4-4, involves decision-making. Decisions have to be made throughout the entire process, either choosing among alternative solutions or deciding whether to continue development, iterate, or terminate the project. It also involves balancing between project schedule, cost and risk.

Decision-making is merely *making a choice among a set of alternatives*. Following Dixon (1966), decision making requires the following three elements:

1. **An objective:** In a decision situation there is some desired goal – a task to be accomplished, a material to be selected etc. Without some desirable end, there is no need to decide anything.
2. **Alternative courses of action:** In a decision situation there is more than one way to accomplish the objective (otherwise there would be no need to decide). The various alternatives may involve different costs and different probabilities of success. The costs and probabilities may or may not be known.
3. **Relevant criteria:** To choose the best among the different alternatives. Different criteria will yield different optimal solutions.

   Managing the NPD process involves multi-criteria decision making. Often there are several factors outside the control of the decision-maker so that decision making needs to take into account the underlying uncertainty. Often there is more than one decision-maker, each with different preferences and attitudes to risk. This leads to multi-criteria group decision making under uncertainty and this topic has been studied extensively by Keeney & Raiffa (1993). However, the bulk of the engineering literature chooses to ignore the uncertainty and the group aspects of decision-making (some claim that these issues are too complex to consider in an NPD process).

Part II of the report deals with the tools and techniques needed for effective decision making.

4.6 Data and Information Flow

Decision making requires building appropriate models to evaluate alternate options. Model building involves (i) model formulation and (ii) parameter estimation. Both of these require relevant data and information.

Often data, information and knowledge are considered to be synonymous (e.g., Webster's and Collins' dictionaries). One needs to differentiate between them. Hicks et al (2002) propose a model describing the relationship between data, information and knowledge in a decision-making context and this is illustrated in Figure 4-5.

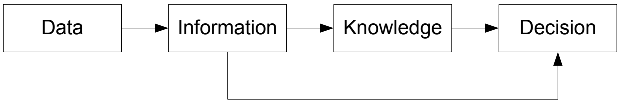


Figure 4-5: The relationship between data, information and knowledge.

Data represents a measurable quantity such as annual sales, strength of material etc. Information is extracted from data through analysis and can be viewed as being comprised of a number of data parts and their descriptions. Knowledge is the ability of individuals to understand the information, and the manner in which the information is used in a specific context. As a result, data, information and decisions are sequentially linked with data analysis and models the linking elements as illustrated in Figure 4-6.

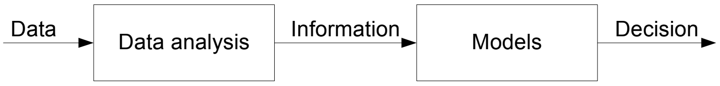


Figure 4-6: Data, information, and decisions.

In a multi-level decision making process, information derived at one stage can become the data for a subsequent stage.

As an example, the market data (monthly sales) collected can be analysed to extract information regarding sales trends. This information is then used to make decisions regarding changes to production, plant upgrade, product development, etc.

In the context of NPD, the relevant data may be grouped into the following four categories:

- Technical data: Product properties, field performance
- Market data: Sales, warranty claims, customer needs, etc.
- Historical data: Data relating to earlier products
- Vendors' data: Component suppliers, component reliability, etc.

Data and information needs for decision making in the different phases of the NPD process are discussed in Part II, Section 4.

5 Product Specification

There are many different definitions of product specification in the literature. In this section, we first discuss the alternate definitions, then propose a definition and discuss it in more detail in the remainder of the section.

5.1 Concept and Definition

Specification according to the Oxford Dictionary is as follows:

> "*A detailed description of the particulars of some projected work in building, engineering, or the like, giving the dimensions, materials, quantities, etc., of the work, together with directions to be followed by the builder or constructor; the document containing this.*"

More technical definitions of specification are as follows:

ISO 9000 (2000):

> "*A document stating requirements*".

BS 5760-4 (1986):

> *"A specification is a means of communicating in writing the requirements or intentions of one party to another in relation to a product, service, a procedure or test. A specification may be written by the product supplier, the user, the designer, the constructor or by the manufacturer."*
>
> *"A specification may define general characteristics or it may be specific."*
>
> *"A specification consists of two parts, the first defines requirements, and the second defines the means by which compliance with requirements can be demonstrated."*

Ulrich and Eppinger (1995)

> "*A specification (singular) consists of a metric and a value. The product specifications (plural) are simply the set of the individual specifications."*

Blanchard and Fabrycky (1998):

> *"The technical requirements for the system and its elements are documented through a series of specifications [...] top level specification leads into one or more subordinate specifications [...], covering applicable subsystems,*

> *configuration items, equipment, software, and other components of the system"*

Kohoutek (1996):

> *"A specification is usually a document that prescribes, in a complete, precise, and verifiable manner, the requirements, constraints, expected behaviour, or other characteristics of a product or system."*

Dieter (1991):

> *"The Product Design Specification (PDA) is a detailed listing of the requirements to be met to produce a successful product or process. The specification should say what the product must do not what it must be. Whenever possible the specification should be in quantitative terms, and when appropriate it should give limits within acceptable performance lies."*

Zeng and Gu (1999):

> *In a design process, design requirements are represented by design specifications. Based on the specifications, candidate product descriptions are generated. Design specifications are the formulation of design requirements, which manifest themselves as a set of desired product descriptions or product performances*."

As can be seen, the scope and focus of these definitions vary considerably. However, what they have in common is that a specification can be viewed as a means of stating the characteristics of a product at some stage in a development process. The Oxford Dictionary defines it as a document describing a process in detail, subsequent to the process' development. Others, like Dieter (1991), view specification as a document which states the desired characteristics of a product or process prior to its development, a view shared by Zeng and Gu (1999). On the other hand, Ulrich and Eppinger (1995), and Blanchard and Fabrycky (1998) define specifications as documents initially serving as input to the design process, but being refined as the design proceeds through different design phases. The initial specification of Blanchard and Fabrycky (1998) is the system specification, and the final is the product, process and materials specification.

We define the specification of an object (product or system, sub-system and down to part level) as:

> *“A set of statements about an object derived during pre-development stage to achieve some desired performance.”*

Note that the specifications for the three phases of Stage I (pre-development stage) are different and there is a close link between performance and specification.

5.2 Relationship between Objective and Performance

An *objective* is a business level statement that identifies the expectations that the management has with regards to a new product from an overall business perspective. The objective defines a set of statements about the performance (both commercial and technical) of the product to be designed. The objective comprises of the following:

1. Statements relating to performance (as discussed in Section 3) of the new product, relative to other products in the market.
2. Statements indicating the desired impact of the new product on business performance measured through indicators such as market share, return on investment, revenue, etc.
3. Statements relating to various constraints, such as health and safety, societal, legal, cost and time limits, etc.

The desired performance of the product is deduced from the business level objective. In formulating the desired performance we have to consider the potential technological principles that might be used in the design and manufacture of the product. The statements describing the desired performance will in general be more specific than the statements in the objective.

Let $\underline{y}^0$ denote the performance variables used in stating the objective. It may be constrained by a relationship: $\underline{y}^0 \in \Omega^0$ that defines the imposed constraint. Let $\underline{y}^1$ denote the variables of the desired performance deduced from the objective statement. It may constrained by a relationship $\underline{y}^1 \in \Omega^1$ that defines the constraints. Some of the variables of the objective statement might overlap with the variables defining the desired performance. In general, $\underline{y}^1$ will be more detailed and specific than $\underline{y}^0$.

Note that that the desired performance must be deduced in a manner such that if the desired performance is achieved, then the objective is fulfilled.

Example 2 [Continued]

The objective, $\underline{y}^0$, of a pump manufacturer may be to increase the market shares by 5%. Market surveys indicate that in order to do so, the performance, $\underline{y}^1$, of the pump should be 120 litres/minute at head 7 meters, with a 10% reduction in power consumption. Note that the desired performance is deduced from the objective, and is also more specific than the objective.

If, on the other hand, repeated customer complaints indicate that the power consumption of the manufacturers pump (pumping 120 litres/minute at head 7 meters) is too high, the objective of the manufacturer could be to develop a pump with 10% lower power consumption. This would also be the desired performance so that there is an overlap between the objective and the desired performance. ■

5.3 Relationship between Performance and Specification

Performance and specifications are strongly interlinked, and play a central role in the NPD process. In this section we explore this topic in more detail.

There are two kinds [forward and backward] of relationships between performance and specification as indicated below.

- *Forward Relationship [Performance to Specification]:* The desired performance outlines *what* is to be achieved in the NPD process. The specification describes *how* this performance can be achieved (using a synthesis process involving evaluation of alternate solutions to select the best solution), with desired performance as input to the process. Thus, the specification becomes a function of the desired performance. Often there are several alternative solutions yielding the same desired performance. This results in several specifications (defining alternative solutions) so that the forward relationship is one-to-many.
- *Backward Relationship [Specification to Performance]:* The actual performance of a product built to stated specifications will, in general, differ from the desired performance used in the formulation of the specifications. The actual performance

can be viewed as a function of the stated specification. Note that this is a one-to-one relationship as a set of specification leads to a unique actual performance of the product.

Note: The actual performance is affected by several uncertain factors beyond the control of the manufacturer. In this case, one measures performance in a statistical sense so that the expected (or average) actual performance is related to the specification through a one-to-one relationship.

5.4 Performance and Specification Links in the NPD Process

In Section 4 we discussed the six phases of the NPD process and suggested a matrix representation involving two stages (Stages I and II) and three levels (Levels I – III) as shown in Figure 4-4. In each of the three levels of Stage I, specifications are derived in terms of desired performance. In the three levels of Stage II, we have actual performances that are functions of the specifications defined at the end of Stage I. In this section, we discuss these links in more detail.

5.4.1 Stage I

This stage involves three levels and the last two levels can involve several sub-phases (depending on the product) that are sequentially linked. The specification at each sub-phase needs to be derived in terms of performance at the sub-phase and this in turn is linked to the specification at the earlier sub-phase. The sub-phases are numbered 1 through I and we consider sub-phase i.

For sub-phase i, the desired performance DP_i (for the object under consideration) serves as the input for deriving the specification SP_i which describes how the desired performance (for the object) may be attained. The specification SP_i is expressed through a set of functional, form, and other characteristics, i.e., $\underline{y}^i \in \Omega^i$, and this in turn is used to define the desired performance, DP_{i+1}, for the subsequent sub-phase $(i+1)$ as indicated in Figure 5-1.

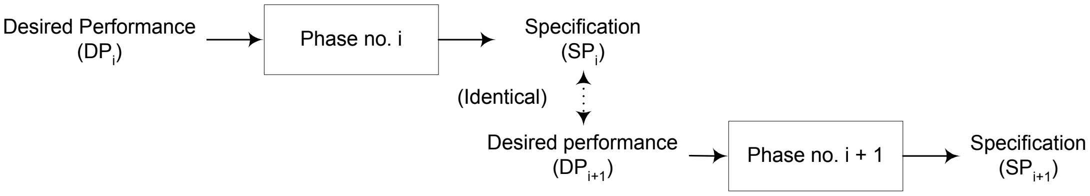


Figure 5-1: Specification – Performance Link in the Pre-Development Stage.

This process repeats at an increasing level of detail as one proceeds through Levels II and III of Stage I, until the final specifications are obtained. These become the input for the execution of Stage II.

Specification SP_{i+1} is a further elaboration of a solution with increasing detail. The degree of detail in specification SP_{i+1} is dependent on how far the design has progressed. In each sub-phase, constraints are decomposed from the previous sub-phase, or new ones arise, such that the solution space is increasingly restricted by constraints.

Evaluations of alternative solutions take place within each sub-phase of the pre-development stage, as discussed in Section 4.4. As solutions are generated in sub-phase i, their predicted (or theoretical) performance, PP_i, is established and compared to the desired performance, DP_i. When none of the PP_i's match the DP_i, one needs to iterate back to an earlier sub-phase in a manner similar to that shown in Figure 4-4.

At each sub-phase, the predicted performance is obtained using non-physical (abstract) models. The numerical values assigned to the model parameters are based on extrapolation of past historical and handbook data for similar objects, engineers' intuitive estimates, and so on.

5.4.2 Stage II

In Stage II there are several sub-phases in Levels II and III. At each sub-phase one can obtain an estimate of the actual performance of the object (component through to product) through test data. We shall denote this as the predicted performance so that PP_i is predicted performance at sub-phase i. It is compared with the desired performance, DP_i at the corresponding sub-phase in Stage I, as indicated in Figure 4-3. If there is a significant deviation between PP_i and DP_i, one needs to iterate back to an earlier sub-phase of the NPD process in a manner similar to that indicated in Figure 4-4.

Note that the predicted performances at Levels II and III of Stage II are different from the corresponding ones in Stage I. The prediction performances in Stage I are based on vendors data, designers intuition, etc. The corresponding ones in Stage II are based on data obtained under controlled test conditions. Once the product is launched, the actual product performance for deterministic variables (at Level I) can be assessed. To assess probabilistic variables, the product needs some time in use such that data may be collected and analysed.

From the discussion so far, we have a family of performance and specification for a new product, as indicated in Figure 5-2. Product specification needs to be defined at each of the three levels of Stage I. At Levels II and III the specifications need to be defined at each of the sub-phases.

Defining the specifications at different sub-phases of Stage I must take into account the link between specifications and performances in the context of the overall NPD process. We discuss a conceptual model for doing this in the next section.

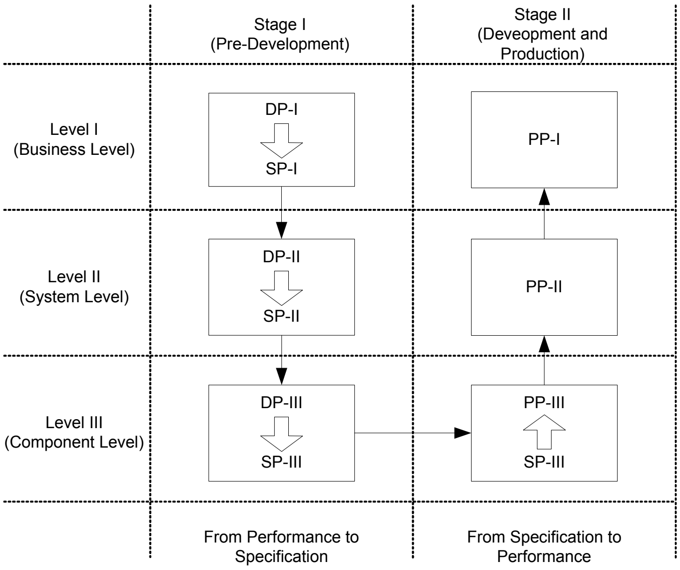


Figure 5-2: Specification and Performance in the NPD context.

6 Conceptual Model for Product Specification

A conceptual model for defining the specifications for a new product, taking into account the link between performance and specification discussed earlier, is shown in Figure 6-1. As can be seen it is an integration of Figure 4-4 and Figure 5-2. In this section we discuss the model in more detail and some related issues.

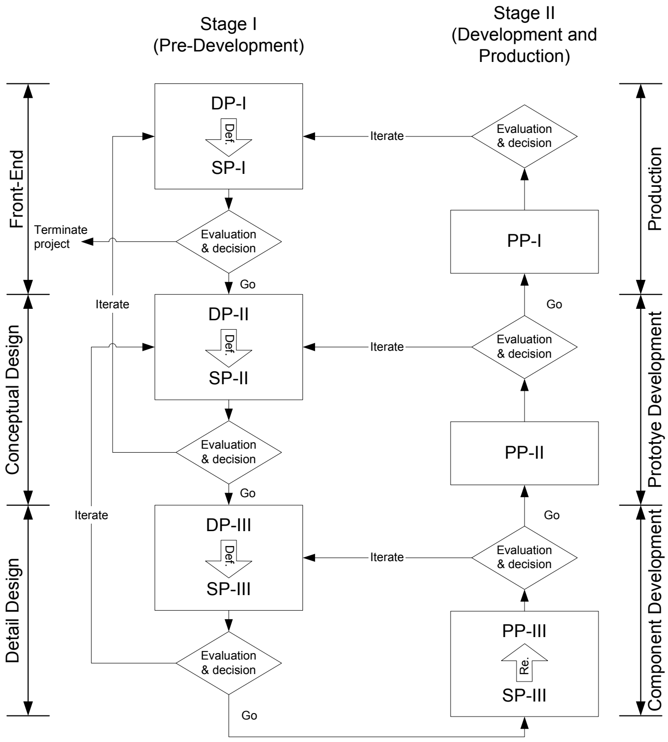


Figure 6-1: Conceptual Model for Product Specification.

6.1 Front-End Phase (Stage I, Level I)

The starting point is the identification of the need for a new product. It could be either market or technology driven. An important factor is that it must fit with the overall business strategy to achieve the desired business performance. Khurana and Rosenthal (1998) state that the front-end activity is completed when *"a business unit either commits to the funding and launch of an NPD project, or decides not to do this"*. They provide an extensive bibliography concerning the front-end of NPD. We focus our attention on desired performance DP_I as the input to obtain specification SP_I as the output. This involves the following steps:

1. Establish an overall business objective for the NPD process.

2. Derive DP-I from the overall objective.
3. Consider alternative SP-I that can achieve DP-I .
4. Evaluate the various SP-I's and determine whether to proceed with the project or not.

The different factors influencing the objective are discussed in Section 6.5.5.

Deriving DP-I from the objective is an iterative process, where management has to take into account technology and commercial implications. The alternative technologies that can be used become elements of the different SP-I.

A critical evaluation of alternative technologies (ranging from well developed to new and evolving) is needed in terms of their implications for success during the later development phases of the NPD processes as uncertainty in outcome is a significant feature of any development activity.

An evaluation of SP-I at the end of the Front-end phase determines whether to proceed to Level II (go) or to scrap the idea (no-go). This is done by building suitable models and is discussed in Part II of the report.

6.2 Design Phases (Stage I, Levels II and III)

If the decision at the end of the Front-end is "go", then SP-I is transferred to the design team involved with the Levels II and III of Stage I.

Level II requires the design team to look at alternative system architectures for the product and this can involve more than one sub-phase depending on the complexity of the product. The first task in the first sub-phase is to translate SP-I into DP-II. This is similar to that in the Level I where the DP-I was obtained from the Objective. For each system architecture, the set of technical statements that will allow one to realise DP-II defines SP-II$_1$. Note that this involves the forward linking between DP-II which involves both technical and non-technical variables and SP-II$_1$ that is mainly comprised of technical variables.

All the subsequent sub-phases of Level II are similar (but differ from the first sub-phase) in the sense that the variables of the desired performance and the specification at each sub-phase are mainly technical. Note that SP-II is the collection of the specifications of all the sub-phases in Level II.

The predicting of performance at each sub-phase for evaluations, and the identification of constraints, are dictated by technical and economic considerations and the constraints from Level I. Note that the constraints get more detailed as one proceeds through the different sub-phases. One might need to execute one or more of the sub-phases more than once and also one might need to iterate back to Level I if the predicted performance and the desired performance do not match. When they do match at the end of Level II then one can proceed to Level III of Stage I.

Level III is concerned with establishing geometrical shape, dimensions, tolerances, surface properties, and materials of the product. This can involve several sub-phases depending on the complexity of the product. The specifications at the last sub-phase become the input for Level III and define DP-III$_1$. The end result of activities in Level III is that all individual components and parts are fully specified and laid down in assembly drawings and parts lists (Pahl and Beitz, 1988).

The linking of performance to specifications in each sub-phase of Level III is similar to sub-phases 2 onwards in Level II. Also, in each sub-phase the performance and specification variables are mainly technical.

The predicting of performance at each sub-phase for evaluations, and the identification of constraints, is similar to that in Level II. However, these takes place at a greater degree of detail. One might need to execute one or more of the sub-phases more than once and also one might need to iterate back to Level II if the predicted performance and the desired performance do not match. When they do match at the end of Level III, the detailed designs become the input for the execution of Level III of Stage II.

6.3 Development Phases (Stage II, Levels II and III)

Stage II is concerned with embodying the solutions provided in the last sub-phase of Level III of Stage I. The embodiment starts at a high level of detail, concerning parts and component development, and evolves through the different product levels illustrated in Figure 4-2, ending with a product prototype.

If, at Level III, the desired performance of a component is greater than the design limit, then R&D is required to achieve the desired performance. The actual performance of components is determined by testing the physical components. In general, testing is limited so that the actual performance is a predicted estimate based on the test results. The actual performance is compared with the desired performance to decide whether to proceed forward or to make modifications. In the latter case, one needs to iterate back to a lower sub-phase or to Level III of Stage I. The modifications involve a process of test and fix to improve the performance.

The process is similar at Level II. As a prototype is built, the actual performance at higher levels (assembly, sub-system, etc) can be estimated based on test data and compared with the corresponding desired performance at Level II of Stage I. Based on this comparison, the process either moves forward if satisfactory or iterates back if not.

When the final prototype testing indicates that the actual performance matches the desired performance, then SP-III is finalized and released for production.

6.4 Production (Stage II, Level I)

Until the production process is fine-tuned, the actual performance of items produced, will in general, be lower than the actual performance of the prototype. The production process is adjusted so that the actual performance matches the desired and this is referred to as process stabilization. Once this is achieved, full-scale manufacturing commences, and the product is launched to the market.

The actual field performance of the product can now be assessed through data obtained from customers and compared with the desired performance. This information is used to make fine adjustments to the production process and to product design. Also one can now compare the actual outcomes at the business level and compare it with DP-I. This then allows the manufacturer to reassess the business objectives and making decisions with regards further product developments.

6.5 Factors Influencing Objective and Performance

In this section we discuss factors that are relevant to (i) formulating the objective and the DP-I at Level I of Stage I, (ii) for predicting performance in Levels II and III of Stages I and II, (iii) the actual field performance in Level I of Stage II.

6.5.1 Objective

The establishment of the overall objective is influenced by several factors, such as:

- **Competitive pressure**: Competitors launching products superior to the manufacturer's own products, thus demanding a response from the manufacturer.
- **Business strategy**: Managements' desire to increase market share or improve revenue, profits etc.
- **Customer demands**: Complaints from customers regarding the current product.
- **Organizations and magazines**: Product reviews and presentations indicating success of own and competitors' product success.
- **Technological advance**: New technologies resulting in new products with better performance.
- **Changes to laws, standards and directives**: New requirements regarding product safety, environmental aspects, or stringent product liability legislation which the current products fail to meet.

For large companies, individual product objectives are also influenced by company and product family objectives (Kohoutek, 1996). As a result, the factors influencing the objective are as shown in Figure 6-2. Competitors' actions usually play a significant role in setting the objectives for the NPD. In general, the objective is determined by taking into account all of these factors.

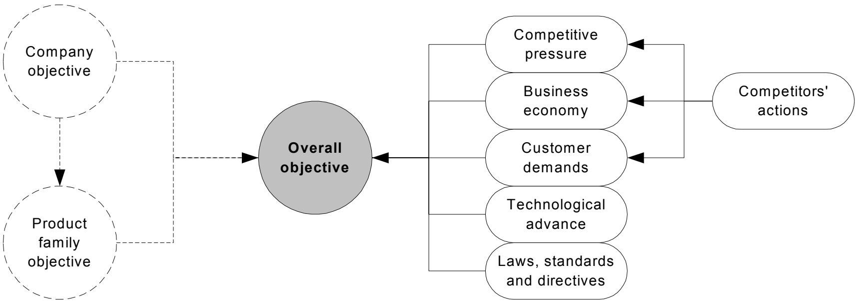


Figure 6-2: Factors Influencing the Objective.

6.5.2 Desired Performance [DP-I]

DP-I is obtained from the overall business objective. Three important factors influencing DP-I are (1) the performance of earlier and current products, (2) advances in technology, and, (3) customer/user requirements. However, there are many other issues that need to be addressed in formulating the desired performance from the objective. The six different types of trade-off that needs to be considered are shown in Figure 6-3 (adapted from Minderhoud, 1999) and it involves four other factors as indicated below:

- **Program expense:** Costs incurred in developing the product
- **Development speed:** Time from concept to market launch
- **Production cost:** Manufacturing cost over the product life cycle
- **Economic performance:** Revenue generated and post-sale servicing costs incurred over the product life cycle.

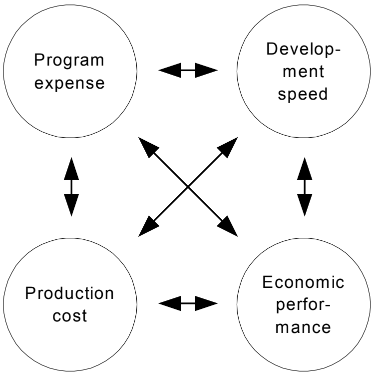


Figure 6-3: Different trade-offs in determining DP-I.

As a result, the trade-offs between the different factors that need to be examined in defining the desired performance are shown in Figure 6-4.

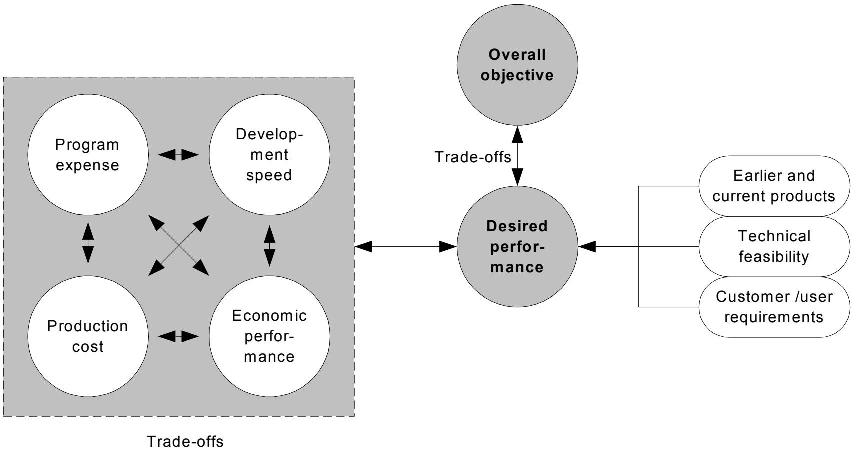


Figure 6-4: Factors and Trade-Off in Defining Desired Performance.

Since desired performances II and III are deduced from desired performance I, this implies that they are indirectly affected by the factors discussed above.

6.5.3 Predicted Performance

Factors influencing the predicted performance in Levels II and III of Stage I are the following: (1) choice of design properties, (2) choice of models used for prediction, and (3) the quality of the data used in the prediction.

As physical testing starts at Levels III and II of Stage II, additional factors that influence the predicted (or estimated) performance (component level through product level) include (1) test environment (normal versus accelerated testing, environmental testing), (2) test duration, and (3) methods used to analyse the test data.

6.5.4 Actual Field Performance

The actual performance of the product in the field is dependent on several manufacturing factors, such as quality control, production process capability, materials used, and quality of components supplied by vendors. The performance is also influenced by several customer related factors, such as usage intensity, usage environment, and maintenance of the product. Even storage and transport can, in some cases, influence product performance in the field. As a result, the factors influencing the actual field performance are illustrated in Figure 6-5.

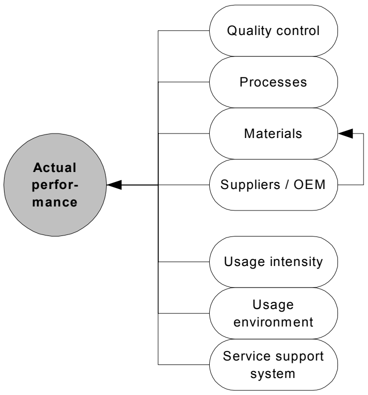


Figure 6-5: Factors Influencing Actual Performance During Production and Use.

6.5.5 Overview of Factors Influencing Product Performance

An overview of the important factors influencing the different product performance is obtained by integrating Figure 6-2– Figure 6-5 as shown in Figure 6-6.

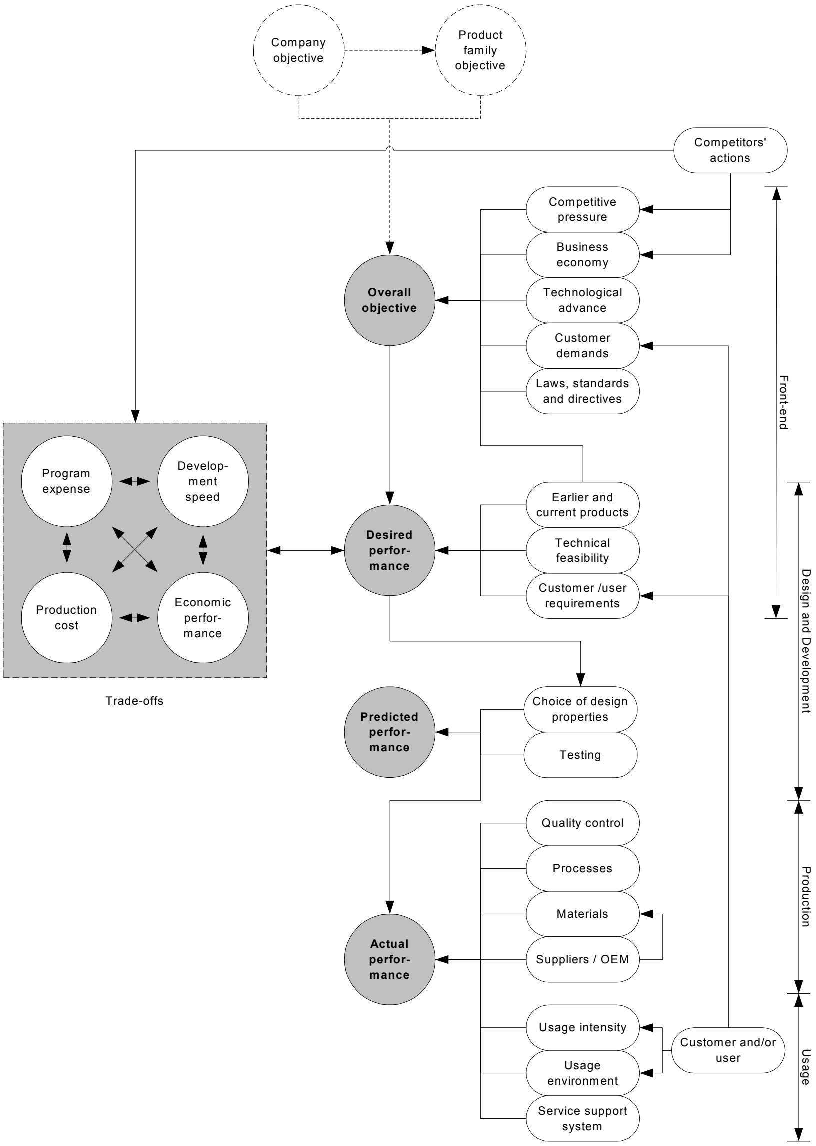


Figure 6-6: Overview of Factors Influencing Product Performance.

7 Product Reliability

In this section we discuss some basic concepts from reliability theory that will be needed in Section 8 for the study of reliability specifications and for use in Part II of the report.

7.1 Definition of Reliability

As discussed in Section 3, reliability is an important aspect of a product's quality. Reliability of a product conveys the concept of dependability, successful operation or performance and the absence of failures. Unreliability (or lack of reliability) conveys the opposite. Since the process of deterioration leading to failure occurs in an uncertain manner, the concept of reliability requires a dynamic and probabilistic framework. We use the following definition from Blischke and Murthy (2000):

> *The reliability of a product (system) is the probability that the product (system) will perform its intended function for a specified time period when operating under normal (or stated) environmental conditions.*

A more informal way of defining reliability, often seen in literature, is *"the persistence of quality over time"* (e.g., Chan and Tortorella, 1998).

7.2 Product Degradation and Failures

Reliability is strongly related to the concept of failure, as indicated in the definition of reliability above. Most products degrade with age and/or usage, and this naturally affects the product reliability. When the product performance falls below the desired level then the product is said to have *failed*. Two definitions of *failure* are:

> *The termination of the ability of an item to perform a required function." (IEC 50(191), 1990).*
> *"Equipment fails, if it is no longer able to carry out its intended function under the specified operational conditions for which it was designed." (Nieuwhof, 1984).*

From an engineering point of view, it is useful to define failure in a broader sense.

Witherell (1994) elaborates as follows:

> *"It (failure) can be any incident or condition that causes an industrial plant, manufactured product, process, material, or service to degrade or become unsuitable or unable to perform its intended function or purpose safely, reliably, and cost-effectively."*

Failures occur in an uncertain manner and are influenced by factors such as design, manufacture or construction, maintenance and operation. In addition, the human factor is also important. In many situations, improper operation of a machine, unsafe driving habits, and unpredictable human behaviour generally lead to accidents and other types of failures.

Actions by the user, such as operations and maintenance have an impact on failure, and individuals and businesses need to understand the implications of this. For example, operating a pump at a higher load than that for which it is rated will result in increased output but hasten its failure and can lead to economic loss rather than gain in the long run.

7.2.1 Failures Related to Functions

The key term in the above definitions for reliability is the inability of the system or product to *function* as required. Rausand and Øien (1996) suggest a classification for the different functions of items of a complex system and is as follows:

1. *Essential functions*: This defines the intended or primary function. In Example 1, there may be many essential functions; to entertain, to provide work support, and so on. The essential function in Example 2 is to pump fluid from A to B. In Example 3, there are again many several essential functions, generally one for each subsystem, for example engines to provide the thrust, and wings to provide the lift.
2. *Auxiliary functions*: These are required to support the primary function. In Example 2, the pump house serves as an auxiliary function, preventing the pump from leaking when in use.
3. *Protective functions*: The goal here is to protect people, equipment and the

environment from damage and injury. In Example 1, the CPU fan protects the CPU from overheating. In Example 3 the catapult would provide a safe ejection mechanism when the pilot has to ditch the aircraft.

4. *Information functions*: These comprise condition monitoring, gauges, alarms, etc. In Example 1, the battery level indicator would be such an information function. In Example 2, the pump unit could be fitted with automatic condition monitoring, providing information on the status of critical parts in the pump.
5. *Interface functions*: These deal with the interface between the item under consideration and other items. In Example 2, connecting wires and cables to the power supply provide this function. If the connection is broken, then the performance of the system is affected.
6. *Superfluous functions*: In some cases a product may have functions that are never used. This is sometimes the case wirh electronic equipment that have a wide range of "nice-to-have" functions that are not really necessary. Superfluous functions may also be found in systems that have been modified several times. In some cases, failure of a superfluous function may cause failure of other functions (Rausand & Høyland, 2003).

A *fault* is the state of the system characterized by its inability to perform its required function. (Note, this excludes situations arising from preventive maintenance or any other intentional shutdown period during which the system is unable to perform its required function). A fault is hence a state resulting from a failure.

It is important to differentiate failure (fault) and error. According to IEC 50(191), an error is a *"discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition."* As a result, an error is not a failure because it is within the acceptable limits of deviation from the desired performance (target value). An error is sometimes referred to as an incipient failure. Figure 7-1: **Definition of System Failure based on System Performance.**Figure 7-1illustrates these concepts. See, Rausand and Øien (1996) for further discussion.

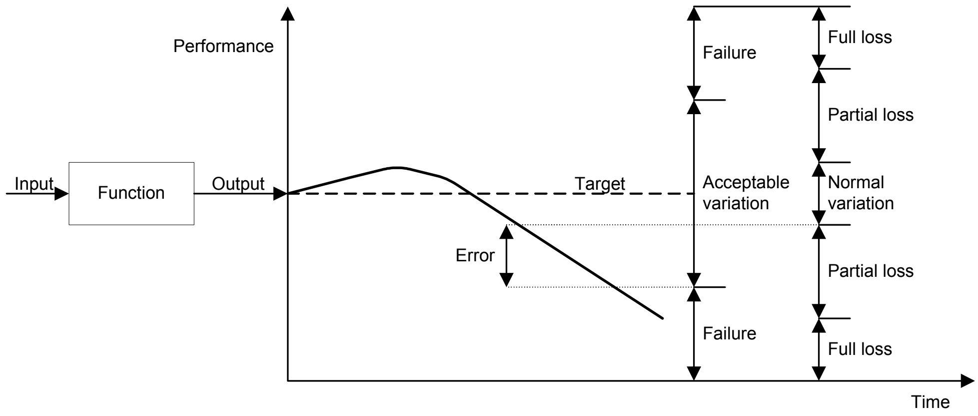


Figure 7-1: Definition of System Failure based on System Performance.

Due to the strong link between functions and failures, as illustrated in **Figure 7-1**, the proper identification of potential product failures in NPD requires a systematic approach to function identification and modeling, through for example function trees (see, e.g., Fox, 1993) and/or function block diagrams (e.g., Pahl & Beitz, 1988).

7.2.2 Failure Modes

A *failure mode* is a description of a fault. It is sometimes referred to as fault mode (for example, IEC 50(191)). Failure modes are identified by studying an object's functions, and their function requirements. As such, a failure mode may be seen as a functional performance falling outside the acceptable performance variation (illustrated in Figure 7-1). In this manner, both the concepts of reliability and failure modes are inevitably connected to functions and function requirements.

In a system hierarchy, a failure mode on one indenture level is the cause of a failure mode on the next higher indenture level, and the effect of another failure mode on the next lower indenture level, as illustrated in Figure 7-2.

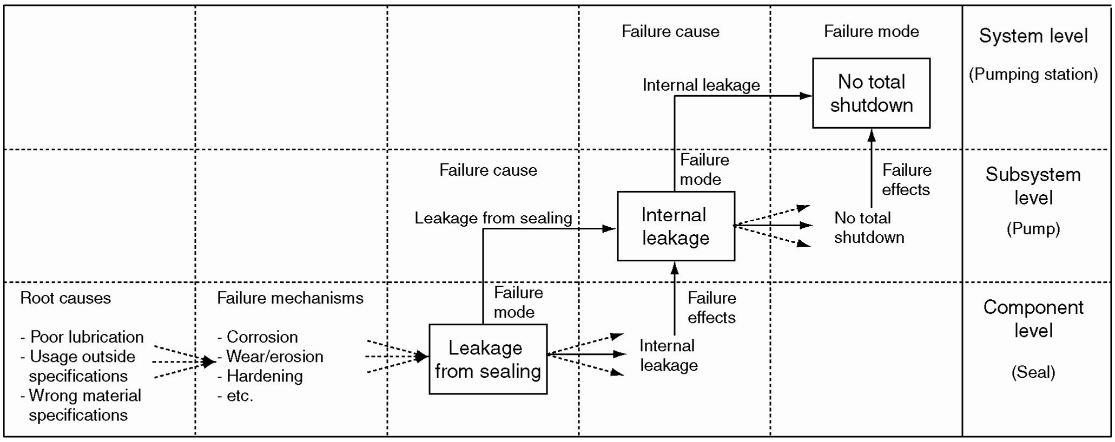


Figure 7-2: Failure modes, causes and mechanisms (from Rausand & Øien, 1996)

Knowing that there is a hierarchical level of failure modes, and these are related to functions, function requirements also are hierarchical, as illustrated in **Figure 7-3**.

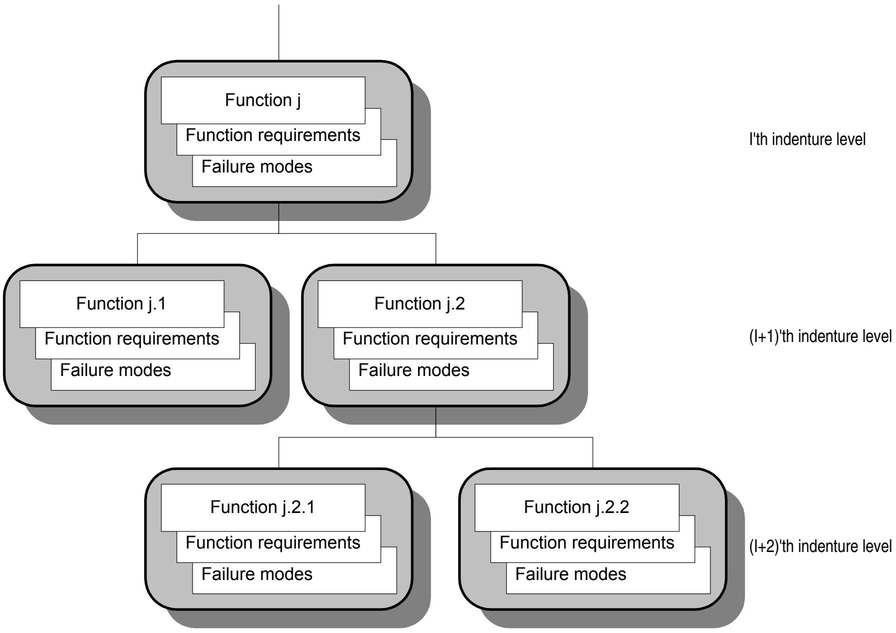


Figure 7-3: Functions, requirements and failure mode hierarchy.

Blache and Shrivastava (1994) suggest a classification scheme for failure modes as shown in Figure 7-4. A brief description of the different failure modes is as follows:

1. *Intermittent failures*: Failures that last only for a short time. A good example of this is software faults that occur only under certain conditions that occur intermittently.

2. *Extended failures*: Failures that continue until some corrective action rectifies the failure. They can be divided into the following two categories:
    a) *Complete Failures* that result in total loss of function.
    b) *Partial Failures* that result in partial loss of function.

   Each of these can be further subdivided into the following:
    a) *Sudden failures*: Failures that occur without any warning.
    b) *Gradual failures*: Failures that occur with signals to warn of the occurrence of a failure.

A complete and sudden failure is called a *Catastrophic failure* and a gradual and partial failure is designated a *Degraded failure*.

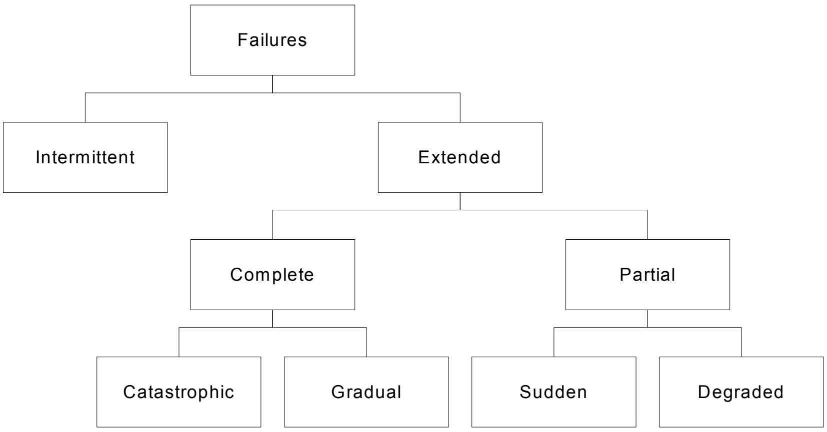


Figure 7-4: Failure Classification (from Blache and Shrivistava, 1994)

<u>*Example 2 [Continued]:*</u>

In the case of a pump, a complete failure occurs when the pump does not pump at all. A partial failure may be when the pump is pumping less than normal. Each of these failures may be sudden or gradual. A sudden failure may be due to short circuit in the motor, and a gradual failure may be due to impeller cavitation. ■

7.2.3 Failure Causes and Severity

According to IEC 50(191), *failure cause* is "the circumstances during design, manufacture or use which have led to a failure". Failure cause is useful information in the prevention of failures or their reoccurrence. Failure causes may be classified in relation to the life cycle of a product as illustrated in Figure 7-5.

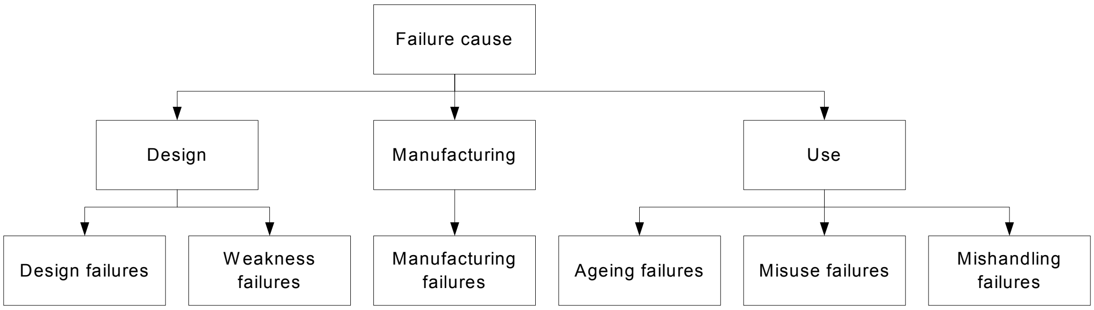


Figure 7-5: Failure Cause Classification [from IEC 50 (191)].

We briefly describe each of these failure causes:

1. *Design Failure*: Due to inadequate design.
2. *Weakness failure*: Due to weakness (inherent or induced) in the system so that the system cannot stand the stress it encounters in its normal environment.
3. *Manufacturing failure*: Due to non-conformity during manufacturing.
4. *Aging failure*: Due to the effects of age and/or usage
5. *Misuse failure*: Due to misuse of the system (operating in environments for which it was not designed).
6. *Mishandling failures*: Due to incorrect handling and/or lack of care and maintenance.

Note that the various failure causes above are not necessarily disjoint. Also, one needs to differentiate between primary (or root) cause and secondary and other levels of failures that result from a primary failure.

Finally, the severity of a failure mode signifies the impact of the failure mode on the system as a whole and on the outside environment. A severity ranking classification scheme (MIL-STD 882B) is as follows:

1. *Catastrophic*: Failures that result in death or total system loss
2. *Critical*: Failures that result in severe injury or major system damage
3. *Marginal*: Failures that result in minor injury or minor system damage
4. *Negligible*: Failures that result in less than minor injury or system damage

Another classification is given in the Reliability Centred Maintenance (RCM) approach (see, Moubray, 1991), where the following severity classes (in descending order of importance) are used:

1. Failures with safety consequences
2. Failures with environmental consequences
3. Failures with operational consequences
4. Failures with non-operational consequences.

7.2.4 Deterioration

Failure is often a result of the effect of deterioration. The deterioration process leading to a failure is a complicated process, and this varies with the type of product and the material used. Failure mechanisms may be divided into two broad categories (Dasgupta and Pecht, 1991), (i) overstress failures, and (ii) wear-out failures.

Overstress failures are those due to brittle fracture, ductile fracture, yield, buckling, large elastic deformation and interfacial de-adhesion. Wear-out failures are those due to wear, corrosion, dendritic growth, interdiffusion, fatigue crack propagation, diffusion, radiation, fatigue crack initiation and creep.

The rate at which the deterioration occurs is a function of time and/or usage intensity. The following example from Kordonsky and Gertsbakh (1995) illustrates this.

Example 3 [Continued]

An aircraft is a complex system consisting of many sub-systems. We confine our attention to (i) body, and (ii) engine. The different deterioration processes that lead to failures and the time-scales and usage factors that affect the rate of deterioration are as follows:

Sub-system	Time-scale/usage intensity	Deterioration
Body	Calendar time	Corrosion
	Time in air	Wear Accumulation of fatigue
	Number of landings (take offs) or flights	Accumulation of fatigue High amplitude loading

Jet engine	Calendar time	Corrosion
	Operation time	Wear
		Accumulation of fatigue
	Number of operation cycles	Temperature cycling
	Time in take-off regime	High temperature

The final failure is often due to a cumulative effect of these different types of deterioration. ■

7.3 Maintenance and Maintainability

The starting point for the study of maintenance is the *maintenance concept*. This consists of statements and illustrations that define the theoretical means of maintaining equipment and relate tasks, tools, techniques, and people in the maintenance process. Maintenance involves one or more of the following actions:

- Servicing
- Testing/Inspection
- Removal/Replacement
- Repair/Overhaul
- Modification

7.3.1 Maintenance Actions

Maintenance can be defined as actions to (1) control the deterioration process leading to failure of an object, and (2) restore the object to its operational state through corrective actions after a failure. The former is called *preventive* maintenance (PM), and the latter *corrective* maintenance (CM). Preventive maintenance actions may further be split into the following categories:

- *Clock-based maintenance:* Here PM actions are carried out at set times.
- *Age-based maintenance:* Here PM actions are based on the age of the object.
- *Usage-based maintenance:* Here PM actions are based on the usage of the product.

- *Condition-based maintenance:* Here, PM actions are based on the condition of the object being maintained. This involves monitoring one or more variables characterising the wear process (e.g., the crack growth in a mechanical component.
- *Opportunity-based maintenance:* This is applicable for multi-component products, where maintenance actions (PM or CM) for a product provide an opportunity or carrying out PM actions on one or more of the remaining components of the product.
- *Design-out maintenance:* This involves carrying out modifications through redesign of the component. As a result, the new component has better reliability characteristics than the old.

7.3.2 Maintenance Costs

The direct costs of maintenance are:

- Cost of manpower
- Cost of materials and spares inventory
- Cost of tools and equipment needed for carrying out maintenance actions
- Other costs (overhead, administration)

In addition, many other costs are affected either directly or indirectly by maintenance, such as:

- Equipment related
  - Accelerated wear, e.g., because of poor maintenance or testing
  - Excessive spare parts inventory
  - Unnecessary equipment redundancy
  - Excessive energy consumption
- Production related
  - Production loss during maintenance
  - Rework
  - Excessive scrap and material losses
  - Idle operators due to breakdowns
  - Delays in fulfilling orders
- Product related

- Quality and reliability issues
- Dissatisfied customers

7.3.3 Maintainability

Carrying out maintenance involves additional cost to the customer, and is only worthwhile if the benefits from such actions exceed the costs. From the customer's point of view this implies that maintenance must be examined in terms of its impact on product performance. Maintenance is of importance to manufacturers as well, since the ease and ability to carry out maintenance actions depends on the inherent characteristics of the product design. This notion is defined through the concept of *maintainability*. Maintainability may be defined as:

> *"the different functions (or activities) necessary to keep an object in, or restoring it to, an acceptable state (or operating condition)".*

Maintainability is different from maintenance. Maintainability is the *ability* of a product to be maintained, as opposed to maintenance, which constitutes a series of actions to restore an object or keep an object in an operational state. As such, maintainability is a design parameter and maintenance is a result of design. The reason that maintainability is important is that the usefulness of the product is lost if (1) breakdowns cannot be diagnosed to a level of detail needed to pinpoint the cause in a short time, and (2) repairs require extremely long times for completion. During the NPD process, effective maintainability considerations require addressing one or more of the following questions:

1. What parts have high failure rates?
2. How can these failures be diagnosed easily?
3. How quickly can the system be repaired?
4. How much downtime is acceptable?
5. What kind of PM needs to be performed?

These issues must be addressed in the context of the useful life of the product and involves linking reliability, maintenance and logistics with maintainability. These must be done in the context of the total life cycle and is important in the overall management of the NPD process.

7.4 Consequences of Failures

As mentioned in the Introduction, products are becoming more and more complex. This, combined with the use of new materials and new construction methods, often increases the risk of failure and the possible damage that may result. In this sub-section, we discuss the consequences of product failures, seen from both the customer and the manufacturer's point of view.

7.4.1 Customers Point of View

When a failure occurs, no matter how benign, its impact is felt. For customers, the consequences of failures may range from a mere nuisance value (for example failure of air-conditioner) to serious economic loss (for example failure of freezer) to something serious damage to environment and/or loss of life (for example, brake failure in a car). All of these lead to customer dissatisfaction with the product.

Some of the important factors leading to customer dissatisfaction are the following:

- **Time of failure:** Failures occurring fairly soon after purchase causes a high degree of dissatisfaction, however, this dissatisfaction tends to decrease as time passes. In the case of products sold with warranty, the same dissatisfaction pattern may occur after the warranty expiry date, as illustrated in Figure 7-6. Failures occurring shortly after the warranty expiry will cause very high dissatisfaction, as the customer have to cover related expenses. The degree of dissatisfaction decreases towards the end of product life, since the customer expects the product to fail.

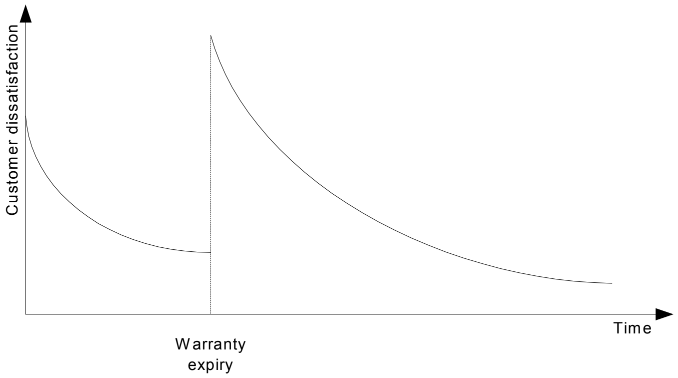


Figure 7-6: Relationship between Customer Dissatisfaction and Time of Failure.

The number of failures over the useful life of an item also strongly influences the degree of dissatisfaction. Multiple failures in a relatively short time span can strongly increase product dissatisfaction.

- **Severity of failure:** This was discussed in Section 7.2.3.
- **Operating environment:** A customer operating the product in a harsh environment may expect more failures than a customer operating the same product in a less harsh environment. For example, a field engineer may expose his laptop to harder conditions than a businessman, and may thus expect more failures in his product.
- **Product type:** For some types of products, customers expect and tolerate failures. This is the case with new products based on unproven technologies. The degree of dissatisfaction associated with failure is less for these products than for well established products that perform reliably. Customers expect more failures with laptops than desktops. This is because components in a laptop are packed closer than in desktops, and thus operate under higher temperatures. Dissatisfaction with laptop failures is therefore likely to be less than for desktops.
- **Acquisition cost:** Dissatisfaction is also related to purchase cost. Customers may consciously buy cheaper products and accept more frequent failures during operation. A customer buying an expensive product will expect higher reliability performance.
- **Maintenance Costs:** Frequent and expensive maintenance to prevent failures can lead to customer dissatisfaction.

When failures or other downtime causes such as preventive maintenance, have a significant economic impact, the time needed to carry out the specified maintenance tasks becomes important. In these cases, the frequency of maintenance, and the maintenance duration becomes important issues for customers. This is particularly true for production systems and also for defence systems. Here, customers would therefore focus on the cost of ownership or the Life Cycle Cost (LCC).

7.4.2 Manufacturers Point of View

Lack of desired reliability performance impacts the manufacturer in a number of different ways, from low sales and/or loosing market shares due to customer dissatisfaction, to high warranty costs, costs of recalling products from the market or even compensations following liability claims as manufacturers are some times required to provide compensation for any damages resulting from failures of an object. This has serious implications for manufacturers of products since reliability performance is strongly related to business success.

There is no way that the manufacturer can completely avoid product failures. High reliability performance can be achieved with high development cost but this might not be the optimal strategy. The challenge to the manufacturer is to balance reliability performance against development cost and time, in order to ensure a competitive product that meets customer satisfaction and results in profit to the manufacturer. The manufacturer also needs to consider the risks of high costs resulting from product recall, excessive liability and warranty claims resulting from poor reliability.

7.5 Product Reliability

There are two different perspectives to product reliability and in this section we briefly look at these.

7.5.1 Life Cycle Perspective

The fact that reliability varies over the life cycle of a product further adds complication to the reliability issue in product development. A typical scenario is as shown in Figure 7-7 (adapted from Blischke and Murthy, 2000). Throughout the design phases the reliability of a product is improved through identification and removal of potential failure causes. Quantitative analyses of 1) alternative product structures' reliability, and of 2) alternative components' reliability, further aid in the process of improving reliability through allowing comparisons in order to find the best solution with respect to reliability. However, this improvement has an upper limit. If the desired reliability performance is below this limit, then the design using available parts and components achieves the desired performance. If not, the reliability needs to be improved during the development phases (Levels II and III of Stage II). This involves testing an item (component, assembly, sub-system) till failure occurs and analysing the causes of the failure. Based on this analysis, changes are made to the design to overcome the identified failure causes. This is called Test-Analyse-And-Fix (TAAF). This process is continued until the desired reliability performance is achieved.

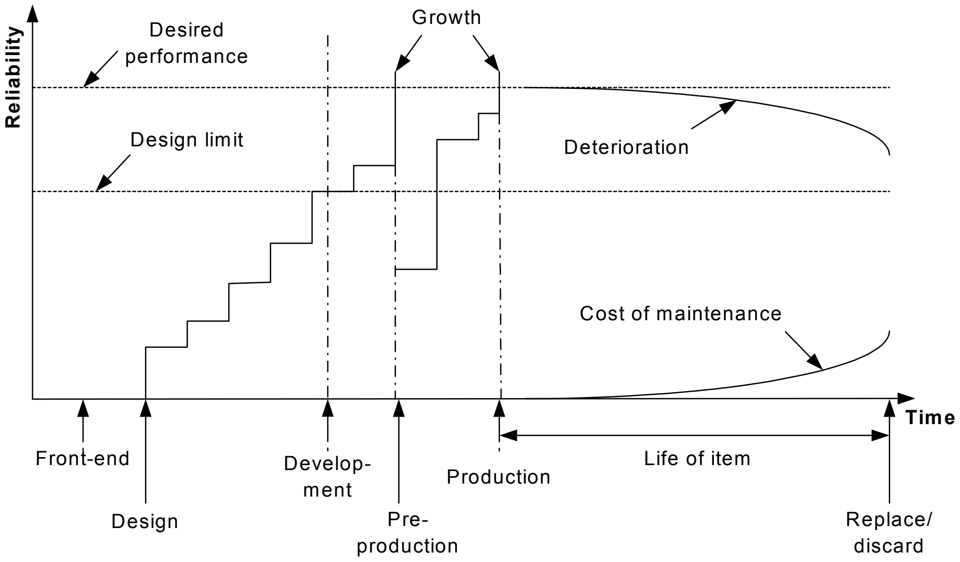


Figure 7-7: Product Reliability over Product Life Cycle.

The reliability of the items produced during the pre-production run is usually below that for the final prototype. This is caused by variations resulting from the manufacturing process. Through adjustments to the manufacturing process, as well as through proper process and quality control, these variations are identified and reduced or eliminated and the reliability of items produced is increased until it reaches the target value. Once this is achieved, full-scale production commences and the items are released for sale. Note that even when the target value is reached, there will be conforming and non-conforming products relative to the target. Quality control schemes must be set up to reduce the number of non-conforming products reaching the market.

When an item is put into use its reliability deteriorates with age. This deterioration is affected by several factors, including environment, operating conditions and maintenance. The rate of deterioration can be controlled through preventive maintenance. The effectiveness of maintenance decreases and the maintenance cost increases as the item ages. This leads to the item being finally discarded and replaced by a new one.

7.5.2 Product Profitability Perspective

When developing a new product, the desired reliability performance must be defined taking into account the tradeoffs between different factors, as discussed in Section 7.4.2, and illustrated in Figure 7-8. Performance of competitors' products, customer satisfaction and time to market are issues that impact the sales of a product. These are related to the product reliability. A minimum reliability is needed for customer satisfaction, but also in order to compete with competitors' products. Achieving the desired reliability performance may, however, result in prolonged development time and hence a delay to the market, a fact that may negatively impact the sales. The achievement of a certain reliability level is also related to NPD program expense (a high reliability level will require extensive TAAF to be attained). Production cost is also influenced by reliability in that the desired product reliability level determines the quality control scheme that has to be set up. Equally, warranty costs may impact the profitability of the product. Potential recall and liability costs are also related to product reliability. The lower the reliability, seen in relation to state-of-the-art, the higher the chance of product recall or even liability costs.

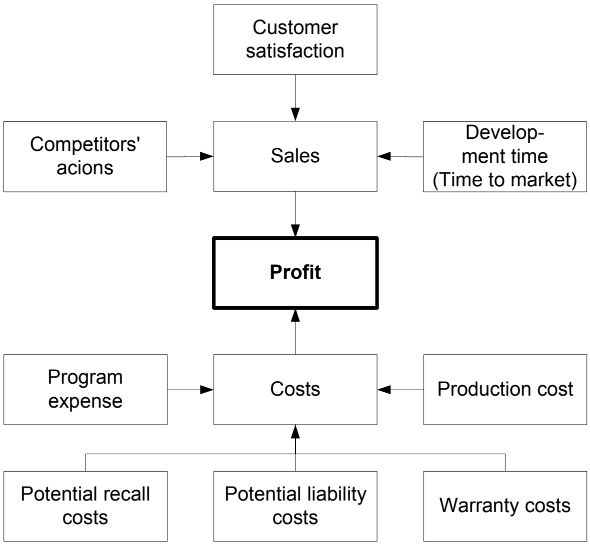


Figure 7-8: Factors Influencing Product Profitability.

7.6 Characterisation of Product Reliability

The reliability of an object at any level (product, sub-system, assembly) can be derived in terms of the reliability of the lower level objects. This is so because a failure of an object can be related to a failure at a lower level.

In this section we discuss alternative characterisations of an unreliable object. We first look at time between failures. We need to differentiate first failure from subsequent failures as the latter depends on whether the object is repairable or not and the type of repair used. We then look at failures over time.

7.6.1 First Failure

Failure Distribution, Density and Hazard Function Characterisation

Let T denote the time to first failure. It is a random variable and characterised through the *failure distribution function* $F(t,\theta)$ given by

$$F(t;\theta) = P\{T \le t\}$$

where θ is the parameter set of the distribution function. The probability that the object survives for a period T is the *survival probability* and is given by

$$S(t;\theta) = P\{T > t\} = 1 - F(t;\theta)$$

[Note: For notational ease, one often suppresses the parameter θ so that $F(t,\theta)$ is written as $F(t)$.]

If the distribution function is differentiable, then

$$f(t;\theta) = \frac{dF(t;\theta)}{dt}$$

is the *density function* associated with *F(t;θ)*. Then,

$$P(t < T \le t + \delta t) = f(t,\theta)\delta t + O(\delta t^2)$$

The hazard function *r(t;θ)* associated with *F(t;θ)* is defined as:

$$r(t;\theta) = \frac{f(t;\theta)}{1 - F(t;\theta)}$$

The hazard function (or failure rate function) can be interpreted as the probability that the object will fail in [*t, t* + *δt*) given that it has not failed at or prior to *t*. The shape of the hazard function can be increasing, decreasing, constant, bathtub or more complex such as roller coaster (Wong, 1988). A typical bathtub shape is illustrated in Figure 7-9.

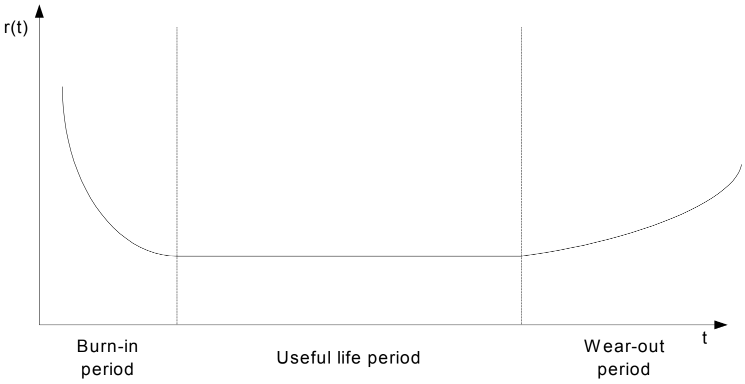


Figure 7-9: The Bathtub Curve.

Moment Characterisation

The first moment given by $\mu = E[T]$ is the mean time to failure. The second central moment $\sigma^2 = E[(T-\mu)^2]$ is termed the *variance* and indicates the dispersion or spread of *T* around μ.

Fractiles, Median and Mode

For a failure distribution, the α-fractile, t_α, for a given α, $0 < \alpha < 1$, is a number such that

$$P\{T \le t_\alpha\} = F(t_\alpha;\theta) = \alpha$$

The fractiles for $\alpha = 0.25$ and 0.75 are called the first and third *quartiles* and the 0.50 fractile is called the *median*. The median corresponds to the time when it is a 50% probability that the failure occurs before this value.

The *mode* corresponds to the value of t where $f(t;\theta)$ reaches a local maximum. There can be one or more modes. Figure 7-10 shows a unimodal density function with mean > mode.

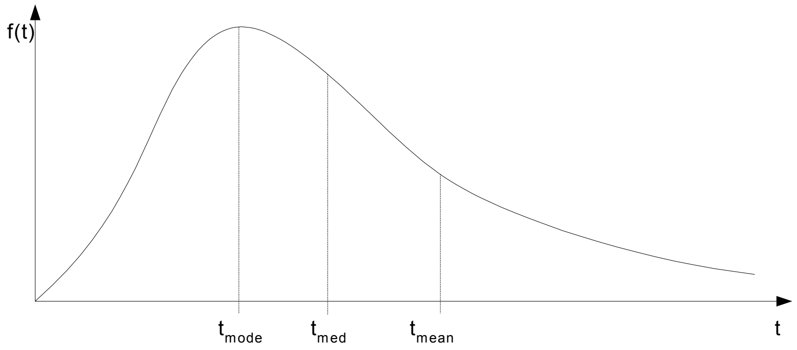


Figure 7-10: Comparison of the Measures of Central Tendency.

7.6.2 Subsequent Failures

The time to failure after the j^{th} repair, T_j is also a random variable that can be characterised in a manner similar to the first failure. The failure distribution function $F_j(t,\theta)$ for T_j (with $t = 0$ corresponding to the time the object is put back into use after repair) depends on the type of repair. The different kinds of repair are as follows:

Back-to-New: In this case $F_j(t,\theta) = F(t,\theta)$

Minimal Repair: In this case the failure rate of the repaired object is the same as that just before failure.

Different from New: Here, the failed object is subjected to a major overhaul that result in the failure distribution of the repaired object being $F_j(t;\theta)$ with mean μ_j decreasing as j increases.

Imperfect repair: The hazard function for the object can lie anywhere between that with minimal repair or back-to-new (better than used but not as good-as-new) or can be greater than that for the minimal repair (worse than minimal repair).

7.6.3 Failures over Time

Failures over time of an object depend on several factors. These include the reliability of the object, the actions taken to rectify the failures and the time needed to rectify the failed object. The time instants of failures can be viewed as random points along a time continuum interspersed with points representing the time at which a failed object is restored to working condition. If the time to repair is small relative to time between failures, then it can be treated as being insignificant and ignored. In this case, rectification can be viewed as being nearly instantaneous. In general, the rectification time is uncertain and can be modelled by a distribution function. As a result, the number of failures over a specified time interval is a random variable. Let $t = 0$ denote the time at which a new object is put into use and let $N(t_1, t_2)$ denote the number of failures over the interval $[t_1, t_2)$. The characterisation of this can be done in terms of the following:

1. Distribution function: $p_n(t_1, t_2) = P\{N(t_1, t_2) = n\}$
2. Moments: For example, the expected value $M(t_1, t_2) = E[N(t_1, t_2)]$
3. Rate of occurrence of failures $\lambda(t)$ which is often referred to as ROCOF. The probability of a failure in $[t, t + \delta t)$ is given by $\lambda(t)\delta t + O(\delta t^2)$.

Expressions for these can be derived in terms of the failure distribution $F(t)$ and the rectification action and is discussed in Part II of the report.

Failures over time are influenced by several other factors such as usage environment, usage intensity and mode, and preventive maintenance. Harsh environment tends to accelerate the degradation process and as a result hasten the failure of the object. Operating the object above the rated load (for example, pumping fluid at rates beyond the recommended upper limit) has a similar impact. In contrast, the effect of preventive maintenance is to control the degradation process. One way of modelling the effect of preventive maintenance is that it lowers the rate of occurrence of failures (ROCOF) as shown in Figure 7-11.

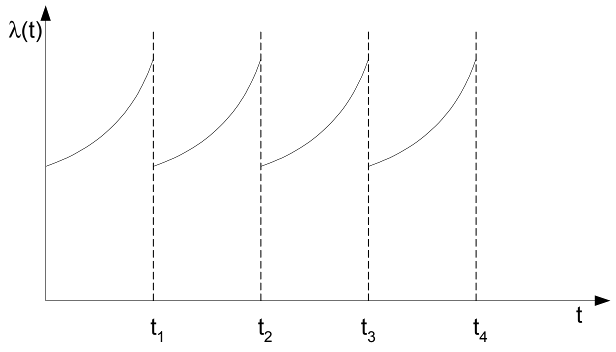


Figure 7-11: Effect of Preventive Maintenance on ROCOF.

7.6.4 Availability

For an unreliable object, the state (working or failed) of the object at any given time instant t is uncertain. It can be described in terms of a binary valued function $X(t)$ which assumes a value 1 if the object is in working state at time *t*, and 0 if it is in failed state. Availability is a measure of the object being in working state. Three common availability measures are the following:

- Point availability at time *t*, $A(t)$, given by

$$A(t) = P\{X(t) = 1\} = E[X(t)]$$

- The average (mean) availability over the interval $[t_1, t_2)$ given by:

$$\overline{A}(t_1, t_2) = \frac{E\left[\int_{t_1}^{t_2} X(t)dt\right]}{t_2 - t_1}$$

  Note that with $t_1 = 0$ and $t_2 = t$ this is called as "mission availability".

- The limiting average availability (also called "steady-state availability") is given by:

$$\overline{A}_\infty = \lim_{t_2 - t_1 \to \infty} \overline{A}(t_1, t_2)$$

For products that are required to perform a function at any random time (e.g., a missile to intercept an incoming enemy aircraft or a back-up generator to supply power when the regular power supply is interrupted), the reliability goal may be defined in terms of instantaneous availability. For products used continuously (e.g., a pump in a chemical plant), the steady-state availability is of importance. For products where the usage is determined by a duty cycle (e.g., an airliner on a 12-hour flight) the mission availability is of importance.

8 Reliability Specifications

8.1 Introduction

The previous sections looked at specification in NPD in general. In this section we focus our attention on reliability specifications. Product reliability is important for a variety of reasons. Poor product reliability results in frequent failures. This in turn results in greater costs to both the manufacturer (from servicing claims under warranty) and the customer (higher maintenance cost during the post-warranty phase of the product life). It can lead to greater customer dissatisfaction, which in turn can affect sales and the overall business performance. This implies that reliability specification is very important in the overall product specification for new products.

In Stage I of the NPD process, one starts with the business objectives which define DP-I and then derive specifications at Levels I – III (SP-I, SP-II and SP-III) based on this. In Stage II, the actual performances at Levels III – I depend on SP-III and several other (development, production and customer related) factors.

In this section we focus on reliability specification and performance. Note that the strategic management policy decisions made by top management to arrive at the business objective are outside the scope of our work. As such, we do not consider that aspect here.

8.2 Literature Review

The literature on reliability specifications in NPD is rather limited and we review this briefly.

8.2.1 Selecting the Desired Reliability Performance

Kohoutek (1996) discusses the product reliability, in the context of new product development, in terms of desired reliability performance and we discuss this first. According to him, mature companies establish goals (objectives) on different levels:

1. Company level
2. Product family level
3. Individual product level

The reliability goals on the different levels have different driving forces and take different form as shown in Table 8-1.

Table 8-1: Driving forces for reliability goals on different levels (adapted from Kohoutek, 1996).

Reliability goal type	**Driving forces**	**Forms**
Company level	• Market demands • Competitive pressure • Business economics	• Reliability policy statement • Goals for companywide improvement program • Goals for the reliability engineering function
Product family	• Product price erosion • Technology progress • Regulations and standards	• Design requirements • Reliability growth maps
Individual products	• Customer requirements • Competitive product's reliability • Cost of reliability • Reliability assurance technology	• Direct: - MTTF, MTBF, failure rate or - Warranty cost limits • Indirect: - Testability requirements - Required production reliability screening - Environmental ruggedness specifications

The ideal goal setting process starts with company level goals from which product family level goals are deduced and from these follow the individual product level goals. This process insures that the company product policy guides the development of new products.

Kohoutek outlines several approaches to establishing the desired reliability performance from a manufacturer's point of view, as indicated below:

1. **Arbitrary Goals:** These can be either qualitative or quantitative, as for example
   - (i) Failure rate less than 0.1 per year over the warranty period,
   - (ii) Expected warranty cost less than 0.5% of the sale price, or
   - (iii) Mean time to repair less than 3 hours
2. **Goals Based on Market Sensitivity Assessment:** Goals of this type are based on fairly vague in-house opinion with regard to market sensitivity to certain reliability-related issues. This vague opinion is translated into

measurable quantities by defining different levels of "discomfort" to the business. As an example, every second item failing within the first six months might be deemed as being a "major disaster" whereas one in five hundred items sold causing minor trouble would be "ideal". These two would form the extremes on the "discomfort" axis, with one or more intermediate levels of discomfort — e.g., "difficult" might correspond to profits (sale price - manufacturing cost - warranty servicing cost) being 5% of the sale price.

3. **End Product and Company Requirements:** Goals of this type deal with long-term reliability goals and warranty performance of the end product. This involves warranty trend analysis and the linkage of the reliability goal to the end product requirements. For example, the current warranty cost may be 5% of the sale price and the reliability goal in the long term is to reduce this to 3% in two years, and to less than 1% in five years.
4. **Goals Based on Past Performance:** This is appropriate when a new product that does essentially the same function, but involves new technology replaces an existing product. The reliability goals are set to achieve a higher reliability based on the benefits of the new technology. As an example, reducing the expected failure rate in the first twelve months from 5 to 3 percent.
5. **Goals Based on Reliability Cost Optimization:** The total cost of manufacturing a product is the sum of the following three costs — cost of reliability design (a function of the number of cycles needed for achieving the desired reliability), cost of reliability production (fixed and variable costs of controlling reliability during manufacturing) and warranty cost (which depends on the environment and usage intensity). The reliability goal is selected to minimize this total cost.

The approach by Kohoutek is informative in a general sense, but does not provide any guidance on how to actually arrive at these goals, and in turn how to handle the reliability goals as the NPD project progresses.

Other sources, such as Priest (1988) and O'Connor (1995), briefly discuss reliability goal setting, but also in a very qualitative sense. This also applies for IEC 60300-3-4 (1996) that describes the process of identifying reliability goals, and the concerns that must be addressed in order to arrive at realistic goals. Examples of reliability goals are also provided.

Note that qualitative performance measures may also be part of the specification. These may be expressed in terms of design criteria for the product, for example (IEC 60300-3-4) as;

- single fault criterion, i.e., the product has to be such that no single fault can lead to a critical state of the product;
- accumulating fault criterion, i.e., the product has to be such that no undetected fault, when combined with additional faults, can cause system failure;
- path separation, i.e., redundant subsystems have to be kept independent by using separate paths for cables, pipes etc., for signalling channels, power supply and other supporting supplies;
- monitoring of critical functions, i.e., provision has to be made for automatic or manual checking of critical functions either continuously or at intervals, in order to maintain a specified level of reliability performance.

Virtanen and Hagmark (2003) discuss reliability design. They focus on the reliability allocation carried out in Levels II and III of Stage I. They present a simulation-based approach to allocation.

8.2.2 Reliability Specification Document

A reliability specification document, in addition to defining the desired reliability performance, must also deal with factors influencing the reliability performance (see, e.g., IEC 60300-3-4):

1. How the product will be installed and used.

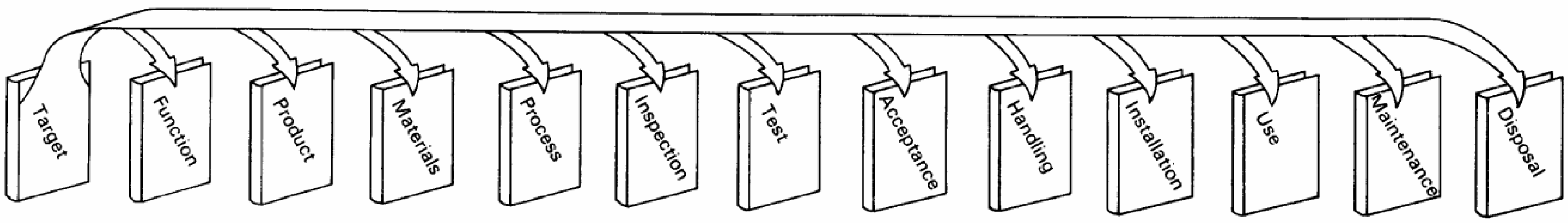
2. Definition of failure, i.e., what constitutes a failure in the particular product.
3. Obligations and responsibilities of customer, supplier and any third parties.
4. The various operating and environmental conditions under which the product will be used.
5. The qualifications and responsibilities of the personnel operating and maintaining the product.
6. Reliability improvement activities to be applied during design and development of the product (for example TAAF programs).
7. The maintenance policy and the associated procedures and support arrangements.

8.2.3 The Reliability Specification Process

BS 5760-4 provides a qualitative discussion on the reliability content of specification process in a broader context. The specifications process, shown in Figure 8-1, encompasses target specification at one end and specifications for tasks and activities such as handling, installation, maintenance at the other end. The first four specifications overlap with the specifications in Levels II and III of Stage I of our conceptual model. Liebesman (1988) proposes a different model (shown in Figure 8-2) for the reliability specification process and some of the elements overlap with Levels II and III of Stage I.

8.2.4 Conclusions

As can be see from the review of the literature on reliability specification, the discussion is broad and fairly general. The focus is on the reliability specification process. However, answers to central questions, such as how quantitative reliability specifications are established, and how they are applied to the NPD process in a structured manner, are not addressed effectively. In the remainder of the section we try to address this issue using the conceptual model for product specification developed in Section 6. The process described in the following is the same for both standard and custom-built products except for Phases 1 and 6. As such, for these two phases we consider the two cases separately.



Target specification	Function specification	Product specification	Materials specification	Process specification	Inspection specification	Test specification	Acceptance specification	Handling, storage and transport specification	Installation specification (Manual)	Use specification (Manual)	Maintenance specification (Manual)	Disposal specification (Notice)
Storage and use conditions Lifespan (durability) Reliability characteristics (Failure rate, MTBF*, etc) Maintainability and maintenance objectives Resistance to misuse	Limitation of the performance, ratings and characteristics to give a compromise between level of function and reliability objectives Definition of failure classes	Design features critical for the achievement of the reliability objectives and requirements	Choice of materials and components for compromise between production/construction, convenience and reliability objectives Storage of parts to avoid deterioration likely to induce failure	Assembly methods, treatments and procedures which minimize the introduction of failure mechanisms	Checks during assembly/construction and on completion of details critical for failure Use of FMECA† information	Endurance and environmental tests Accelerated tests FMECA† analysis Resistance to misuse The object is to protect the reliability objectives and requirements in the target specification	Inspection and conformity/reliability test data necessary for product acceptance, approval and certification	Procedures for packing and transportation to ensure that the conditions encountered by the equipment do not exceed those for which it is rated	Unpacking and installation procedures with lowest risk of introducing external causes of failure	Instructions for setting up, operating, using, controlling and adjusting the product which are consistent with the reliability objectives and give the lowest chance of misuse	Preventive and corrective maintenance procedures which give maximum availability consistent with reliability characteristics	

* Mean time before failure.

† Failure mode, effects and criticality analysis.

NOTE 1 This diagram does not call up design or management techniques to be used.

NOTE 2 See BS 4778 for definitions of these specifications.

Figure 8-1: The Reliability Content of Particular Specifications (BS 5760-4).

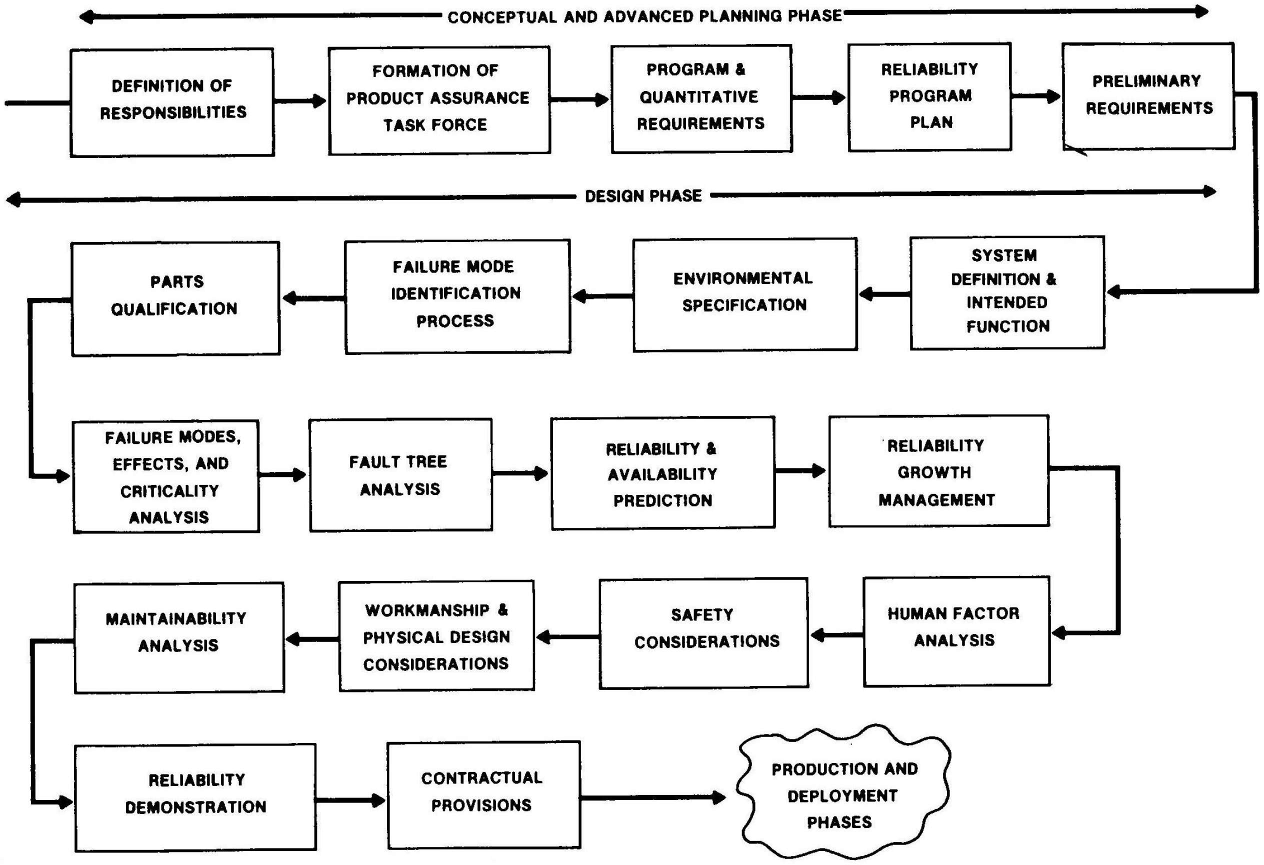


Figure 8-2: Reliability Specification Process (Liebesman, 1988)

8.3 Phase 1 [Stage I, Level I] [Standard Products]

This is the “Front End” phase and is concerned with establishing what the product to be developed should do for the business. It starts with the business objectives to be achieved through the new product. An evaluation of the implications (such as research and development needed, and acquisition of new technologies, investment for opening new markets) and the associated costs determine whether to proceed with the new product or not. If the decision is to proceed then one needs to execute the subsequent phases of the NPD process. Defining DP-I is the first step in this process.

Figure 8-3 illustrates the key elements that allow one to decide on SP-I given DP-I. In the remainder of the sub-section we discuss each of these elements.

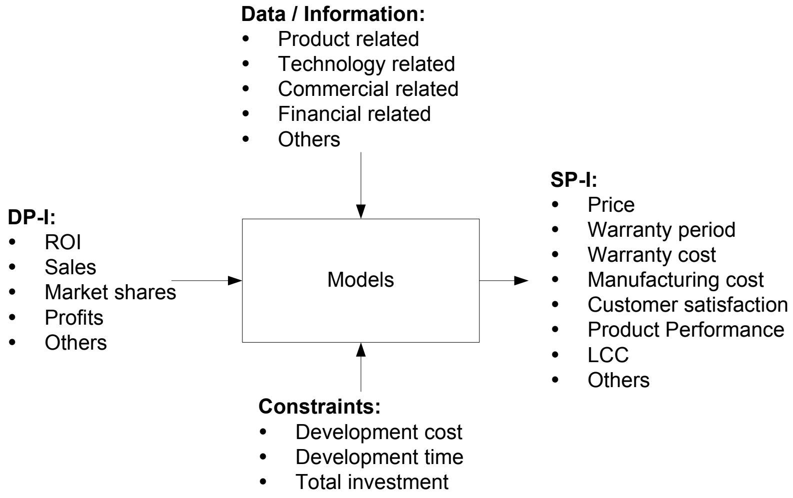


Figure 8-3: Product Specification at Phase 1.

8.3.1 DP-I

DP-I is stated in terms of what the new product should achieve in terms of its impact on the overall business performance. This can be defined in terms of one or more of the following statements:

- Return on Investment (ROI) > some specified value
- Total sales > some specified value
- Market share > some specified value
- Profits > some specified value
- Others

It is important that the statements be consistent and compatible. For example, achieving a certain level of sales might require that the price be low which can lead to profits below the specified level so that we have incompatible objectives.

Product performance and price have an impact on the market share. The left curve in Figure 8-4 represents combinations of performance and price that yield a 70% share of the market. Market share can be increased either by reducing the price for the same performance or increasing the performance for the same price. This implies that the curve needs to move to the right to achieve a bigger market share as indicated in Figure 8-4.

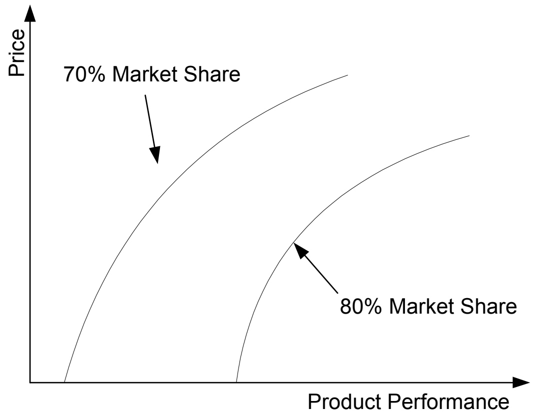


Figure 8-4: Product Price – Performance and Market Share.

8.3.2 SP-I

The stated DP-I, in general, can be achieved through several options with each option characterized by a unique SP-I. The enumeration of the different options is a creative process and many techniques, such as brain storming, are useful in assisting the process. Each option or SP-I describes the technological product, manufacturing, distribution and marketing principles that has the potential of meeting the stated DP-I.

One of the main drivers of any product development process is to make sufficient profit. The profit depends on sales, which in turn, is influenced by how attractive the manufacturer' product is, compared to the competitors' products, in terms of one or more of the following:

- Technical features,
- unit sales price,
- warranty period,
- operating costs,
- Life Cycle Cost, and
- others.

The costs to the manufacturer may be related to:

- Manufacturing costs,
- marketing costs,
- distribution costs,
- warranty costs, and
- others

Each potential SP-I can involve one or more of the above variables as indicated in Figure 8-3. The values assigned to each of the variables can be an interval, a minimum or maximum value, or an exact value.

The process of arriving at a potential SP-I involves tradeoffs and the resulting implications. Some of the issues that need consideration in this context are (e.g., Meyer and Utterback, 1997):

- Customers: Targeting new customer groups/markets is far more time consuming and costly than familiar customer groups, primarily due to the difficulty of learning new customer demands and of building new relationships with external distribution firms.
- Competitors: The intensity of competition has implications for the manufacturer's maximum unit sales price, the product technology to be chosen as well as the warranty period, since the product performance must appear attractive to potential customers, such that desired total sales or the desired profit may be met.
- Marketing: The manner in which the product will need to be marketed to reach, and attract, the desired customer groups has cost implications, but is a necessary consideration in order to meet the total sales demands.

- Technology: Unfamiliar and/or new technology is more expensive and time consuming to develop than familiar technology. New technology may require in-house development or technology acquisition. In-house development has implications for the R&D needed, and thus directly influences time and cost. The number of different core technologies that need to be integrated into the product also influence time and cost significantly.

The process of arriving at a good balance between product attractiveness (a prerequisite for gaining the desired market shares and meeting the desired total sales volume) on the one hand, and total costs on the other, is an iterative decision-making process. Trade-offs must also be made between development time and cost, production cost and the product's economic performance in the market (as discussed in Section 6.5.2).

A potential SP-I under consideration needs to be tested to see whether it achieves the stated DP-I. This is done through the use of models which yield the predicted performance (PP-I) for a given SP-I. If the PP-I is not satisfactory (in terms of matching with DP-I) then one needs to look at alternate specifications (SP-I) as indicated in Figure 8-5.

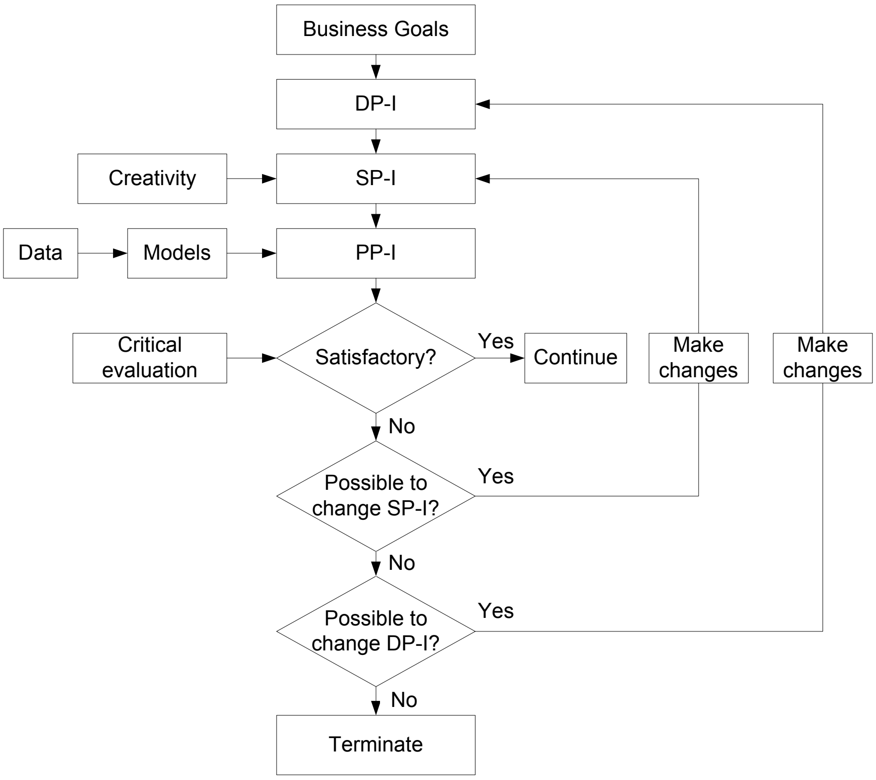


Figure 8-5: The relationship between DP-I, SP-I and PP-I.

Note that if none of the potential specifications under consideration yield the desired performance then one needs to revise the desired performance.

Example 1 [Continued]

A computer manufacturer wants to gain 50% of the home computer market and maintain an 8% ROI. This defines the manufacturer's DP-I. He then comes up with alternative approaches that may meet the desired business level performance, through the creative process shown in Figure 8-5:

- Option 1 based on the following potential SP-I:
  - Medium range performance in terms of processors, RAM etc.
  - Use earlier generation technology
  - Three years warranty to all home computer customers
  - Warranty costs per unit < $20
  - Sale price < $1000
- Option 2 based on the following potential SP-I:
  - Use latest technology

  - One year warranty
  - Warranty costs per unit < \$40
  - Sale price < \$1500

For each of these two options the predicted business performance PP-I is determined based on models which take into account the technology and the market implications. If neither option is acceptable then either one or more new options need to be explored or DP-I needs to be altered – for example, increase the sales price or reduce the warranty period:

Two new options are the following:

- Option 3 based on the following SP-I:
  - Medium range performance in terms of processors, RAM etc.
  - Use earlier generation technology.
  - Three years warranty
  - Warranty costs per unit < \$20,
  - Sale price < \$1200 (rather than \$1000),
- Option 4 based on the following SP-I
  - Medium range performance in terms of processors, RAM etc.,
  - Use earlier generation technology,
  - Two (rather than three) years warranty
  - Warranty costs per unit < \$20,
  - Sale price < \$1000.

Again, the predicted performance for each of these two needs to be determined and compared with DP-I. If, say, Option 4 is satisfactory, then it becomes the input for Level II of Stage I. ■

Example 3 [Continued]
When establishing the desired performance of a specialized product such as an aircraft, the customer usually states the desired performance for the product. The manufacturer then needs to consider whether the customer's desired performance can be met ensuring acceptable returns to the manufacturer subject to time and cost constraints. This serves as the basis for the manufacturer to tender a bid. If successful,

it can lead to an iterative process between the customer and the manufacturer to come up with a new product solution that is acceptable for both parties. ■

8.3.3 Constraints

New product development involves various kinds of resources, such as manpower, and development facilities. They all impact on the total cost. As such, the stated DP-I must be achieved taking into account one or more of the following constraints:

- Development time
- Development cost
- Total costs (which includes technology acquisition cost, modification to existing operations etc)

Example 1 [Continued]

Typical constraints might be one or more of the following:

- Development time < 6 months
- Development cost < 2 million dollars ■

8.3.4 Models

Several different models are needed to obtain PP-I for a given SP-I. Some of the models are the following:

- Technology forecasting models for predicting future trends
- Development cost models as function of product performance
- Sales model as a function of product performance and price
- Economic models to predict economic conditions

The models allow one to

- Decide on the optimal choice if there are two or more SP-I which will achieve DP-I.
- Carry out sensitivity and risk analysis.

We shall pursue this further in Part II of the report.

8.3.5 Data / Information

The different kinds of data and information needed to build models can be grouped into the following four categories:

- **Product related**, such as product performance trends, and competitor's product performance.
- **Technology related**, such as changes in material, process, and support technologies.
- **Commercial related**, such as potential sales, competitors' products, market trends, consumption patterns, and customer needs.
- **Financial related**, such as development cost, total investment for the project, and R&D cost.

Comment: As can be seen product reliability does not appear implicitly in either DP-I or SP-I. This is to be expected as the front-end deals with decision-making at the business level. However, as will be indicated later on, reliability impacts on one or more of the variables of SP-I and DP-I.

8.4 Phase 1 [Stage I, Level I] [Custom-built Products]

Characteristics common to almost all custom-built products include the following:

1. Complex product
2. Clearly defined performance requirements from the buyer
3. Ability to evaluate performance during construction and in field
4. Requirement for design changes if field performance targets are not achieved
5. A contract between the buyer and the manufacturer
6. Cost to the buyer

Reliability, maintainability and supportability performance terms may include one or more of the following items:

1. A guaranteed mean time between failure (MBTF)
2. A guaranteed turnaround time (TAT) for repaired or replaced units

3. A supply of consignment spares for use by the buyer at no cost until the guaranteed MTBF is demonstrated
4. Accuracy of testability [Built in test (BIT)]
5. System mission availability (point availability or interval availability)

If the objective of the contract is only to ensure that the product performance meets some minimum level, then it is an assurance contract. In this case the aim of the improvement is to ensure that this is achieved. In contrast, in some cases the buyer is interested in encouraging the contractor to exceed the minimum level and as such the contract includes incentive features to achieve this. This is accomplished by tying the payment to the performance level achieved by the manufacturer.

In the case of standard products, the manufacturer makes all the decisions at Phase I. The buyer is not directly involved in the decision process. In contrast, in the case of custom built products, the buyer is actively involved in Phase I as well as later phases since the performance terms are usually negotiated by the two parties and the focus is on the total life cycle. As a result, the buyer has a strong input into product development and the nature of post-sale support needed subsequent to putting the product into operation.

Proposal and Contract: The buyer specifies performance requirements along with constraints (time, money etc). The manufacturer (contractor) evaluates the requirements and starts the negotiation process where changes are made to performance requirements and/or constraints. This can involve several iterations before both parties are satisfied and sign the contract. The process is indicated in Figure 8-6.

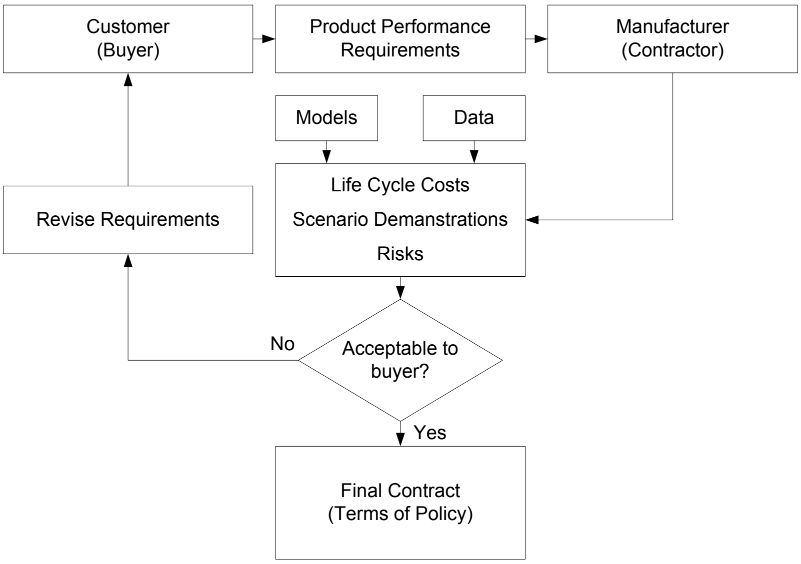


Figure 8-6: Bid Proposal and Contract

The contract needs to address the following issues. This indicates which of the characteristics discussed above are included. One or more of the following questions are addressed:

- Is it an assurance or incentive contract?
- What are buyer and contractor obligations?
- What issues are covered?
- What are the exclusions?

Product Performance: The performance of the product must be stated properly so that there is no scope for ambiguity. Reliability-related performance needs to include the time frame for data collection, the type of data to be collected, and the procedures to assess performance in terms of the data. In the case of MTBF, one must specify whether a point or interval estimate is to be used. Similarly, during development the contract needs to indicate the kind of testing to be carried out and how to translate the test data into assessing performance at component, sub-system or system level. If these are not done properly, it can lead to disputes and litigation at a later time.

Costs: There are several different types of costs involved. These include the following:

- Development cost
- Production cost

- Support cost (for spares etc)
- Warranty Costs

Risks: The contractor faces several kinds of risk. These include the following:

- Technical Risk: This results from not achieving the performance levels stated in the contract and, as a consequence, incurring a large penalty through high warranty costs and/or high cost of engineering design modifications
- Project Risk: This results from not delivering the product in time and/or cost overruns during development and production

Similarly, the buyer also faces the risk of the product not meeting the performance levels stated in the contract and/or the contractor not providing the necessary post-sale support etc.

These risks can be assessed through a proper scenario analysis where one looks at alternate scenarios and assess the probabilities of these occurring and the resulting consequences.

Dispute Resolution: In most cases the product, as well as the contract is complex. This implies that the contract might not address some issues that can lead to potential problems and disputes after the contract has been signed. Also, the interpretation of contract (for example, the testing conditions or operating environment) and other unverifiable factors (for example, the cause of failure being either due to operator error or design weakness) can lead to possible conflicts. As such, both parties (buyer and contractor) need to look at alternate dispute resolution mechanisms during Stage 1.

8.5 Phase 2 [Stage I, Level II]

In general there are several sub-phases. Let J denote the number of sub-phases. In each sub-phase we need to derive the specification in terms of the performance.

In the first sub-phase, the specifications SP-II_1 deal with product reliability at the system level as the product can be viewed as a system. The specifications at the subsequent sub-phases (2 through *J*) are concerned with reliability at lower levels (e.g., system → sub-system → assembly down to component and material levels).

8.5.1 Reliability Specification SP-II$_1$

Reliability has, among other factors, obvious implications for product price, warranty period, warranty costs, LCC, and other performance measures that would be stated in DP-II$_1$, as well as the constraints; development time and cost. Thus, the challenge is to develop a reliability specification, SP-II$_1$ that captures these implications. This requires

1) defining appropriate reliability notions for SP-II$_1$ (that achieve the reliability related desired performances stated in DP-II$_1$), and
2) quantifying the notions through assigning specific numeric values.

The reliability specification at the system level can be defined in terms of the failure distribution function $F(t)$, the density function $f(t)$, the reliability (survivor) function $S(t)$ or the hazard function $r(t)$.

A hazard function for most products has a bathtub shape as illustrated in Figure 8-7.

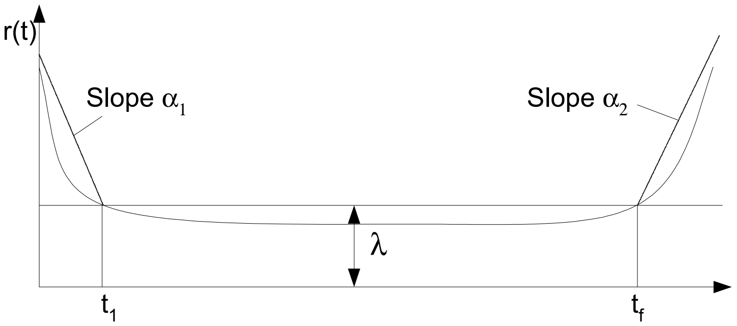


Figure 8-7: Bathtub Hazard Function.

This is characterised by a small set of parameters as indicated below.

- Useful life: $[t_f, t_1)$
- Burn-in period: $[0, t_1)$
- Failure rate over the useful life: λ
- Slope of hazard function during burn-in period: α_1.

- Slope of hazard function after useful life: α_2.

As such, the specification of the product reliability can be done in terms of these parameters or as functions of these parameters.

Figure 8-8 shows schematically the different elements involved in deriving SP-II$_1$ from DP-II$_1$ (= SP-I). It is important to note that SP-II$_1$ contains reliability and non-reliability components and we focus our attention only on the former.

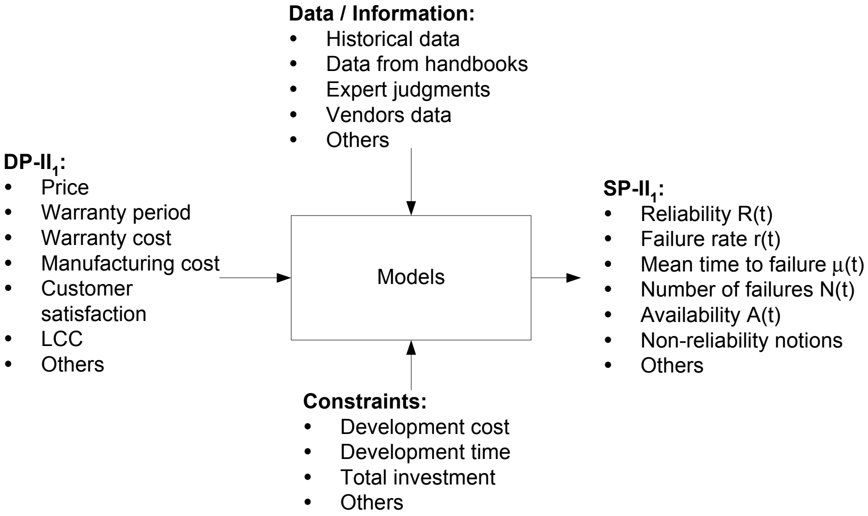


Figure 8-8: Determining Reliability Specifications SP-II1.

We first look at some of the reliability related variables of DP-II$_1$.

Customer satisfaction: This is usually difficult to quantify. Wang (1990) reports that customer expectations to car reliability may be stated in vague terms such as “last for a long time”, “starts every morning”, “a well-made car”, “no breakdown”, and so on. The reliability specification requires that these vague notions are translated into well defined reliability related measures as part of DP-II$_1$.

Warranty period and warranty cost: Warranty is an assurance to the customer that the manufacturer will repair all failures occurring over the warranty period at no cost to the customer. Warranty has been effectively used as promotional tool to market the product. However, offering warranty implies additional costs resulting from the servicing of failures over the warranty period. Warranty costs are usually stated as a fraction of the sale price.

Life Cycle Cost: This is the cost of operating and maintaining the product over its useful life. These costs are borne by the customer. The maintenance (preventive and corrective) costs are related to product reliability with the costs decreasing (in a statistical sense) as the product reliability increases.

The link between the reliability related performance variables and reliability specification is illustrated through the following statements:

- One notion of customer dissatisfaction is when the product fails very soon after purchase – e.g., within the interval $[0, t_e)$ subsequent to the purchase. The probability $F(t_e)$ denotes the probability that a customer will experience an early failure and also the average a fraction of the population that will experience such failures. DP-II$_1$ should specify an upper limit for the fraction of dissatisfied customers (p) and define the value for t_e. The reliability specification to achieve this would be given by the requirement - $F(t_e) \leq p$.
- Customer dissatisfaction is high should the product fail within a short period after the warranty expires. To ensure high customer satisfaction, DP-II$_1$ might specify an upper limit on the probability (p) of such a failure. This translates into a reliability specification involving conditional distribution function and given by the requirement - $F(W + t_e | W) < p$, where W is the warranty period.
- For non-repairable products sold with warranty, the manufacturer has to replace the failed component by a new one. As part of controlling the warranty costs, DP-II$_1$ might require that on the average less than a fraction q of the items sold fail within the warranty period. This translates into a reliability specification given by $S(W) \geq (1-q)$ where W is the warranty period.
- The warranty costs depend on the number of failures $N(W)$ (a random variable) over the warranty period. If DP-II$_1$ requires that the average warranty cost per unit must be less than a specified value δ then it translate into a

reliability specification requirement $C_r E[N(W)] \leq \delta$ where C_r is the average cost of each repair. $E[N(W)]$ is a function of $F(t)$ and the type of repair.

- If availability is a component of DP-II$_1$, then it depends on $F(t)$ and the repair time distribution function $G(t)$. In this case, the reliability specification is derived in terms of these two distribution functions and the desired availability.
- Failures of complex products are sometimes repaired through minimal repair. If DP-II$_1$ requires that on the average failure rate (expected number of failures per unit time) be less than ν, then it translates into a reliability specification requirement - $r(t) < \nu$ over the useful life of the product.
- The cost of operating and maintaining over the useful life of product is termed the Life Cycle Cost. The cost of maintenance can be related to equipment reliability and maintenance. This can be used to translate the performance requirements into a reliability and maintainability specifications for the product.

As seen from the above discussion there are many different reliability notions that capture the relationship between DP-II$_1$ and SP-II$_1$ and which ones are relevant varies from case to case. The popular approach to setting the desired reliability performance through a single number, such as Mean Time between Failure (MTBF) is inappropriate and has been criticized in the literature (see, e.g., Wang, 1990 and Moss, 1996).

Example 1 [Continued]

For Option 4, since the warranty cost must be less than \$20, this translates into a reliability specification given by $E[N(W)] \leq 20 / C_r$ where C_r is the average cost of each repair. ■

Maintainability

Issues that the manufacturer needs to consider are for example how to achieve the desired reliability performance. The manufacturer must find whether the desired reliability performance can be achieved with existing technology, alternatively by the development of new technology, within the desired timeframe of the project. In the former case, one way of achieving the reliability targets is through preventive maintenance but this would increase the cost of ownership to the customer. In the latter case, R&D is needed and this results in increased development costs. Reliability growth (see Part II, Section 5.3) models allow one to identify the effort and time needed to reach the desired targets.

The above two alternative strategies for ensuring desired reliability targets are illustrated in Figure 8-9.

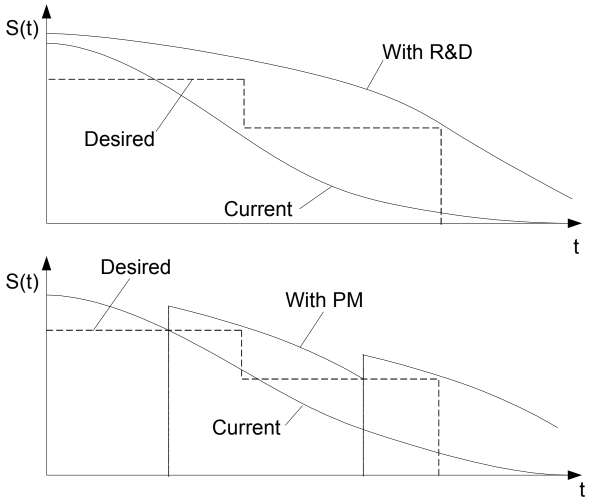


Figure 8-9: Reliability Assurance - R&D versus Maintainability.

Some Other Issues

Several other issues need consideration when establishing SP-II$_1$. These include the following:

- Variations in customer expectations.
- Variations in customers' usage/environment.
- Variations in production.
- Product's useful life.
- Project trade-offs.
- Project cost and feasibility.
- Project risk.
- Others.

Variations in expectations and usage/environment follow due to customer heterogeneity. The challenge is to come with a set of reliability specifications that achieves a specified level of customer satisfaction. This implies designing based on some nominal conditions for usage/environment and then determining the effect of variations on the level of dissatisfaction. This usually involves an iterative process.

The number (or fraction) of dissatisfied customers is critical to the manufacturer as it affects product sales. The different strategies to reduce this number are as follows:

1. Increase the level of desired product performance. This implies that the product is over designed for most customers.
2. Develop products with different performance levels to meet different needs. However, this increases the manufacturing complexity.

Variations in production depend on product design, production, and material. The material issue is resolved in Phase 3. The choice of process and its implication for product performance need to be taken into account in deciding on the specifications. A very stringent specification might result in a high defect rate. Often non-conforming products have a much shorter useful life. This implies that one needs proper quality control to ensure the desired product life.

Finally, there is always a small risk that the desired reliability performance might not be achieved within the given time, economic and technological constraints. The risk of project failure needs to be assessed and strategies devised to reduce the risk. Another risk is that the manufacturer might need to recall the product, either due to too high warranty costs, or due to excessive customer complaints.

Models (e.g., for warranty cost analysis, Life Cycle Cost analysis and customer dissatisfaction analysis), data and information (e.g., historical data, vendors data, expert judgements) needed to arrive at SP-II_1 are discussed in Part II.

8.5.2 Reliability SP-II_j ($2 \leq j \leq J$)

For the remaining sub-phases of Phase 2, the reliability specification process becomes a matter of deciding on the specifications at lower levels. Figure 8-10 shows the specification process at sub-phase j, $j = 2,3,....,J$. As a result, SP-II is a vector of $\{SP\text{-}II_i, i = 1,2,....,I\}$.

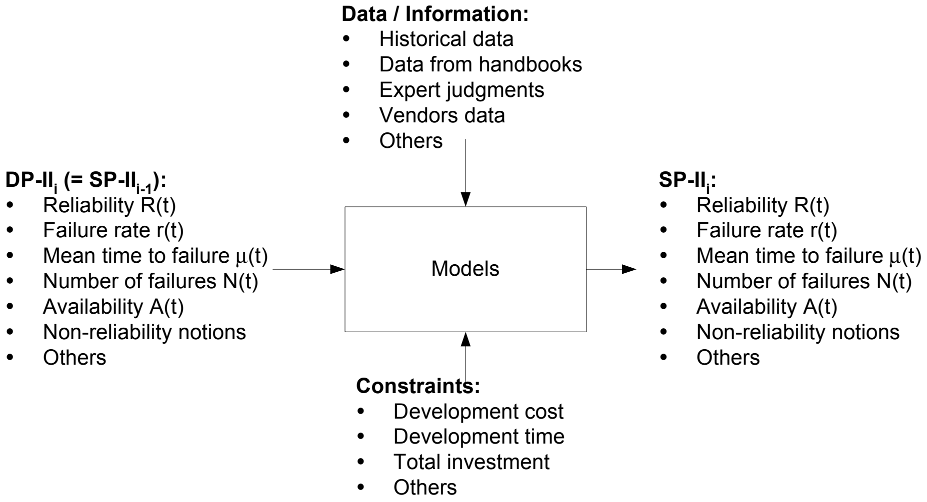


Figure 8-10: Sub-phase *j*.

The process of deciding on the specifications is very similar to that for $SP\text{-}II_1$. It is important to note that reliability measures appears in the input (specification from a higher level sub-phase) and also at the output (specification for the sub-phase under consideration).

Models (e.g., for reliability allocation and reliability growth), data and information (e.g., historical data, vendors data, expert judgements) needed to arrive at $SP\text{-}II_j$ are further discussed in Part II, Section 5.1.

8.6 Phase 3 [Stage I, Level III]

This phase can involve several sub-phases. The process for deciding on specification at each sub-phase is essentially similar to that for the later sub-phases of Phase 2. Hence, they are derived along the lines of Figure 8-9 and we do not discuss it any further.

Models (e.g., for reliability allocation and reliability growth), data and information (e.g., historical data, vendors data, expert judgements) needed to arrive at $SP\text{-}III_j$ are further discussed in Part II, Section 5.1.

There are three other issues that need to be addresses in this phase. They are as follows:

- Risk Analysis
- Final design review
- Planning the subsequent development effort

8.6.1 Risk Analysis

Once we have the final design specification we can carry out FMECA to do risk analysis. FMECA is further described in Part II, Section 5.4. The purpose of the risk analysis is to identify and treat unacceptable risks that the product may cause in terms of harm to humans, environment and/or material properties. Faber and Stewart (2003) provide a good overview of risk analysis, and illustrate an approach as illustrated Figure 8-11. Textbooks and standards on the subject present similar approaches.

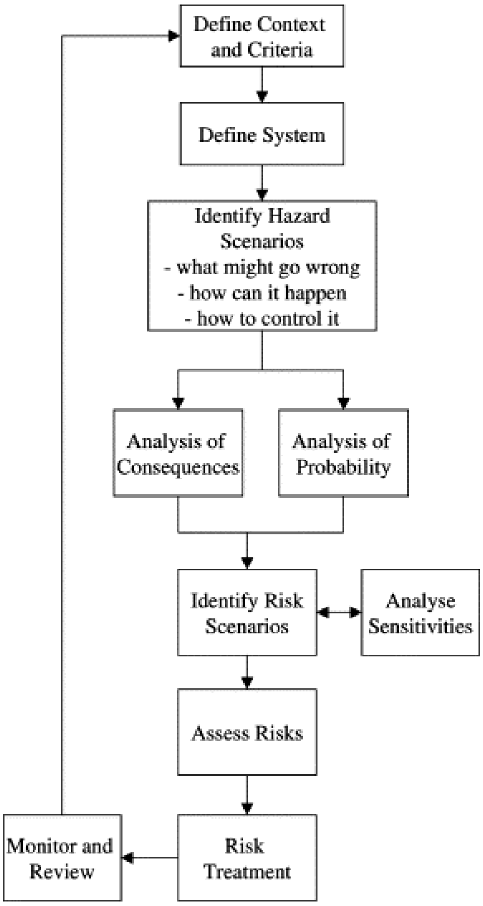


Figure 8-11: Generic Representation of the Flow of Risk-Based Decision Analysis (from Faber and Stewart, 2003).

8.6.2 Reliability Design Review

As the name implies, this is a review of the reliability of the final design to ensure that the desired reliability performance has been attained. Lloyd ad Lipow (1962) give a checklist for effective reliability design review. Two important checks in the context of a new product design are:

- What are the critical weaknesses? What provision has been made in the design so that modifications can be made at the earliest possible time if these and other weaknesses show up in testing?
- Has the product been designed as simply as possible? Have human factors been considered to prevent errors such as reversed wiring for an electronic product or mis-assembly for a mechanical product?

Critical for carrying out an effective reliability design review is knowledge of object reliability. This is obtained by development of a proper reliability and failure reporting system. IEC 61160 (1992) also provides guidance to the formal design review.

8.6.3 Planning the Subsequent Development Effort

Predictions in detail design also serve as a purpose of evaluating alternative solutions with respect to their ability to meet the desired reliability performance. However, the predictions made at this stage may also form the basis for planning types and extent of experiments carried out in the development phases. Predictions may indicate where, and how much growth effort is required, and it may be considered whether reliability growth of components may ensure the desired performance at all. These may also indicate where and how much research is required where current technology cannot attain the desired performance. With this information, the design of experiments may start, and the needed growth rate may be predicted, prior to the development phases. Growth models may be used to reveal how much testing is required to attain the desired performance.

8.7 Phases 4 and 5 [Stage II, Levels II and III]

In this stage the actual performance is assessed through testing. The test provides data which can either give the actual performance or can be used to predict the actual performance. This is compared with the desired performance and if not satisfactory, then one needs to iterate back to Stage I and make changes to specifications. Part II of the report discusses the tests and assessment of product performance.

8.8 Phase 6 [Stage II, Level I] [Standard Products]

If the NPD project has survived design and development, the production and marketing of the product may start. It is now that the actual business level performance may be measured in terms of profit to the manufacturer. The actual product performance may be compared to the desired business level performance defined in the Front-end. If the actual performance falls below the desired performance, the manufacturer may decide to 1) re-design the product (change the specifications), 2) improve quality control, or 3) terminate the project.

8.9 Phase 6 [Stage II, Level I] [Custom-built Products]

Although the predicted performance during design and development and during production tests may meet or exceed the stated performance measures, this does not guarantee that the desired performances are achieved during field operation. This is because of the limitations of models used prior to and during testing and of the data available from tests. As a result, the requirements are not met and the product fails in the field at a rate greater than anticipated in the context of reliability related performance. This implies that the contractor needs to initiate engineering design changes, as indicated in Figure 8-12.

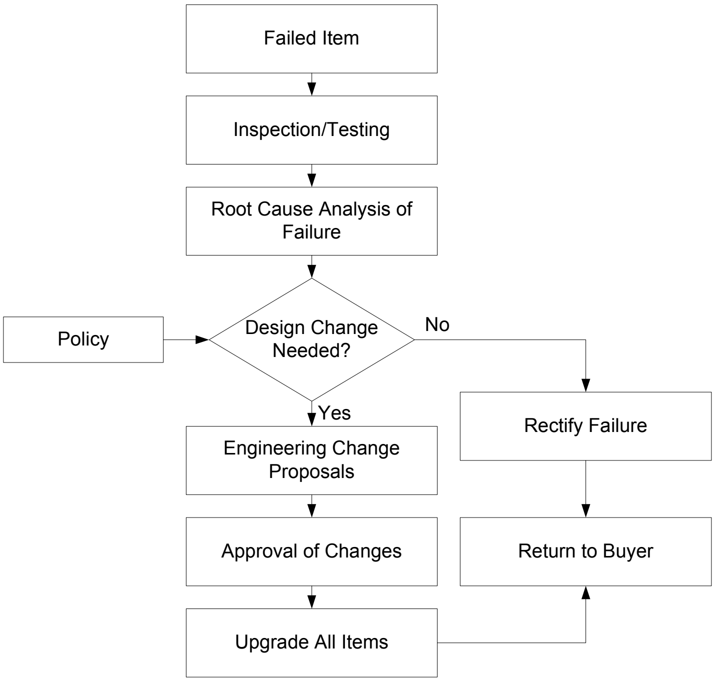


Figure 8-12: Engineering Design Change and Implementation

Whenever an item fails in the field, the first stage is to carry out inspection and testing. This is followed by a root causes analysis of the failure. Estimates of performance measures are updated and evaluated to determine whether any design changes are needed or not. If no design change is needed, then the contractor has to rectify the failed item (either through repair or replacement spare) as per the terms of the contract. If this is not done (for example, the TAT exceeds the specified value), then the manufacturer can incur a penalty depending on the terms of the contract.

However, if the root cause the analysis indicates a major potential problem or that the performance terms are not being met, then the contractor needs to provide the buyer with engineering change proposals that will overcome the problem and ensure that the performance levels are met. This involves a proper evaluation of the modified design and in some cases test data to prove the claims of the contractor. Once the buyer gives approval, the manufacturer needs to carry out changes on all the items delivered or being held as spares.

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Reliability Performance and Specifications in New Product Development

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Part II:

Tools and Techniques

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1 Introduction

Part I of the report looked at a concept for reliability specification and performance for a new product that will ensure the desired overall business objectives being achieved. It involves a two-stage process with three phases in each stage. In Stage I, the reliability specifications are derived in a sequential manner starting from the overall product level and proceeding through several sub-phases to the lowest level dealing with component or material. To assess the different specification options at each sub-phase and to determine the best specification requires building models that link specification to performance. In Stage II, the product is fabricated starting from the lowest level and proceeding up to the highest level. Here, the actual performance is assessed using data generated through various forms of testing. A proper design of experiments is essential to obtain maximum information for a given test effort and similarly, one needs a good understanding of statistical inference to assess reliability performance.

Part II of the report focuses on models, techniques for analysis and optimisation, together with various topics in statistical inference needed to execute the different phases in Stages I and II. We discuss the underlying concepts and some of the issues involved. A proper understanding of these is important for deciding on reliability performance and specification in the context of new product development.

The outline of Part II is as follows. Section 2 discusses the role of data and models in reliability specification and performance in new product development. Section 3 deals with models and modelling, and Section 4 with data collection issues in general. These are then discussed in a more specific context in the next two sections. Section 5 looks at the use of different tools and techniques in Stage I in the context of deciding on reliability targets. Section 6 presents the tools and techniques for assessing and predicting reliability based on test data and the related issues. Section 7 examines some organisational issues relevant in the context of reliability management. The report concludes with a template for evaluating current practices for reliability specification and reliability management in a manufacturing business and forms the starting point for case studies reported in Part III of the report.

The major part of the conceptual material is from Blischke and Murthy (2000) which is referred to as B&M in the remainder of the report. Another book that is cited extensively in Section 5 is Meeker and Escobar (1998) and is referred to as M&E. There are many specialised books that deal with specific topics in greater detail than the above two books and some of these are cited at the appropriate place. These references should form a good starting for any interested practitioners to get more details.

2 Role of Models and Data in New Product Development: An Overview

Many different types of models and data are needed for the implementation of the reliability specification process outlined in Section 8 of Part I. The models and data needed in Stage I are, in general, different from those needed in Stage II. The main activity in the different phases of Levels II and III of Stage I is deriving the specification SP_i from desired performance DP_i at Phase i. This involves the use of models to determine the predicted performance PP_i for a given SP_i and then comparing it with DP_i as shown in Figure 2-1. If PP_i does not meet DP_i, then one needs to iterate back as indicated in Figure 2-1. The models for reliability can be based on using the black, white or grey box approach. The required reliability can be achieved either through redundancy or maintainability that does not involve any R&D effort or through reliability growth involving R&D effort. The models for determining the reliability for each of these cases are different. Also, shown in Figure 2-1 are some of the data needed for building the needed models. The models and data needed in Stage I are discussed further in Section 5.

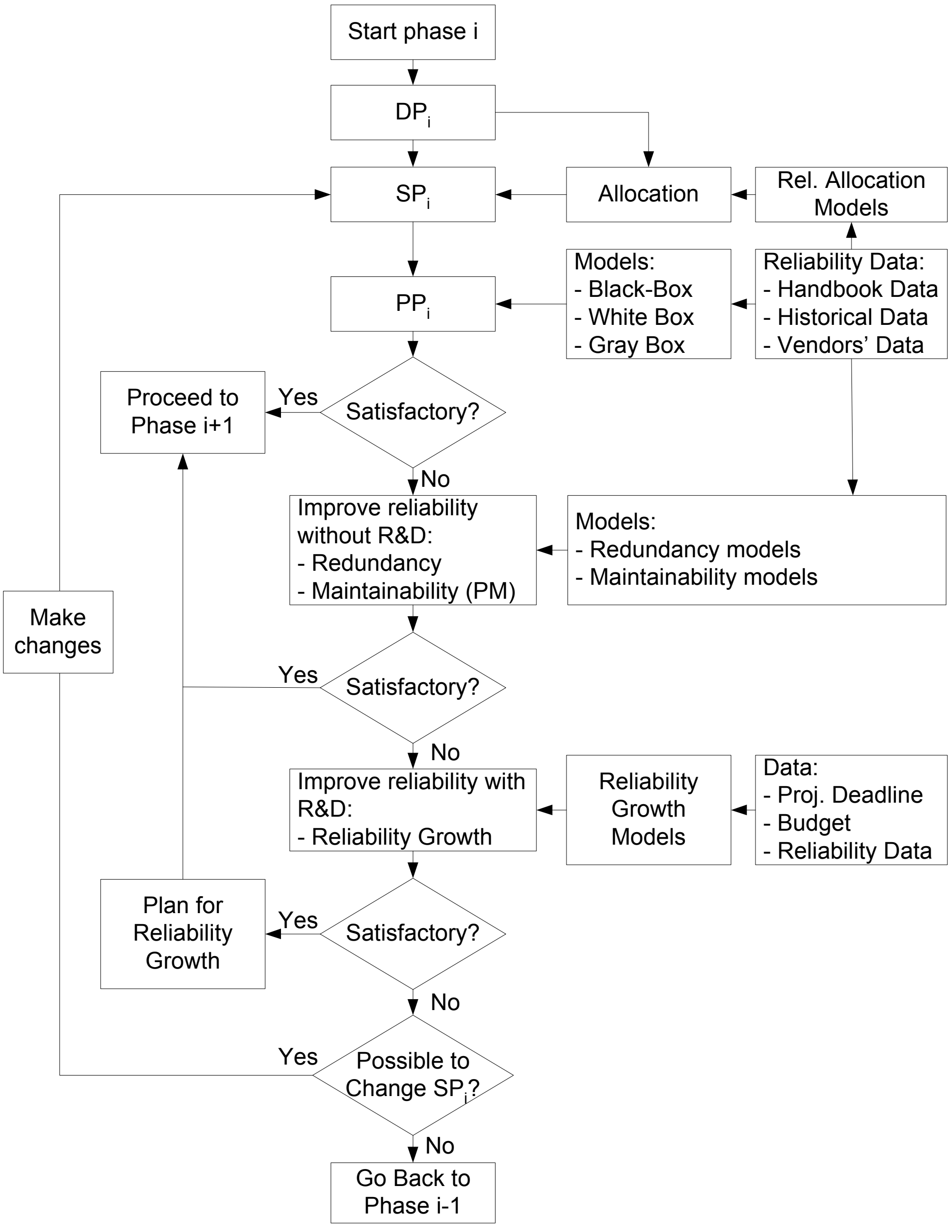

Figure 2-1: Activities of Stage I, Levels II and III

For Stage II $DP-III$ from Level III of Stage I is the starting point. Level III is concerned with component development. This is needed only if reliability improvement through R&D is the option selected at Level III of Stage I. At Level II, it is similar except that one is dealing with developments needed to ensure desired reliability at higher levels (sub-assembly, assembly through to sub-system and system). Figure 2-2 shows the activities involved during the development process.

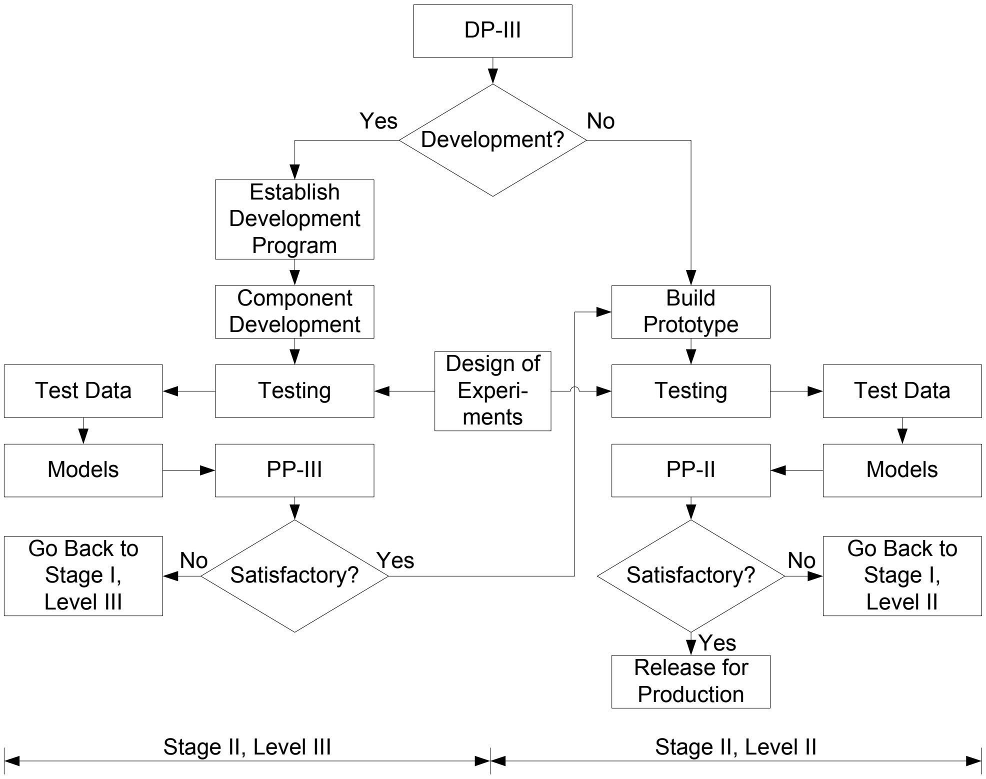

Figure 2-2: Activities for Stage II, Levels II and III.

Properly designed experiments are needed to ensure that the testing provides the data to obtain best estimates of parameters and other variables of interest. Different types of techniques are needed for checking the validity of the models used in Stage I and for predicting the actual reliability performance based on the data. If the models used are not appropriate, proper data analysis allows for making modifications to the models used in Stage I and as a result changes to specifications in Stage I.

The development proceeds through the phases of Level III and Level II and stops when the actual performance of the prototype built meets the desired performance. When this occurs, the final product designs are released for production.

3 Models, Model Building, Analysis and Optimisation

3.1 Models

Models are representations of the real world and play a vital role in solving a variety of problems. Problems can be classified in several different ways as indicated below.

1. Based on the phases in the Product Life Cycle: For example, the decision problem in the front-end phase to decide on whether to proceed to the next phase or not.
2. Based on the disciplines involved: For example, to understand better the failure mechanism of a metallic component under a specific environment (scientific problem), predict the limits of a design (engineering problem), predict total sales for a new product (marketing problem), predict total cost of development (economic problem), and so on.
3. Based on the nature of the problem: For example, analysis problem, design problem, synthesis problem, forecasting problem, optimization problem, and so on.

Reliability specification for new product involves decision making at all three levels of Stage I and assessing reliability at all three levels of Stage II. Models play an important role in decision making and for reliability assessment.

Models can be broadly grouped into two categories as indicated below.

1. Physical Models: These are physical entities such as a scaled model for testing in a laboratory, an analogue model (an electrical representation of a mechanical or pneumatic object), and so on.
2. Abstract Models: These are non-physical entities such as a descriptive model (involving some natural language), a figurative model (a schematic representation of a system in terms of its components), a mathematical model (involving an abstract mathematical formulation), and so on.

We confine our attention to mathematical models and call them simply as models in the remainder of this report.

Model Classification

Mathematical models can be classified into four different categories as indicated below based on the nature of the variables and the relationships in the underlying mathematical formulation.

	Static	Dynamic
Deterministic	I	II
Random	III	IV

Type I Model [Static and Deterministic]: The variables of the formulation do not change with time and the relationships between the variables are given by deterministic functions. An application of this is the modelling of stress-strain relationship for a mechanical component.

Type II Model [Dynamic and Deterministic]: One or more of the variables of the formulation change with time and the relationships between variables are given by deterministic functions. An application of this is the wear of a machine tool with usage.

Type III Model [Static and Random]: The variables of the formulation do not change with time but with one or more of them assume values that cannot be predicted exactly. In other words, some are random variables and need to be described probabilistically. As such, these models are referred to as probabilistic models. An application of this is modelling the strength of components where the strength varies from component to component due to variability in material properties, machining etc.

Type IV Model [Dynamic and Random]: One or more of the variables of the formulation change with time and in an uncertain manner. These are dynamic versions of Type III models and are referred to as stochastic models. An application of this is the degradation of the strength of a component over time.

The models needed for decision making in the context of product reliability are either Types III or IV models. This is because uncertainty is a significant factor that needs to be properly accounted for.

3.2 Model Building

Model building involves several steps as indicated below. The execution of each stage requires a good understanding of concepts and techniques from many disciplines.

Step 1: System Characterisation

This can be viewed as a process of simplification of the real world relevant to the problem. This is done through the identification of the different variables and the interactions between the variables. If the problem is to understand system failures, then the variables used are from the relevant engineering sciences; if the problem is to study the impact of reliability on sales, then one would use variables from the theory of marketing and economics and so forth.

Step 2: Model Selection

A mathematical model is obtained by linking the system characterisation to a suitable mathematical formulation. It is important to note that without the link, the mathematical formulation is abstract and makes no sense outside mathematics. By linking, the formulation is translated into a mathematical model.

For reliability related decision problems, most of the variables used in the system characterization are dynamic (changing with time) and probabilistic (with uncertain outcomes). Hence the mathematical formulations needed are obtained from statistics, probability theory and stochastic processes.

Step 3: Estimation of Model Parameters

Once a model has been formulated, one needs to assign numerical values to the various parameters of the model. This involves relevant data and again depends on the problem. For Types III and IV models, statistical methods need to be used for parameter estimation. This is further discussed in Section 5.

Step 4: Model Validation

It is important to ensure that the model is adequate for solving the problem under consideration. This is called model validation. A basic principle in validating a model is through an assessment of the predictive power of the model as it provides a basis for generalisation. Assessment of the predictive power of a model is basically a statistical problem for Types III and IV models and is discussed further in Section 5.

In general, obtaining an adequate model is an iterative process, wherein changes are made to the system characterization and/or the mathematical formulation during successive iterations.

Approaches to Model Building

The two different approaches to building mathematical models are as follows:

1) *Theory Based Modelling*: Here, the modelling is based on the established theories (from physical, biological and social sciences) relevant to the problem. This kind of model is also called *physics based model* or *white-box model* as the underlying mechanisms form the starting point for the model building.
2) *Empirical Modelling*: Here, the data available forms the basis for the model building and it does not require an understanding of the underlying mechanisms involved. As such, these models are used when there is insufficient understanding to use the first approach. This kind of model is also called *data dependent model* or *black-box model*.

Both these approaches are used extensively in the context of solving reliability related decision problems.

3.3 Model Analysis

Model analysis is needed usually to answer "what if?" type questions. This requires the ability to predict the effect of changes to one set of variables and/or parameters on another set of variables. Model analysis can vary from very simple to very involved depending on the type of model formulation and the complexity of the model. The three different approaches to model analysis are as follows.

1) *Analytical*: Here the results of the analysis can be expressed as an analytical expression of the variables and parameters that allows one to draw various inferences by looking at the form of the expression. Unfortunately, this is possible only for a very few model formulations.
2) *Computational*: This involves assigning numerical values to the model parameters and results are obtained as a set of numbers through numerical methods. As such, they provide less information than analytical solutions and the process needs to be repeated with different parameter values to get a good picture of the effects.
3) *Simulation*: Here one simulates the model on a computer so as to generate an outcome for a given situation. For the same set of parameter values, the outcome

would change from run to run in the case of Types III and IV models as the uncertain effects vary with each run. As a result, we have different time histories in the case of Type IV models and each history corresponding to a possible outcome. The analysis of the simulation results provides estimates of the desired results. The accuracy of the estimated results depends on the number of independent simulations -- the accuracy increasing with the number of runs.

3.4 Optimisation

Often decision making involves choosing the best decision among a set of decisions. This requires defining an objective function that forms the basis for the optimisation problem. The optimisation problems can be classified into four types based on whether (i) the objective function is scalar or vector and, (ii) the decision variables are static or dynamic. The time and effort needed to obtain the optimal solution depends on the type of optimisation problem and the model complexity (which depends on the number of variables of the formulation).

Another complicating factor is the constraints on the variables. They can be either equality or inequality constraint. Finally, the technique for optimisation is different for discrete and continuous variables. As a result, one needs to use computational techniques to obtain the optimal solutions.

Over the last few decades several heuristic techniques have been developed which in most cases yield near optimal solution with considerably less effort and time.

3.5 Further Reading

- There are a large number of books on mathematical modelling. Murthy, Page and Rodin (1990) list most of the books published prior to 1990.
- For a basic introduction to probability models, see Ross (1983) and to stochastic processes, see Ross (1996).

4 Data Classification and Sources

Model building requires appropriate data for (i) parameter estimation and (ii) model validation. They are also needed for evaluating the outcome of decisions and making periodic changes to the decisions as part of the overall management process. Data collection is a costly exercise and due care must be given to issues such as what to collect and how to collect.

4.1 Types of Data

Many different kinds of data are needed to build models for reliability related decision making at each of the six phases of product life cycle. The data can be broadly grouped into several different categories as indicated below.

Product Related Data

This includes the following:

1. Product Performance Data: These can be divided into (i) reliability related (such as failure times, and causes) and (ii) non-reliability related data.
2. Design Data: Design details.
3. Development Data: Various kinds of test data. The data can be at the system level or the component level. The hierarchy can be separated into as many levels as required – System, Sub-system, Component, Part, Material, and so on.

Technology Related Data

Manufacturing of products involves many different types of technologies. An interesting feature of technologies is that they are changing with time due to scientific advances and technology breakthroughs. Technology related data relevant to manufacturing of new products include the changes in the following technologies:

1. Material Technologies: Different kinds depending on the product
2. Process Technologies: Different kinds based on the product
3. Support Technologies: These are technologies to support the various operations (transportation of material, management of inventories, material flow etc)

The data can include historical trends, limits of technologies etc.

Scientific Data

Scientific data and information comprises of the following:

1. New understanding of physical phenomena
2. Empirical estimates of the parameters of scientific theories
3. Limits of scientific theories

Commercial Related Data

Commercial data comprises of the following:

1. Market Related: This includes, total sales over time, number of competitors etc
2. Competitor Related: Sales, price, promotion effort, market share etc of each of the competitor
3. Legislative: Various legislative laws relevant to the product. Examples include, warranty legislation, health standards (for products consumed by humans or animals) etc
4. Industry-wide Data: Trends over time

Customer Related Data

Customer related data can be at two different levels.

1. Industry Level: Consumption patterns over time, age profile, income distribution etc
2. Individual Customer Level: Needs, satisfaction with past products, usage mode and intensity, income, satisfaction and dissatisfaction

Financial Related Data

Financial data comprises of revenue data and cost data. The cost data is comprised of the following costs for past products:

1. Development cost
2. Production cost per unit
3. Life cycle costs
4. Warranty servicing costs

Cost data can be broadly divided into two categories -- as direct and indirect. Direct costs can be described as the cost of materials and labour that result in the final product, and indirect costs are those that are required to support the activities in the different phases of the product life cycle. For example, the cost of the metal, plastic, oil, components, technical labour, etc. that make up the product are direct costs; the cost to design the product, set up and maintain the production plant, perform administrative tasks, service, and market the product, and manage the entire process are indirect costs.

Intuitive Judgemental Data

When hard data are sparse or lacking altogether, it is not unusual to use "engineering judgment" in attempting to predict item characteristics, including reliability. Estimates of this type, based on quantified subjective or partially subjective information, enable the analyst to introduce engineering knowledge and experience into the reliability assessment process. This type of information may also form the basis of an important input element (the "prior distribution") to Bayesian analysis, which provides a method of incorporating this information with test data as it is obtained and using all of this information in refining and updating reliability predictions.

Reliability Perspective

From the reliability perspective, technical data encompasses data that affects the reliability of the product including material strengths, component specifications, system configurations, test data, environmental measurements, and production equipment specifications and records, repair times, failure times, failure modes and mechanisms, and operating conditions.

Commercial data includes data that has a marketing impact such as price and warranty terms, sales volume (demand), risk, and profits. Marketing data focuses on consumers (potential customers) while post-sale support deals with customers. It includes warranty terms and costs, customer complaints with respect to many different aspects of the product.

4.2 Sources of Data

There are several sources from which data needs to be collected. We discuss briefly some of these. In the process, we highlight some issues of relevance to managing product reliability.

Historical (Archival) Records

Historical records are generated from data obtained from the various business management systems when the product becomes obsolete and is replaced by a new one. The importance of this data in new product development is that a new product that has undergone major design change or is based on completely new designs often has some parts or even major components in common with earlier products. As such, data and information relating to earlier products obtained from historical (archival) records are of importance.

Business Management Systems

Businesses use many different kinds of management systems to manage the different activities. These, along with the kind of data they provide, are as follows:

- Accounting System: Cost data
- Project Management System: Product related data during development
- Production System: Product related data (for example, conformance to specification) during production
- Supply Management System: Material flow data
- Customer Support System: Customer related data

As mentioned earlier, data from such systems for earlier products create the historical records.

As a new product evolves through the different phases of the product life cycle, these systems collect data. Data collected in earlier phases are needed for building and revising models in later phases for effective decision making.

Scientific Journals and Conference Papers

These provide scientific data and information. There are several search engines and databases that make it easy to obtain the information.

Vendors

Vendor data includes components, materials, and/or sub-systems that are purchased from outside the manufacturing organisation. Test data from vendors can be obtained and verified by in-house testing, if necessary, and used the same way as historical data.

Tests

Several different kinds of tests are carried out during the development and production phases of the product life cycle.

Test data allows performance to be quantified and reliability to be estimated. Experiments should ideally be designed and carried out under controlled conditions so that the information obtained is meaningful. If the product is complex and expensive, testing may be required at several levels: material, component, and system. For simple products, it may be adequate to test only the completed product. As the complexity of the product increases, so do the data and analysis required for aggregation of meaningful information.

Random samples are often taken when inspecting items from the production line. The data are used to estimate production quality and other metrics of interest.

Environmental data includes temperatures, stresses, etc. that are encountered during tests or during operational life (if recorded). These variables can be used to evaluate the effect of different environments on product performance in field.

Scientific and Technical Handbooks

Handbook data includes specifications and calculations obtained from technical publications. Data of this type may typically include labour costs in certain regions, formulae for various technical relationships, market indices for commodities, and so on.

In theoretical assessments of reliability, for example at the part level, physical failure models are sometimes used. The models typically require inputs such as geometrical configurations, materials and their properties, environments in which the item will be operated, and measures of variability in all of these variables. Much of this information can be obtained from standard engineering, physics and chemistry handbooks.

Experts

Experts are the source for the intuitive judgemental data. They can be either in-house or external consultants.

Market Surveys

Market surveys are carried out to obtain commercial and customer related data. Rarely does one have access to an entire population or the resources to seek the response of every individual. A Simple Random Sample (SRS) is a sample selected in such a way that every sample of size n drawn from a population of size N is equally likely to be selected. This is done by use of a computer program or a random number table. Another issue is the type of questionnaire used as it can have a significant impact on customer response.

Warranty Servicing and Field Support

Warranty service and field support (such as spares used) data provide valuable information regarding product performance in field. If the data is collected properly, it also provides useful customer related information such as usage mode and intensity, customer satisfaction and needs.

Customer Feedback

Customer feedback information is a valuable data source and can provide product related and customer related information.

Consumer Reports and Magazines

Consumer groups carry out different kinds of tests on similar products and customer surveys. The findings of their study are usually reported in magazines or reports and constitute a valuable source for relative comparison between different products.

4.3 Scales for Data Measurement

There are four scales for measurement and they are as follows: (i) nominal (for example, ranking businesses in terms of annual sales), (ii) ordinal (for example, customer satisfaction data based on a 1 – 5 scale), (iii) interval (for example, temperature at which a plastic component melts) and, (iv) ratio (for example, lifetime of component). These increase in order of complexity (meaning, basically, information content) and, correspondingly, in the number and types of arithmetic operations that can meaningfully be applied to the data. Nominal and ordinal data are inherently qualitative in nature, representing item attributes; interval and ratio data are inherently quantitative, representing amounts rather than types. In practice, numerical values are used for data on all four scales (especially in computer files). The important differences are in how the numerical values are interpreted and what can legitimately be done with the data.

4.4 Failure Data

Failure data is very important for reliability modelling. Failure data (at component, system or any other intermediate level) may be classified as (i) complete and (ii) censored (or incomplete). The latter can be further sub-divided into different categories. In this section we discuss briefly both these types of data.

Let $T_1, T_2, \ldots, T_n$ denote a sample of *n* independent random variables from a distribution function $F(t, \theta)$, where $\theta = (\theta_1, \ldots \theta_k)$ is a *k*-dimensional parameter. (These correspond to the life times for *n* different items in the reliability context.) Let $t_1, t_2, \ldots, t_n$ denote the actual realised values of the T_i's.

4.4.1 Complete Data

The data set available for estimation is the set $\{t_1, t_2, \ldots, t_n\}$. In other words, the actual realised values are known for each observation in the data set.

4.4.2 Censored Data

In this case the actual realised values for some or all of the variables are not known and this depends on the kind of censoring. There are many different kinds of censoring. These include

- Right, left or interval censoring
- Type I or Type II censoring
- Single or multiply censoring

In reliability context, the following types of censored data are of particular interest.

Right Type I Censoring

Let υ denote a variable (deterministic or random). Under Type I right censoring the data available for estimation is as follows: For item *i*, the actual realised value of T_i is known only if $t_i \leq \upsilon$. When $t_i > \upsilon$ the only information available is that $T_i > \upsilon$.

Right Type II Censoring

Let *r* denote a predetermined number such that $r < n$. Under Type II right censoring the data available for estimation is given by t_i (the actual realised value of T_i) for *r* data and that $T_i > t_{\max}$ for the remaining $(n - r)$ data where $t_{\max}$ is the maximum of the *r* observed t_i's.

Random Censoring

Types I and II censoring are special cases of random censoring. The general formulation of random censoring is as follows. Let s_i be a random variable independent of T_i. The observed value is the given by $\min\{t_i, s_i\}$ so that it is censored if $t_i > s_i$.

Grouped Data [Interval Censoring]

Grouped data are data that have been categorized into classes (usually non-overlapping intervals), with only class frequencies known. As a result, in this case one only knows that t_i is in some interval but its actual value is unknown.

4.5 Further Reading

- B&M (Chapters 2 and 3), M&E (Chapters 1 and 2).

- Most statistical books on reliability discuss this topic in great depth. See, for example, Lawless (1982), Nelson (1982), Crowder et al (1991), Bain and Englehardt (1991) and Kalbfleisch and Prentice (1980).
- Books dealing with reliability data include Cannon and Bendell (1991) and Flamm and Luisi (1992)

5 Tools and Techniques for Stage I

In Stage I, the specifications at a sub-phase are derived from performance targets obtained from the earlier sub-phase. This process involves the use of reliability models (starting from system level down to the lowest component level) and many other kinds of models (for example, reliability growth). In addition, it involves a variety of techniques (for example, reliability allocation). In this section we discuss these issues.

5.1 Reliability Modelling

5.1.1 Component Level

At the component level, a good understanding of the different mechanisms of failure at work will allow building a physics-based model. In contrast, when no such understanding exists, one might need to model the failures based solely on failure (and possibly censored) data. In this case the modelling is empirical or data driven. These are the two extreme situations and referred to as the "white-box" and "black-box" approaches to modelling. In between, we have different degrees of understanding or information. For example if it recognised that there is more than one mode of failure, then the modelling needs to take this into account. In this case, we have a "grey box" approach to modelling.

We need to differentiate between first and subsequent failures. The latter depend on whether the component is repairable or not and the type of repair action in case it is repairable. Also, the failure depends on other factors such as the usage environment, mode and intensity.

Black Box Approach

Here the component is characterised as being in one of two states -- working or failed. The component is in working state to start with and fails after a certain length of time (called the time to first failure) which is uncertain. As a result, it needs to be modelled by a distribution function as discussed in Part I of the report.

The model selection is based on the analysis of the data (failure and censored) available for modelling. Many different graphical plots have been developed to assist in the model selection. WPP (Weibull probability paper) plot is one plot which is useful for deciding if one or more of the Weibull models are suitable for modelling a given data set.

White Box Approach

The failure of a component occurs due to a complex set of interactions between the material properties and other physical properties of the part and the stresses that act on the part. The process through which these interact and lead to a component failure can be complex.

One can divide the mechanisms of failure into two broad categories -- (i) overstress mechanisms and (ii) wear-out mechanisms. In the former case, the component fails only if the stress to which the item is subjected exceeds the strength of the item. If the stress is below the strength, the stress has no permanent effect on the item. In the latter case, however, the stress causes damage (e.g., crack length) that usually accumulates irreversibly. The accumulated damage does not disappear when the stress is removed, although sometimes annealing is possible. The cumulative damage does not cause any performance degradation as long as is it below the endurance limit. Once this limit is reached, the item fails. The effects of stresses are influenced by several factors -- geometry of the part, constitutive and damage properties of the materials, manufacturing and operational environment.

The different failure mechanisms under each of these two groups are as follows:

(i) Overstress Failures

These include brittle fracture, ductile fracture, yield, buckling, large elastic deformation and interfacial de-adhesion

The modelling of over stress failure is done as follows. The strength of the component degrades with time so that is non-increasing. The stress on the component changes with time in an uncertain manner (e.g., the stress on a tall structure resulting induced by wind or stress on the legs of an offshore platform due to waves). The time to failure is the first time instant the strength falls below stress.

(ii) Wear-out Failures:
These include wear, corrosion, dendritic growth, interdiffusion, fatigue crack propagation, diffusion, radiation, fatigue crack initiation and creep

The modelling of wear-out failure is done through a variable that either increases (for example, crack length) or decreases (for example, thickness of pipe) with time in an uncertain manner and failure occurs when it crosses some threshold level.

Grey Box Approach

The black-box approach and the white box approach can be viewed as the two extremes in modelling. In the black box approach we have no information (or understanding) regarding the mechanism of failure and the modelling is based solely on the failure (and censored) data. In contrast, in the white box approach we have complete understanding of the underlying failure mechanisms. Grey box approach can be viewed as something in between the two extremes. Here we incorporate other relevant information in the selection of an appropriate model formulation to model failure.

The kind of extra information that can be used in modelling can vary. We briefly discuss some scenarios to indicate this.

1) If there are several modes of failure at work then one might choose a competing risk model to model the data.
2) Often there is wide variability in manufacturing of components. In this case, one might choose a mixture model to model the data.
3) Suppose that the components used are bought from different suppliers. If the failure data does not include the manufacturer for each component, then the components need to be treated as the pooling of all the components. In this case, the mixture model is again appropriate to model the data.
4) For consumer durables (such as cars, washing machines etc) the usage mode and environment can vary significantly across the consuming population. In

this case, the modelling of failures under warranty must need to take this into account. In this case, models with random parameters are more appropriate to model failures.

5) Finally, sectional models might be appropriate if the degradation mechanism changes after a certain age.

Effect of Environmental Factors

The time to failure for a component is affected by the level of stress on the component. Stress is defined in the broad sense — it could be temperature, voltage, force, and so forth, depending on the item. The effect of increasing stress is to accelerate the deterioration and reduce the time to failure.

Several different approaches to modelling have been proposed. These include accelerated failure models (based on some scaling relationship between failure times at two different stress levels) and the proportional hazard model. The proportional hazard model comprises of a baseline failure rate which is dependent only on time and a multiplicative factor which is independent of time but incorporates the effects of the different factors (called covariates) which affect item failure.

5.1.2 System Level

Here again there are two approaches.

Black Box Approach

The failure of a system is often due to the failure of one or more of its components. At each system failure, the number of failed components that must be restored back to their working state is usually small relative to the total number of components in the system. The system is made operational by either repairing or replacing these failed components. If the time to restore the failed system to its operational state is very small relative to the mean time between failures, then it can effectively be ignored. For practical purposes, this situation is equivalent to minimal repair and system failures can be modelled as follows.

The system failures are modelled by a point process formulation with a cumulative intensity function which is an increasing function of time, reflecting the effect of age.

In general, it is necessary to specify a form for the intensity function and estimate its parameters using failure data.

Systems often undergo a major overhaul (a preventive maintenance action) or a major repair (due to a major failure) which alters the failure rate of the system significantly. The failure rate after such an action is smaller than the failure rate just before failure or overhaul. In the case of an automobile, this would correspond to actions such as the reconditioning of the engine, a new coat of paint, and so on. The time instants at which these actions are carried out can be either deterministic (as in the case of preventive maintenance based on age) or random (as, for example, in the case of a major repair subsequent to an accident).

White Box approach

In the white-box approach, system failure is modelled in terms of the failures of the components of the system. The linking of component failures to system failures can be done using two different approaches. The first is called the **forward** (or bottom-up) approach and the second is called the **backward** (top-down) approach.

In the forward approach, one starts with failure events at the part level and then proceeds forward to the system level to evaluate the consequences of such failures on system performance. *Failure mode and effects analysis* (FMEA) uses this approach. In the backward approach, one starts at the system level and then proceeds downward to the part level to link system performance to failures at the part level. *Fault tree analysis* (FTA) uses this approach.

Instead of the fault tree, one can use a network representation to model the links between different components and the system failure is obtained in terms of component failures based on the linking between components. In either case, the state of the system (a binary valued variable) can be expressed in terms of the component states (each of which is also binary valued) through the structure function.

5.1.3 Data for Reliability Modelling

The usefulness of data from the various sources listed in the previous section for reliability modelling (system component or some intermediate level) depends on the relevance of the data to the problem at hand and on the reliability and validity of the data. Data relevance will depend on the phase of the product life cycle and on the types of models being employed.

Reliability does not appear explicitly in Phase 1 and hence reliability modelling is relevant only for Phases 2 onwards.

In early stages of design considerable use may be made of data from other sources. Historical data, from previous testing of parts or components, either in house or by vendors, can be highly relevant if the same parts are being used in a new product; less so if it is a "similar" part. Handbook data are most often information of a more basic type, e.g., materials properties such as strength as a function of temperature for different alloys, conductivity and other electrical properties, and so forth. Information of this type is generally accepted as valid. Models that employ such data are usually quite complex, involving modelling of stresses at the part level along with environmental and other factors, and requiring computer simulation for evaluation of reliability.

Extra caution must be exercised in using some types of data, particularly those having a subjective component and those over which the analyst has little or no control. This is true of vendor data, where complete information concerning the test procedure should be requested along with the data and analysis. It is certainly true of engineering judgment, which is always at least partially subjective. In order for information of this type to be useful in modelling, it is necessary to quantify it. An approach to accomplishing this is provided by Bayesian approach. This is discussed in Section 5.

5.1.4 Further Reading

- B&M (Chapters 4, 6, 7 and 11), M&E (Chapters 4 and 5).
- Most statistical books on reliability discuss this topic. See for example, Bain (1978) and Bain and Englehardt (1991).

5.2 Reliability Allocation

Once the overall reliability goals for a system are specified, these must be translated into reliability goals for the sub-systems, lower level assemblies, etc., down to the part level. How this is done depends on the design of the system, but it must be done in a manner that ensures design feasibility and is consistent with current technology. In addition, the allocation must be done in such a way that other constraints are not violated. The process of determining subsystem and component reliability goals based on the system reliability goal is called reliability allocation or reliability apportionment. In a sense, this is the reverse of what was done in the previous section, where we obtained system reliability in terms of the reliabilities of its subsystems and components.

5.2.1 Further Reading

- B&M (Chapter 13).
- For further discussion, see Tillman et al (1980)

5.3 Reliability Improvement

When the reliability of the system during the design phase of the product life cycle is below the target value, it is unacceptable and must be improved. There are two basic approaches to improving system reliability, which are

(i)_Use of Redundancy: This involves the use of replicates rather than a single unit. The replication can be carried out at any level ranging from the system level to the part level.
(ii) Maintainability: Preventive maintenance may, for example, be used as an approach to improving reliability at any level.
(ii) Reliability Growth: Here the reliability of a unit (at the assembly or sub-assembly level) is improved through a development process that involves test-fix cycles.
Note: The two first approaches to reliability improvement utilize existing technology, whereas the latter aims at developing new or improving existing technology.

5.3.1 Redundancy

Redundancy is a technique whereby one or more of the components of a system are replicated in order to improve the reliability of the system. Redundancy can only be used when the functional design of the system allows for the incorporation of replicated components. It is used extensively in electronic systems to achieve high reliability when individual components have unacceptably low reliability.

Building in redundancy corresponds to using a module consisting of M replications of a component. The manner in which these replicates are put to use depends on the type of redundancy. A module failure occurs only when some or all of the replicates fail. The decision regarding the use of redundancy always involves a trade-off. Improved reliability is achieved at the cost of designing and manufacturing the system with multiple components, plus the additional operational expense involved. In space systems, for example, this expense can be considerable because of the launch costs due to the extra weight resulting from redundancy, but the added reliability may be well worth the added cost.

Many different types of redundancies are used in practice. The two main types are:

1. Active [Hot Standby]
2. Passive [Warm and Cold Standby]

In active redundancy, all M components of the module are in their operational state, or "fully energised," when put into use. In contrast, in passive redundancy, only one component is in its fully energised state and the remaining components are either partially energised (in the case of warm standby) or kept in reserve and energised when put into use (in the case of cold standby). When the fully energised component fails, it is replaced by one of the partially energised components in the case of warm standby (or by a component from the reserve in the case of cold standby) provided that not all of the components in the module have failed. If all components in the module have failed, then the module has failed. The replacement occurs through a switching mechanism.

Redundancy can be either at the system level or at a lower level (e.g., assembly, sub-assembly or component level). For component level redundancy, in general, the replicates are statistically similar, but in certain situations they can be different, as well.

5.3.2 Maintainability

Maintainability for a system or an item has been defined in several ways, namely

1. “A characteristic of design and installation which is expressed as the probability that the item will be retained in or restored to a specified condition within a given time period, when maintenance is performed in accordance with prescribed procedures and resources.” [MIL-STD-721]
2. “A system effectiveness concept that measures the ease and rapidity with which a system or equipment is restored to operational state after failing.” [Lalli and Packard (1997)]

Maintainability is different from maintenance. Maintainability is the *ability* of a system to be maintained, as oppose to maintenance, which constitutes a series of actions to restore an item to or retain an item in an operational state. As such, maintainability is a design parameter and maintenance is a result of this design.

Effective maintainability requires addressing one or more of the following questions:

1. What components have low reliability?
2. How can the degradation of components be diagnosed easily?
3. How quickly can the product be repaired?
4. How much downtime is acceptable?
5. What kind of preventive maintenance needs to be performed?

These questions must be addressed at the design stage the system and this involves linking reliability with maintenance.

One way of ensuring desired reliability is through proper use of preventive maintenance.

Figure 8-8 of Part I shows how the desired reliability can be achieved through reliability growth and through preventive maintenance actions.

5.3.3 Reliability Growth

In reliability growth, the improvement in reliability is achieved through a Test-Analyse-And-Fix (TAAF) program. In Stage I, reliability growth models are needed to predict the growth over time or development effort, and the cost of development. . TAAF is discussed further in Section 6.1.

5.3.4 Further Reading

- B&M (Chapter 15)
- For more on redundant systems, see Kumar and Agarwal (1980) and Tillman et al (1975)
- For more on maintainability, see Blanchard et al (1995) and Lalli and Packard (1997)

5.4 FMEA and FTA

The linking of component failures to system failures can be done using two different approaches. The first is called the **forward** (or bottom-up) approach and the second is called the **backward** (top-down) approach.

In the forward approach, one starts with failure events at the part level and then proceeds forward to the system level to evaluate the consequences of such failures on system performance. *Failure mode and effects analysis* (FMEA) uses this approach. In the backward approach, one starts at the system level and then proceeds downward to the part level to link system performance to failures at the part level. *Fault tree analysis* (FTA) uses this approach.

5.4.1 FMEA

According to IEEE Standard 352 (IEEE Std 352) the objectives of failure mode and effects analysis (FMEA) are as follows:

1. Assist in selecting design alternatives with high reliability and high safety potential during the early design phase.
2. Ensure that all conceivable failure modes and their effects on operational success of the system have been considered.
3. List potential failures and identify the magnitude of their effects.
4. Develop early criteria for test planning and the design of the test and checkout systems.
5. Provide a basis for quantitative reliability and availability analysis.

6. Provide historical documentation for future reference to aid in the analysis of field failures and consideration of design changes.
7. Provide input data for trade-off studies.
8. Provide a basis for establishing corrective action priorities.
9. Assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, and automatic and manual override.

FMEA involves reviewing a system in terms of its sub-systems, assemblies and so on, down to the part level, to identify failure modes and causes and the effects of such failures. According to IEEE Standard 352, the basic questions to be answered by FMEA are the following:

1. How can each part conceivably fail?
2. What mechanisms might produce these modes of failure?
3. What could the effects be if the failures did occur?
4. How is the failure detected?
5. What inherent provisions are provided in the design to compensate for the failure?

5.4.2 FTA

A fault tree is a logic diagram that displays the relationship between a potential event affecting system performance and the reasons or underlying causes for this event. The reason may be failures (primary or secondary) of one or components of the system, environmental conditions, human errors and other factors. In this section we focus on qualitative fault tree analysis.

The values of a fault tree (Fussel (1976)) are as follows:

1. Directing the analysis to ferret out failures.
2. Pointing out the aspects of the system important to the failure of interest.
3. Providing a graphical aid in giving visibility to those in systems management who are removed from design changes.
4. Providing options for qualitative and quantitative systems reliability analysis.
5. Allowing the analyst to concentrate on one particular system failure at a time.
6. Providing an insight into system behaviour.

A fault tree illustrates the state of the system (denoted the TOP event) in terms of the states (working/failed) of the system's components (denoted basic events). The connections are done using "gates", where the output from a gate is determined by the inputs to it. A special set of symbols is used for this purpose.

5.4.3 Further Reading

- B&M (Chapter 7)
- Most books on reliability discuss this topic in great depth. See, for example, Høyland and Rausand (1994).

5.5 Warranty Cost Analysis

A warranty is a manufacturer's assurance to a buyer that a product or service is or shall be as represented. It may be considered to be a contractual agreement between buyer and manufacturer (or seller) which is entered into upon sale of the product or service. A warranty may be implicit or it may be explicitly stated.

In broad terms, the purpose of a warranty is to establish liability of the manufacturer in the event that an item fails or is unable to perform its intended function when properly used. The contract specifies both the performance that is to be expected and the redress available to the buyer if a failure occurs or the performance is unsatisfactory. The warranty is intended to assure the buyer that the product will perform its intended function under normal conditions of use for a specified period of time.

Consumer products are sold with either Free Replacement Warranty (FRW) Policy or Pro-Rata Rebate Warranty (PRW) Policy. Warranties for custom built products can be more complex involving complex reliability improvement conditions.

5.5.1 Warranty Cost Analysis

Offering warranty results in additional costs to the manufacturer due to the servicing of any failures that arise during the warranty period. The failures are related to the reliability of the product and other factors such as usage mode, intensity and maintenance. The following costs are of importance to both consumers and manufacturers.

(i) Expected warranty cost per unit sale.

(ii) Expected life cycle cost (LCC) of operation over the product life cycle.

Warranty Cost per Unit Sale

Whenever an item is returned for rectification action under warranty, the manufacturer incurs various costs (handling, material, labour, facilities, etc). These costs can also be random variables. The total warranty cost (i.e., the cost of servicing all warranty claims for an item over the warranty period) is thus a sum of a random number of such individual costs, since the number of claims over the warranty period is also a random variable.

The warranty cost per unit sale is important in the context of pricing the product. The sale price must exceed the manufacturing cost plus the warranty cost or the manufacturer incurs a loss. On the average, warranty cost per item decreases as reliability increases. When a buyer has the option of choosing between different warranty policies, then this cost is of relevance.

Warranty Cost over Life Cycle

This cost depends on the life cycle of the product, that is, the time interval over which consumers buy the product. After this time period, sales of the product cease, often because of the introduction of a new and better replacement product. Let L denote the product life cycle. We assume that the consumer continues repeat purchases over this period. The number of repeat purchases is a random variable. The total life cycle cost is the product of this random variable and the warranty cost per item. As a result, the total cost over the product life cycle is also uncertain.

5.5.2 Further Reading

- B&M (Chapter 17)
- For more on warranty cost analysis, see Blischke and Murthy (1994) and (1996).

5.6 Life Cycle Cost [LCC] Analysis

The reliability of a product has a significant impact on operation and maintenance requirements. A product with low reliability has a smaller acquisition cost but the operating and maintenance costs can be high. On the other hand, a more reliable product will cost more but have smaller operating and maintenance cost. This implies that the reliability of the product is a very important factor in choosing between different options.

One approach to deciding on the strategies for acquisition, operation and maintenance is the Life Cycle Cost (LCC) approach. The LCC is the total cost of owning, operating, maintaining, and finally discarding the product. Maintenance costs are influenced by product reliability and the maintenance strategies (for corrective and preventive maintenance) used.

5.6.1 Further Reading

- For more on Life Cycle Costing, see Blanchard (1998).

6 Tools and Techniques for Stage II

In Stage II the main issues are (i) assessing reliability performance (from component to product level) during development stages (Phases 4 and 5) and product level performance in the field, and (ii) ensuring that the desired reliability growth is attained through TAAF where reliability growth is needed. This requires data and as such data analysis and statistical inference are the key topics. We discuss various issues associated with these topics in this section. We start with a discussion of TAAF, then look at data related issues before proceeding issues relating to statistical inference and design of experiments.

6.1 Reliability Growth through TAAF

A TAAF program is part of reliability improvement through R&D effort and is carried out in an iterative manner, where each iteration involves the sequential execution of the following steps - test, data, analysis and modification.

The process begins with the testing of items, from component level through to system level, usually under increasing levels of stress. Should failures occur, the failure data, including modes of failure, TTF, and any other relevant information, are collected and analysed by engineers to discover the causes of failure. Corrective actions are then taken to eliminate or reduce the likelihood of the occurrence of the failure. This process is repeated until the desired reliability is achieved. It is very important that, in such programs, all failures are analysed fully, and action is taken in design or production to ensure that they do not recur. Tests done at relatively high level, e.g., the subsystem level, concentrate on those with relatively low predicted reliability, since improvements at this level can be expected to have the maximum effect on system reliability. Subsystems not meeting reliability requirements are subject to redesign.

In TAAF, no failure should be dismissed as being “random” or ”non-relevant,” unless it can be demonstrated conclusively that such a failure cannot occur during the normal use of the system. Corrective actions must be taken as soon as possible on all units in the development program. This can cause program delays. However, if faults are not corrected, reliability growth will be delayed, potential failure modes at the ‘next weakest link' may not be highlighted, and the effectiveness of the corrective action will not be adequately tested.

A number of reliability growth models have been developed to monitor the progress of the development program and the improvements in reliability. They are broadly categorised into two types - continuous and discrete models. Each of these can be further sub-divided into parametric and non-parametric models. Parametric models are those based on a specified distribution of time to failure, e.g., the exponential or Weibull distribution. Non-parametric models involve specification of a functional form for the reliability improvement relationship apart from the failure distribution. Data analysis for parametric models includes estimation of the parameters of the assumed distribution. In the non-parametric case, curve-fitting techniques, such as regression analysis, are often used.

In general, continuous models are used in the context of continuous (variable) data and attempt to describe the improvement in the failure rate (or mean time between failures) as a function of the total test time. Discrete models involve discrete (attribute) data and are concerned with incremental improvements in reliability as a result of design changes. These improvements are expressed as functions of the probability of success in test trials. A trial is defined by a period of operation terminated upon successful completion of the test or the occurrence of a failure.

6.1.1 Further Reading

- B&M (Chapter 15)
- For more on discrete growth models, see Fries and Sun (1996).

6.2 Data Analysis

Proper analysis of a set of data requires an accurate and thorough understanding of the nature and structure of the data. This includes the type of data to be analyzed and how and under what conditions they were collected.

There are two basic objectives of data analysis. The first is descriptive, that is, description and summarization of the information contained in the sample data. This is accomplished by selection of appropriate descriptive measures. The second is statistical inference, that is, the use of sample information to make inferences about the entire population from which the sample was drawn. Selection of appropriate methods for inference is basically a mathematical problem.

6.2.1 Basic Descriptive Statistics

In statistics, a *parameter* is defined to be a population characteristic, for example the *mean time to failure* (MTTF) μ. The corresponding quantity in a sample, e.g., the *sample mean*, μ, is called a *statistic*. More generally, a statistic is any quantity calculated from sample data. In this context, the objective of descriptive statistics is to calculate appropriate statistics for purposes of description and summarisation of the information in a set of data. The objective of inferential statistics is to determine appropriate statistics for effectively and efficiently making inferences concerning parameters.

Frequency Distributions

This is a graphical or numerical description of an entire set of data. The objective is to present the data information in a concise form and in such a way that, if possible, the general shape of the distribution is displayed. This not only makes the data more comprehensible, it can sometimes give some insights into structural issues. For example, it may become apparent in looking at failure data in this way that data are concentrated in two or more areas, suggesting multiple failure modes.

Other Graphical Methods

Many additional graphical data displays are available. Some of these are used to show different features of a data set; some are for specialised types of data, different from the complete data on a single continuous variable used as an example in the previous section. Some of these are as follows.

- Boxplots
- Pareto Charts
- Pie Charts and Other Pictorial Representations.
- Time Series Charts
- Higher Dimensional Plots

6.2.2 Statistical Inference

In data analysis, the most important objective is to be able to draw inferences from data in a meaningful way concerning population characteristics. Traditionally this is done through estimation of population parameters or other characteristics, and/or by testing hypotheses about parameter values. In reliability analysis, other characteristics of interest include population fractiles (directly related to product reliability), failure rates, mean time to failure, reliability functions, hazard functions, and related quantities. All of these characteristics will be defined precisely and methodologies for estimating them will be discussed in later chapters.

Selection of an appropriate method for analysis is based on three data-related criteria: (1) the scale of measurement of the data; (2) the structure of the data, including how it was collected and whether it is complete or incomplete; and (3) the assumptions made about the underlying random phenomenon. As will be seen, many important decisions in reliability analysis are data based. It is essential that the data be analyzed correctly.

Many procedures also assume continuous data, though this is not a problem in practice except for small samples. Other methods are appropriate for nominal and ordinal data.

How the data are collected is of critical importance in data analysis. In sampling, this includes whether the sample was drawn with or without replacement. We will ordinarily assume that samples are from very large or infinite populations, in which case this doesn't matter. If that is not the case, and sampling is done without replacement, the procedures given require modification.

In designed experiments, the structure of the analysis is directly related to the design of the experiment. Thus the design drives the analysis, and it is essential to know exactly how the experimental procedure was carried out. If this is not known precisely, it is unlikely that the data will be analyzed properly. Worse, if the data are simply collected haphazardly, there may be no method of analysis that will provide information about the questions and populations of interest. This is particularly true of complex experiments involving multiple, possibly interacting, factors and special structures with regard to randomization.

Because of the importance of data collection methodology in analyzing data, particular caution should be taken in using results from sources about which the analyst has no direct knowledge. Thus historical data, data from outside sources, and some of the other types of data mentioned previously should be carefully evaluated.

Probabilistic assumptions regarding the data also play an important role in analysis. Traditionally, it is assumed in data analysis that data follow the well-known normal distribution or at least that sample sizes are large enough so that the sample means are approximately normally distributed (which follows, for sufficiently large samples, from the Central Limit Theorem). This tradition is not followed to such an extent in reliability analysis, where lifetime data are seldom normal, and many alternative assumptions are more tenable, though large sample theory still plays a very important role.

Finally, the effect of censoring on inference must also be taken into consideration, since this significantly changes the probabilistic representation of the data. For complete data (with a sample of size n), the probability structure is based on the n individual failure times, these being the random elements in the data. For Type I censoring, the number of failed units is random; for Type II censoring, the test duration is random. Including these random elements as a part of the probability structure is a significant complication.

6.2.3 Further Reading

- B&M (Chapter 3), M&E (Chapter 3, 6 and 13).
- Most statistical books on reliability discuss this topic , See for example,

6.3 Parameter Estimation

The parameter to be estimated is θ and t is a *k*-dimensional vector with components $\theta_1, \theta_2, \cdots \theta_k$. There are two approaches to estimation and several methods for each of them. The two approaches are:

- *Point estimation*
- *Interval* (or *confidence interval*) *estimation*

In point estimation, a numerical value for θ is calculated. In interval estimation, a *k*-dimensional region is determined in such a way that the probability that the region contains the true parameter θ is a specified, predetermined value. (If $k = 1$, this region is an interval, hence the name.)

Let $T_1, T_2, ..., T_n$ denote a sample of *n* random variables from a (Type III or IV) model and $\theta = (\theta_1, ...\theta_k)$ be the model parameters to be estimated. Let $t_1, t_2, ..., t_n$ denote the realised values of the T_i's. If all the realised values are known, then the data is said to be complete. If not (in the sense that one or more of the T_i's are not known exactly), then the data is said to be incomplete.

In point estimation, $\hat{\theta}$, is a function of $T_1, T_2, ..., T_n$ or $t_1, t_2, ..., t_n$ for the case of complete data. $\hat{\theta} = \hat{\theta}(T_1, T_2, ..., T_n)$ is called an **estimator** and is a random variable; $\hat{\theta} = \hat{\theta}(t_1, t_2, ..., t_n)$ is called an **estimate** and is the numerical value obtained using the data for estimation. The same is true for the incomplete data case except that the form the function is different from that for the complete data case.

6.3.1 Properties of Estimator

It is essential to understand the various properties such as unbiasedness, variance, consistency, efficiency and asymptotic efficiency of the estimator.

A biased estimator will either under or over estimate the value of the parameter. The variance of the estimator decreases as the data size increases. Hence, a less efficient estimator will need more data to yield the same variance as a more efficient estimator. This has implications for data collection as the cost and effort for collection increases with data size. Also, if the bias is significant, it will lead to wrong decisions being made. In some cases, the bias can be compensated through proper adjustment. It is important to use estimators that are efficient and unbiased.

6.3.2 Methods of Estimation

Many different estimation methods have been developed for estimating model parameters. They can be broadly grouped into two categories.

- Graphical Methods
- Statistical Methods

In graphical methods, the estimates are obtained from one of many different plots. The plot depends on the model selected and hence each needs to be treated separately. The main drawback of these methods is that there is no well-developed statistical theory for determining the small sample or asymptotic properties. However, they are useful in providing an initial estimate for statistical methods of estimation.

The statistical methods, in contrast, are more general and applicable to all kinds of models and data types. The asymptotic properties of the estimators are well understood.

6.3.3 Point Estimator

There are many different kinds of point estimators. Some of the well-known ones are the following:

- *Moment Estimator*
- *Percentile Estimator*
- *Maximum Likelihood Estimator*
- *Bayesian Estimator*

Under certain regularity conditions, maximum likelihood estimators are consistent, asymptotically unbiased, efficient and normally distributed. Hence, when the data set is large, it is best to use the maximum likelihood estimator. The Bayesian approach is very useful in reliability and is discussed further in a later sub-section.

6.3.4 Interval Estimator

In the case where θ is scalar, a confidence interval based on a sample of size *n*, $T_1, T_2, ..., T_n$, is an interval defined by two limits, the lower limit $L_1(T_1, T_2, ..., T_n)$ and the upper limit $L_2(T_1, T_2, ..., T_n)$ having the property that

$$P(L_1(T_1,...,T_n) < \theta < L_2(T_1,...,T_n)) = \gamma$$

where $\gamma (0 < \gamma < 1)$ is called the *confidence coefficient*.

Confidence is usually expressed in percent, e.g., if $\gamma = .95$, the result is a "95% confidence interval" for θ. Note that the random variables in the above expression are L_1 and L_2, not θ, i.e., this is not a probability statement about θ, but about L_1 and L_2. Hence we use the term "confidence" rather than "probability" when discussing this as a statement about θ. The proper interpretation is that the procedure gives a correct result $100\gamma\%$ of the time.

The confidence interval defined above is a *two-sided interval*; if a fraction of the remaining probability, $(1 - \gamma)$, is below L_1 and the rest above L_2 (usually $(1 - \gamma)/2$ on each side). A *lower* one-sided confidence interval is obtained by omitting L_2 in the above equation and modifying L_1 accordingly; the interpretation is that we are $100\gamma\%$ confident that the true value is at least L_1. Similarly, one can define an *upper* one-side confidence interval.

6.3.5 Further Reading

- B&M (Chapters 5 and 8), M&E (Chapters 7 – 9 and 11).
- Most statistical books on reliability discuss this topic in great depth. See, for example, Lawless (1982) and Nelson (1982).

6.4 Hypothesis Testing

In the classical approach to hypothesis testing, two hypotheses are formulated, the *null hypothesis*, denoted H_0, and the *alternate hypothesis*, H_a. By definition, H_0 is the hypothesis that is tested; H_a is the hypothesis that is accepted if H_0 is rejected. In reliability context, the hypothesis can be one of the following:

(1) The failure data can be adequately modelled by some specified distribution function.

(2) The model parameters are the specified values.

The basic idea in testing H_0 is to look at the data obtained and evaluate the likelihood of occurrence of this sample given that H_0 is true. If the conclusion is that this is a highly unlikely sample under H_0, H_0 is rejected and H_a is accepted. If not, we say that we "fail to reject H_0" (not that we accept it). The philosophy here is that we can "disprove" H_0 if the evidence against it is strong enough, but if the evidence against it is not strong, this does not "prove" that it is true. For example, a larger sample may lead to rejection of H_0. (In practice, however, we often proceed as though H_0 is true when it is not rejected, or at least that it is a reasonable approximation of the true situation.)

In setting up a hypothesis testing problem, the first step is determining the appropriate null and alternate hypotheses. This must be done in the context of the experimental objectives. In fact, different objectives often lead to different formulations of the hypotheses and seemingly different conclusions based on the same set of data. The process begins with a determination of what is to be demonstrated or "proven," or, in a managerial context, what conclusion will lead to some action being taken. This is made the alternate hypothesis. A rule of thumb is that the burden of proof is put on H_a.

6.4.1 Test Statistics

In performing tests, we rarely look at the entire sample to determine its likelihood of occurrence. Instead, we calculate *test statistics*, which summarise the sample information about the characteristic in question. These are often based on the "best" point estimator of the characteristic. The requirement is that we can calculate probabilities that assess "likelihood of occurrence". This means that (i) the test statistic must have a known (or determinable) distribution; and (ii) neither the statistic nor its distribution depend on any unknown parameters. It is sometimes difficult to find appropriate statistics having these (and other desirable) properties, and, as in estimation, we often resort to asymptotic results based on the normal distribution to obtain approximate tests.

6.4.2 Type I and Type II Errors and Error Rates

In hypothesis testing as formulated here, there are two possible decisions: (i) fail to reject H_0, and (ii) reject H_0 and accept H_a . It follows that there are two types of errors that can be made: rejecting H_0 when it is true, and failing to reject it when it is not true. These are called *Type I* and *Type II Errors*. We have the following situation:

Decision	**State of Nature**	
	H_0 True	**H_a True**
Do Not Reject H_0	**OK**	**Type II Error**
Reject H_0 and Accept H_a	**Type I Error**	**OK**

"OK" in the two cells means that we have not made an error. Type I and II errors are as indicated. Type I and Type II *Error rates* are the probabilities of making the two types of errors. Error rates depend on the sample size n, the true parameter value τ, and the procedure used.

In order to explicitly specify a test procedure, it is necessary to state what is meant by an "unlikely" sample. This is done in terms of the *level of significance* of the test, denoted α which is an upper limit on Type I error. Usually α is stated as a percent, e.g., if $\alpha = .05$, we say that we are testing at the 5% level of significance, or simple "testing at the 5% level." The *power* of the test is the probability of not making a Type II error. Note, incidentally, that Type I and Type II error rates are inversely related; as one increases, the other decreases. Selection of an appropriate level of significance is based, at least in part, on this relationship. A standard choice of level of significance is $\alpha = .05$. If it is more important to protect against Type I errors, the level of significance should be chosen to be a smaller value, e.g., .01 or less. In this case, the power of the test against any specific alternative will be relatively small, i.e., the Type II error rate will be relatively large. If a small Type II error rate is desired, testing should be done at a higher level of significance, say to 10% or 20% level.

6.4.3 Further Reading

- B&M (Chapter 5).

6.5 Bayesian Statistical Analysis

Throughout the life cycle of a product, a good deal of information relevant to reliability is available to the engineer and manager. Even at the conceptual stage, information based on the performance of similar products and/or components, knowledge of material properties, judgmental assessments of reliability, and many other types of information are usually available. As the process proceeds through design, development, testing, and production, additional sources of information may become relevant and additional data – test data, vendor data, and so forth – will become available. This information, called *prior* information, can contribute significantly to reliability assessment, and its inclusion in the analysis and interpretation of data can greatly influence the results.

Bayesian statistical analysis provides a formal methodology for incorporating prior information, including subjective information, into the analysis of data. This is done by means of a “prior distribution” (prior in the sense of before the acquisition of new data). Assumptions concerning the form of the distribution of time to failure (exponential, Weibull, etc.) are made as usual and uncertainty in the parameters is modelled by the prior distribution. In addition to making use of the prior information, there are two additional distinct advantages to this approach, if done properly: (1) It enables the analyst to make sensible statements concerning reliability estimation and prediction in cases when few or no failures are observed. (2) It provides a natural means of updating reliability assessments as additional information and data are obtained.

The use of a Bayesian approach is especially important in the context of very highly reliable parts or very high reliability requirements. To achieve even reasonably high reliability, very high reliabilities may be required at the part level. Reliabilities at this level are impossible to demonstrate with any reasonable (i.e., affordable) amount of testing. Bayesian methods provide a mechanism for assessing reliability and providing a nontrivial interval estimate even when no failures occur.

The Bayesian approach, although broadly applicable, does introduce a new level of difficulty in applications. It is still necessary, in a parametric framework, to select a specific failure distribution (or probability distribution for discrete data). In addition, it is necessary to select a prior probability distribution to model uncertainty in the parameters, as well as to select parameters for the selected prior distribution.

6.5.1 Use of Aggregated Data in Reliability Analysis

A key problem in the analysis of reliability data (and in data analysis generally) is incorporation of various other types of information that might be available into the analysis and interpretation of results. In principle, the Bayesian approach provides a natural framework for doing this, through the prior distribution. It does not, however, provide a general methodology for formulating the prior. How that is done depends, in part, on the nature of the information that is to be utilised for this purpose. There are a number of approaches and some disagreement as to how a prior should be determined. We look briefly at a few of these.

Note that the lack of a universally (or even widely) accepted formal structure in this context, the subjectivity of the analysis, and the resulting differences of opinion lead to a situation in which different analysts can on occasion arrive at quite different conclusions based on the same set of data. This has led many data analysts to reject the Bayesian approach altogether. The problem with this decision is that it leads to rejection of much valuable and useful information in analysis of the data. This is especially the case in many reliability applications involving complex, evolving systems or product lines. A reasonable approach would appear to be a compromise: Use the classical approach if prior information is not available, if the information that is available is thought to be of questionable relevance, e.g., because of changing circumstances, or if the available information is considered to be highly unreliable. If the available information is relevant and thought to be reliable, formulate a prior distribution that accurately represents this information (along with judgmental information, if appropriate) and use a Bayesian approach.

6.5.2 Further Reading

- B&M (Chapter 8), M&E (Chapter 14).
- For more details, see Martz and Waller (1982) and Press (1989).

6.6 <u>Design of Experiments</u>

A structured experiment is a plan for data collection under which the experimenter has control over the important experimental conditions and other factors that could affect the results. Design of Experiments (DOE) is the statistical discipline that deals with the development of such test plans.

The importance of the notion of structured data is that it is intended to preclude haphazard data collection or uncontrolled factors. Haphazard data collection is unlikely to produce test results that provide a proper basis (such as a true random sample) for inference about the population actually of interest. If important factors are left uncontrolled, the experimenter can never have confidence that the results obtained are reflecting the factors included in the design or are due to those not included.

In analysing the data collected in structured experiments, the key tool that will be used is *Analysis of Variance* (ANOVA). This is the most widely used tool in statistical analysis for comparison of two or more means. It requires certain assumptions regarding the data, which will be discussed in the chapter, but is quite robust in that it is not sensitive to small or even modest violations of the assumptions. Note, incidentally, that for some distributions (e.g., the exponential) comparison of means is equivalent to comparison of reliabilities. For others, this may be true under certain constraints (e.g., Weibull distributions with the same shape parameter).

For unstructured data, a commonly used method of analysis is regression analysis. In cases where some factors are uncontrolled but are measured, an appropriate analysis is Analysis of Covariance (ANCOVA), which is basically a combination of ANOVA and regression. (Note: ANOVA, regression, and ANCOVA can all be subsumed into a structure called the General Linear Model, and, in a general sense, are mathematically identical.)

6.6.1 Mathematical Models in DOE

One of the key tools used in data analysis in the context of designed experiments is representation of the data by a mathematical model. The model is a representation that describes both the structure of the experiment and the structure of the analysis of the resulting data.

6.6.2 Approach to Designing an Experiment

As noted previously, any scientific investigation begins with a description of the context and a problem statement, usually translated into statistical terms (hypotheses to be tested, and so forth). To actually implement this in designing the experiment itself the following issues must be addressed:

- The number of observations to be obtained for each treatment
- The structure of the experiment (order, grouping of experimental units, etc.)
- Randomisation to be used
- Mathematical models to describe the data and assumptions made

Since, as we shall see, a proper analysis of experimental data depends crucially on a proper understanding of the structure of the experiment, data analytical issues should also be addressed at this point. These include

- Choice of appropriate descriptive statistics
- Basic analysis of the data
- Tests of assumptions
- Detailed analyses to be done

6.6.3 Further Reading

- B&M (Chapter 10), M&E (Chapter 10).
- An excellent description of models in DOE can be found in Lorenzen and Anderson (1993).
- For more details, see Hicks (1982), Condra (1993) and Montgomery (1997).

6.7 Testing

Testing can be defined as the application of some form of stimulation to a system (or subsystem, module or part) so that the resulting performance can be measured and compared to design requirements. In the context of new products, one can group testing into three categories:

1. Developmental Testing
2. Manufacturing Testing
3. Field and Operational Testing

6.7.1 Developmental Testing

As the name suggests, developmental testing is the testing carried out during the development phase to assess and improve product reliability. Some of the tests used are:

Testing-to-failure: Tests to failure are usually performed at module and subsystem levels. The test involves subjecting the item to increasing levels of stress until a failure occurs. Each failure is analysed and fixed.

Environmental and Design Limit Testing: This is done at part, subsystem and system levels and should include worst-case operating conditions, including operations at the maximum and minimum specified limits. Test conditions can include temperature, shock, vibration, and so forth. Any failures resulting from the test should be analysed (through root cause analysis) and fixed through design changes. These tests are to assure that the product performs at the extreme conditions of its operating envelope.

Critical Item Evaluation and Part Qualification Testing: The purpose of these tests is to verify that a part is suitable under the most severe conditions encountered under normal use. The tests to be performed depend on the product. For example, in the case of computer chips, test conditions might involve vibration and temperature; for a mechanical component used to pump chemicals, they might be resistance to solvents and seal tests. Other test factors include strength, thermal shock, and humidity, to name a few.

6.7.2 Testing During Manufacturing

The purpose of testing during manufacturing is to eliminate manufacturing defects and early part failures. The type of testing to be done depends on the product (electrical, mechanical or electronic). For very expensive products (e.g., defence systems or commercial satellites), where a high level of reliability is absolutely essential, 100% testing would be employed, whereas for most other products (particularly consumer durables), testing can sometimes be substantially less than 100%. In either case, testing may be done under various environmental conditions.

In addition, testing requirements can change over the period of production. For a new product, in the early stages of production, considerable testing is required to establish the process characteristics and the effect of process parameters on the reliability of the product. As the product matures, the testing requirements are reduced. Two types of testing used are

1. Environmental Stress Screening [ESS]
2. Burn-in

ESS is the process of subjecting a part or assembly to various environmental extremes to identify and eliminate manufacturing defects prior to customer use. Typical methods used are temperature cycling, random vibrations, electrical stress, thermal stress, etc.

Burn-in is a process used to eliminate the high initial failure rate due to manufacturing defects. It involves putting items on a test bed to detect early failures, so that they can be weeded out before the item is released for sale. Burn-in involves testing all items for a period τ. Those that fail during testing are scrapped. The rationale for this is that non-conforming items are more likely to fail than conforming items and hence are weeded out.

6.7.3 Operational Testing

Testing during development and manufacturing is often done under conditions which tend to simulate the real world environment. Often, the simulated condition is a poor representation of the real world environment and usage. One way of overcoming this limitation is for the manufacturer to have a small number of users test the product by using it in realistic applications. Such tests provide useful data relating to product reliability and performance in the real world. Based on the resulting data, changes can be made to the product design and/or the manufacturing process to improve the reliability of a product so that it meets the needs and expectations of the customer.

Operational testing is a joint effort involving the manufacturer and buyers. Such tests allow the manufacturer to evaluate all characteristics by utilizing actual users, maintenance procedures, and support equipment in an operational environment.

6.7.4 Testability

Testability is a concept closely related to testing. It is a process through which a failure in a system can be detected and identified so that corrective actions can be initiated to rectify the failure. If the failure is due to an external factor (e.g., loss of power supply to a computer), then testability allows for its detection and identification.

Testability can either be built into the product (called BIT — built-in test) or it can be carried out by equipment external to the product. For complex electronic systems, testability can be done at different levels, ranging from the system level down to the part level. Testing often involves the processing of measurements made by sensors, so that testability involves both hardware and software. As such, both of these are important in the context of design for testability.

6.7.5 Accelerated Tests

Accelerated testing is especially important in the context of highly reliability items, where it is often virtually impossible to demonstrate that a reliability goal has been attained. In these cases, accelerated testing is necessary, and in many less extreme applications, it is desirable for reasons of cost effectiveness and timeliness.

The major difficulty in the use of accelerated testing is that it is necessary to relate the results obtained under conditions of higher stress to those that would result under normal conditions. This requires an adequate understanding of failure mechanisms and appropriate models that express the relationship. There is a great deal of literature dealing with these topics.

Design of Accelerated Tests

Stress that accelerates the failure process may be applied in many forms, high or low temperatures, humidity, cycling between excessively high and low conditions, excess usage, electrical stress, vibration, and so forth. Test designs follow the basic principles of DOE. Particularly appropriate are factorial experiments, with the factor or factors involved usually being quantitative. Split-Plot experiments of various types are often appropriate if two or more factors are involved, particularly when time is a factor.

An additional concern that must be addressed in designing experiments of this type is the possibility of the excess stress causing failures that would not occur in normal operations, for example, melting of materials, weakening of bonds, or expansion of materials at high temperatures. Furthermore, if an item can fail in several ways, acceleration may affect failure rates for the different modes differently. For this and other reasons (e.g., cost and test equipment requirements), accelerated tests are most often done at the part or small component level. Furthermore, because of the complexity of relating failures (or failure related characteristics) to more than one stress factor, accelerated tests most often involve only a single accelerating factor, e.g., temperature alone rather than temperature and humidity or temperature, humidity and time. Two-factor experiments are not uncommon, but many-factor experiments are not usually appropriate in this context, particularly if interactions are present.

Selection of levels of a factor to use in testing depends on the context (materials, stresses, and so forth). Important considerations are that

1) levels are not so extreme that the failure mechanism changes,
2) levels are within the range over which the selected model is appropriate, and
3) excessive extrapolation is not required.

In the first two cases, the model may be invalidated and the test data not relevant to normal conditions. Excessive extrapolation has not only these difficulties, but the added problem that confidence intervals, even if valid, will be so wide as to be useless.

6.7.6 Further Reading

- B&M (Chapter 13), M&E (Chapters 18 - 21).
- For more on accelerated testing, see Nelson (1990).
- For more on burn-in, see Jensen and Peterson (1982) and Leemis and Benke (1990)

7 Reliability Management

Reliability management must be part of the overall strategic management. As such, we start with a brief discussion on strategic management before proceeding to look at some of the issues in reliability management.

7.1 Strategic Management

Strategic management is the process for the long term planning of a business firm. The process starts with formulation of **mission** and **vision** statements. The former defines the reason for the existence of the firm and address the question -- Why are we in business? The vision statement describes where the firm is heading and what it wants to be in the future. The next step is formulation of (strategic) **goals**. These are broad statements that set the direction that the firm must take in order to realize its mission. **Strategies** are key actions towards achieving the goals.

For a business firm with several diversified business units, the strategies have a nested hierarchical structure. At the top is the **business strategy** is the managerial plan for the business. A business can be broken down into functional areas (or departments), each responsible for its own performance and strategies. These are called **functional strategies**. The functional activities for a firm can be broadly grouped into three categories -- technical, commercial and support. The technical activities are design, research and development, manufacture, quality control, and so on. The commercial activities are marketing, post-sale service, finance, and accounting. Support activities relate to legal issues, human resources, etc. The functional strategies are supported by **operational strategies**. Responsibility for operational strategies lies with the lower-level managers within functional areas, although approval for these lies with those responsible for functional strategies.

Figure 7-1 shows the hierarchy of strategies for a manufacturing firm, beginning with the overall business strategy.

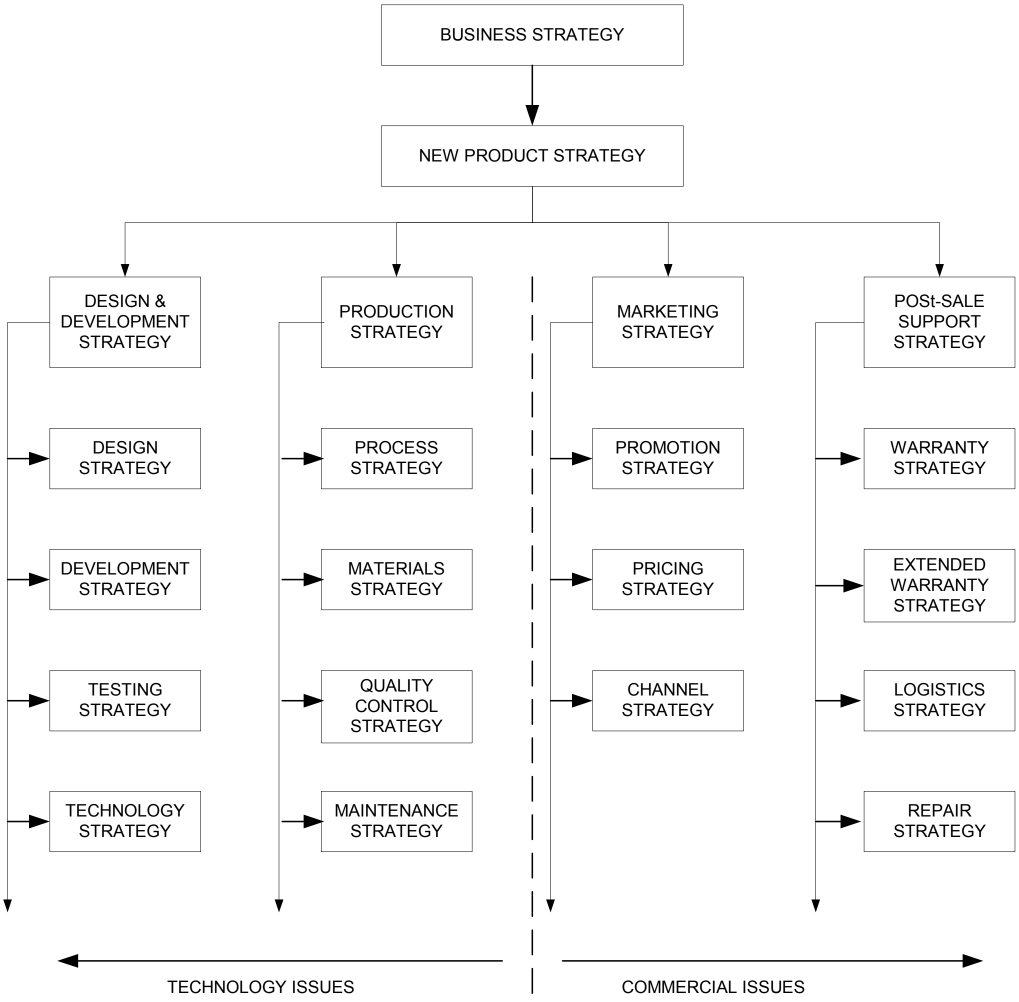

Figure 7-1: Strategy Hierarchy for New Products.

The different strategies must address both the long-term **strategic objectives** and the shorter-term **operational goals**. Strategic management aims to integrate these various strategies into a consistent overall business strategy which outlines the future direction of the company (medium to long term), while operational management is responsible for achieving the day-to-day intermediate steps needed in order to reach those strategic objectives (short to medium term). Effective strategic management requires that strategies at each level support those in higher levels in the hierarchy. The hierarchy of strategies is often called the “business plan” for the firm.

7.2 Reliability Program

Reliability affects many of the functional operational strategies indicated in Figure 7-1. Reliability management deals with this issue. In Part I we discussed several reliability related strategies. These included warranty strategy in Phase 1, strategies to achieve desired product reliability in Phases 2 and 3, testing strategies to assess reliability in Phases 4 and 5. A reliability program is essential for the achievement of the desired reliability performance. It provides a framework for a systematic approach for definition and management of the various reliability-related tasks. It includes a comprehensive list of activities that are considered to be essential to the success of the product. It further contains a description of each task and an assignment of responsibility and accountability, as well as estimates of time, cost and manpower requirements. Reliability programs deal with reliability strategies at the functional as well as the operational levels.

Department of Defence in several countries and several professional organisations have produced standards for Reliability Programs. Reliability programs are influenced by the policies of the organisations involved, the product being developed, and by the unique practices of the organisations. Some of the well-known standards are the following:

- MIL-STD-785
- ISO Standards-9000 Series
- British Standards-BS5760
- IEC standards – 60300 Series
- SAE M-100
- Norwegian Petroleum Industry Standard (NORSOK Z-016)

The planning of the reliability program (also called reliability program plan) starts at the end of Stage I, Level I as shown in Figure 7-2 which is based on an extract of IEC 60300-1. As can be seen, systems for data collection and analysis are integral elements of the reliability program.

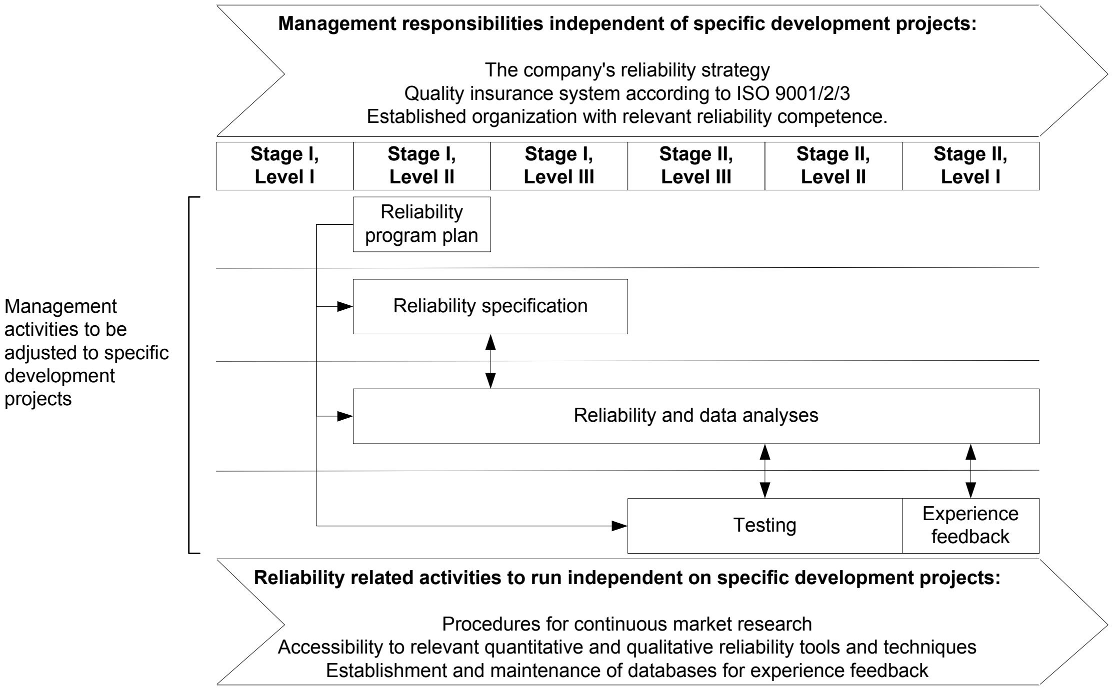

Figure 7-2: Aspects of Reliability Management.

7.3 Reliability Group

New product development requires an inter-disciplinary team approach, involving specialists from different engineering disciplines. Reliability group, comprised of engineers, scientists and statisticians, provides the skills to ensure that reliability issues are tackled at the design stage and that reliability is controlled during the manufacturing stage. In order to do this effectively, the reliability group needs to have the training to carry out many different reliability related tasks. Some of these tasks are as follows:

1. Participate in all design reviews and modifications
2. Decide on reliability allocation and apportionment
3. Carry out reliability estimation, prediction and growth plans
4. Plan and conduct reliability tests
5. Perform statistical analysis of test data
6. Maintain a reliability data system
7. Provide reliability related assistance to other sections such as
   (i) Manufacturing, (ii) Purchasing, and (iii) Post-sale servicing
8. Write reliability specification for parts to be purchased
9. Identify causes of reliability degradation
10. Continuously improve the reliability of the product

7.4 Risk Management

In any decision making process, one can have serious negative consequence resulting from an undesirable outcome of an action. Risk deals with this negative consequence and the likelihood of the undesirable outcome.

7.4.1 New Product Risk

In the case of new products, the cost of development can be very high. These costs are recovered if the product is a success. Failure of the product can be due to either technical and/or market-related factors. Such failures can be costly and it is necessary for manufacturing firms to evaluate the associated risk before beginning any new product venture.

From a reliability point of view, an important risk element is the research and development needed to improve reliability, since an R&D venture is a highly risky proposition. An example of this risk is failure to achieve the desired reliability performance within the given time and cost constraints. Another is the risk associated with estimating product reliability. Overestimating the reliability performance can lead to high warranty costs and possible design changes after the product has been launched on the market. Similarly, underestimating the reliability performance can lead to more money and effort being spent than needed. Market risk can be due to liability claims that can follow because of the failure of a product to perform satisfactorily.

The notion of *vulnerability* is very relevant in this context. A product is vulnerable to a cause, either external or internal to the product, if it leads to a failure with serious consequences. A spectacular example of this is the space shuttle disaster where the failure of the O-ring led to loss of lives and the vehicle. All products are vulnerable to some cause or combination of causes. A product can be made less vulnerable or robust through increased investment in design and manufacturing. Reliability management examines the trade-off between the increase in the cost of making the product less vulnerable and the benefits derived from reducing its vulnerability. In many cases, the benefits are mainly economic, but often they are non-economic (e.g., customer good will) as well.

7.4.2 Product Liability

When product reliability has an impact on safety, lack of adequate reliability of a component (for example, an unreliable brake system in a car) may result in the manufacturer incurring high legal costs. In such cases, the manufacturer may be forced to recall the product to repair or replace the unreliable component. This can be very costly, not only in terms of the direct costs involved, but also as a result of damage to the reputation of the product and/or of the manufacturer. There are several examples which highlight this – the recall of the Ford Pinto some years ago because of the danger of fire in a rear end collision is perhaps the best known of these.

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Evans and Lindsay (1996, p. 234) note that many businesses do not introduce new products into the marketplace because of liability suits resulting from inadequate product reliability. Because reliability has serious implications in terms of product liability, businesses must ensure that they have effective liability prevention mechanisms to minimise liability-related claims.

7.5 Establishing the Reliability Practices

Effective reliability management requires establishing good reliability practices within the organisation that can be transferred from one project to another. Ireson et al (1996) suggests the following three–stage approach to achieving this.

1. Define the practices that fit the manufacturer's particular organization, products and market environment.
2. Implement the practices through training and education.
3. Continuous improvements to the practices as one moves from one project to another.

7.6 Further Reading

- B&M (Chapter 12)
- For more details, see Priest (1988) and Ireson et al (1996),

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