Springer Series in Reliability Engineering

D.N. Prabhakar Murthy Wallace R. Blischke

Warranty Management and Product Manufacture

Springer

Springer Series in Reliability Engineering

Series Editor

Professor Hoang Pham
Department of Industrial Engineering
Rutgers
The State University of New Jersey
96 Frelinghuysen Road
Piscataway, NJ 08854-8018
USA

Other titles in this series

The Universal Generating Function in Reliability Analysis and Optimization
Gregory Levitin

Maintenance Theory of Reliability
T. Nakagawa
Publication due September 2005

System Software Reliability
H. Pham

D.N. Prabhakar Murthy and
Wallace R. Blischke

Warranty Management and Product Manufacture

With 83 Figures

Springer

D.N. Prabhakar Murthy, B.E. (Hons), M.E. (Hons), M.S., Ph.D.
Division of Mechanical Engineering
The University of Queensland Brisbane
Queensland, Q 4072
Australia
p.murthy@uq.edu.au

Wallace R. Blischke, B.S., M.S., Ph.D.
5401 Katherine Avenue
Sherman Oaks, CA 91401
USA
Cblischke@aol.com

British Library Cataloguing in Publication Data
Murthy, D.N.P.
Warranty management and product manufacture.—(Springer series in reliability engineering)
1. Warranty 2. Quality control 3. Manufactures
I. Title II. Blischke, W. R., 1934–
658.5′6
ISBN 1852339330

Library of Congress Control Number: 2005924560

Springer Series in Reliability Engineering series ISSN 1614-7839
ISBN 1-85233-933-0
Springer Science+Business Media, Inc.
springeronline.com

Typesetting: Camera-ready by the author
Printed in the United States of America (IBT)
69/3830-543210 Printed on acid-free paper

Dedicated to our ever patient,
supportive and loving wives,

Jayashree and Carol

Preface

In industrialized societies, new products are appearing in the marketplace at an ever-increasing pace. Their introduction is either market driven – a result of increasing customer expectations and needs – or technology driven – resulting from advances in technology. In addition, the complexity of products tends to increase with each new generation. A further complicating factor is that customers are uncertain about, and have no easy way to research, new product performance.

Two items that are becoming more critical and important in the customer purchase decision process are:

1. Pre-purchase services – including information regarding product performance, useful life, cost of operation, etc., and
2. Post-purchase support services – including training in product use, availability of spares, maintenance, assistance with problems, etc.

Customers want assurance that the product will perform satisfactorily during the useful life of the product. Manufacturers not only need to provide this assurance, but more importantly, need to ensure customer satisfaction as well. Without this, survival in a fiercely competitive global market environment would be impossible. Warranties play an important role in this context.

The use of warranties is widespread and they serve many purposes. These include protection for manufacturer and buyer, signals of product quality, assurance that the product will perform satisfactorily, providing a means of compensating buyers when a purchased item does not perform as promised, and resolving disputes between buyer and manufacturer. Many different types of warranties have been studied in detail from various points of view. A warranty of any type, since it involves an additional service associated with a product, will lead to potential costs beyond those associated with the design, manufacture and sale of the product. These costs, in fact, are unpredictable future costs and have a significant impact on the total profits for a manufacturing business. In most cases, these costs range from 1% to 10% of total sales, depending on the product and the manufacturer. At present, the North American automotive industry spends about 8.5 billion dollars on servicing warranty claims each year. The costs of warranty depend on product reliability and warranty terms. Product reliability, in turn, is influenced by the decisions made during the design and manufacture of the product.

Warranty management deals with decisions with regard to product warranty. Warranty decisions must be integrated with decisions relating to technical issues such as design, development and manufacturing, and to commercial issues such as marketing, price, sales, revenue, etc. Warranty must be managed so as to ensure that the business objectives – profits, return on investment, market share, and so forth – are achieved, while at the same time providing adequate assurance to customers and ensuring customer satisfaction.

Unfortunately, most businesses view warranty as only providing the assurance, and warranty management as efficient administering of warranty claims. The focus is on monitoring claims to ensure that they are valid and to prevent loss through warranty fraud. This can be termed Stage-1 warranty management. Few businesses have moved beyond this to Stage-2 warranty management, where the focus is on improving business performance through actions that lead to warranty cost reduction and/or increase in customer satisfaction. This is achieved through changes to product design, production and warranty servicing logistics through a proper analysis of data obtained during the servicing of warranty claims. In both of these approaches to warranty management, warranty is viewed as an afterthought and warranty decisions are not linked to other product life cycle decisions. Stage-3 warranty management views warranty from a strategic perspective. This begins with a warranty strategy that is linked to the various technical and commercial strategies from the very start of the new product development process. The aim of warranty management is to achieve the overall business objectives by focusing on product performance assurance as well as ensuring customer satisfaction.

This book deals with Stage-3 warranty management and looks at both strategic and operational aspects. It is the third and final book in the warranty trilogy written/edited by the authors. The first two books are *Warranty Cost Analysis* (Marcel Dekker, 1990) and *Product Warranty Handbook* (Marcel Dekker, 1994).

The objective of the book is to provide a comprehensive, integrated framework for strategic warranty management. This requires an understanding of the role and impact of warranty on design, engineering, development and production of a product, as well as on quality assurance, marketing, and post-sale service. Each of these aspects of warranty is discussed in some detail in the book. The approach taken is conceptual, using few symbols and no mathematics, with some formulas and mathematical discussion given in footnotes for the interested reader, and references cited for details and further results. Finally, some accounting and legal aspects of warranty that are relevant for effective warranty management are briefly discussed.

The book is primarily intended for managers at all levels (senior, middle and junior) in manufacturing businesses. We recommend the following sequence for initial reading of the book:

Senior Level Managers

CEO: Chapters 1, 3, 4 and 14

Manager in charge of Design and Development: Chapters 1, 2, 3, 4, 5, 14

Manager in charge of Production: Chapters 1, 2, 3, 4, 5, 9, 14
Manager in charge of Marketing: Chapters 1, 3, 4, 5, 10, 14
Manager in charge of Post-sale Support: Chapters 1, 3, 4, 5, 11, 14

Middle and Junior Level Managers
All managers: Chapters 1 – 14

Managers at the middle and junior levels should supplement this by extra reading as indicated in the endnotes for the various chapters.

The book can also be used as textbook for a graduate level course in Business Management, Operations Management and Industrial Engineering programs as part of managing new product development.

The authors wish to thank Anthony Doyle and Oliver Jackson of Springer-Verlag, London, for their assistance and support in producing the camera-ready version. The first author would like to thank the Department of Quality and Reliability Engineering at the Technische Universiteit Eindehoven and the Department of Production and Quality at the Norwegian University of Science and Technology for the visiting appointments during 2004 and for providing a stimulating environment for writing the initial drafts of the book.

D. N. Prabhakar Murthy
Brisbane, Queensland, Australia

Wallace R. Blischke
Sherman Oaks, California, USA

Contents

1

Introduction and Overview

1.1 Introduction

In the purchase decision, buyers of a product typically compare characteristics of comparable models of competing brands. When competing brands are nearly identical, it is very difficult, in many instances, to choose a particular product solely on the basis of the product-related characteristics such as product price, special features, perceived product quality and reliability, financing offered by the manufacturer, and so on. In such situations, post-sale factors – warranty, parts availability and cost, service, maintenance, and so forth – take on added importance in product choice. Of these, warranty is one that is known (or at least potentially known) to the buyer at the time of purchase.

In the case of new products, another feature is that each new generation is more complex than the earlier generation it replaces. Often customers are uncertain about new product performance. Here warranties play an important role in providing product assurance to customers in the sense that the manufacturer will make provision for some remedial action should the product not perform satisfactorily over the warranty period. Many different types of warranties are offered, depending on the product, the manufacturer, and the buyer. As a result, product warranty plays an increasingly important role in consumer and commercial transactions.

The use of warranties is widespread and they serve many purposes. In the simplest terms, a warranty is a contractual agreement between the manufacturer and the buyer that requires the manufacturer to either rectify item failures or compensate the buyer for failures that occur within the warranty period subsequent to its sale. Purposes of warranty include protection for both manufacturer and buyer, signaling of product quality, and assurance to buyers that items will perform as promised. In addition, warranty terms are often an important element of marketing strategy. Warranties play an important role in the resolution of disputes that may arise between buyer and manufacturer. They also pose serious challenges to legislators in terms of formulating sensible warranty policy legislation that will protect the interests of both buyers and manufacturers.

The outline of the chapter is as follows. Section 1.2 traces the historical evolution of warranty from the twenty-first century B.C. to the present time. Following this, we discuss alternate theories of warranty. This provides the background for a discussion of warranty in the context of modern manufacturing, which is the topic of Section 1.4. In our discussion, we highlight the ways in which warranty impinges on the various stages of manufacturing and how warranty decisions must be made in a framework that integrates the different technical and commercial issues that are encountered in this context. Section 1.5 defines the scope and objective of the book and we conclude with an outline of the book in Section 1.6.

1.2 Historical Perspective

The origin of the word warranty is interesting. In a study of the origin and history of the concept, Loomba [1] states:

> *The words* warranty and guarantee, *known to linguists as "doublets," are derived from same original source but traveling to today's English language by different routes. The origins of the word* warranty *can be traced back to the Old North French word* warant and warantie, *to the Old High German word* werento *meaning "protector". During the Middle Ages, the original expressions used included* hoc ex condicione, warrantizavit, promisit, *and* sub tali plevina.

1.2.1 Pre-Industrial Revolution

The earliest record of warranty can be found in the Babylonian and Assyrian tablets of the twenty-first century B.C. Since then it has evolved over time and in many different societies. Some of the key milestones in this evolution were:

i. Roman laws of the fifth century B.C.,
ii. Bavarian laws at the start of the Christian era,
iii. Jewish commercial laws of the second century A.D.,
iv. Hindu religious laws of the fifth century,
v. Islamic laws of the eighth century,
vi. Egyptian formularies of a slightly later period,
vii. Scattered Russian codes of the early tenth century, and
viii. The customs of the church rule of medieval times and customs of the English borough.

It is clear that the concept of product warranty has maintained a significant position in trade practices of many societies through the ages. Warranty assumed a special role subsequent to the industrial revolution.[1]

1.2.2 Post-Industrial Revolution

The start of the Industrial Revolution in the sixteenth century brought a major change to manufacturing. Components were produced by different businesses and often no single entity was responsible for the product as a whole. The refusal of public authority, through public legislature and a formal judiciary system, to accord effective protection to the purchaser was reflected by the growing acceptance of *caveat emptor* or "let the buyer beware." The expression *caveat emptor* appeared in print for the first time in the sixteenth century. Under the code of *caveat emptor,* buyers were not entitled to receive compensation for any problem associated with the product short of outright fraud on the part of the vendor, unless the vendor had explicitly guaranteed the item in question.

Until the first half of the nineteenth century, *caveat emptor* was the rule and sellers rarely offered any sort of formal warranty on their goods. In the late nineteenth century, warranties were treated as standardized contracts with extremely limited scope. Typical product warranty coverage usually excluded remedy for failed component parts, transportation charges, ensuing damages, and so forth. Manufacturers imposed one-sided standardized warranty terms as mechanisms to unilaterally limit their legal obligations to consumers. At the same time, deceit associated with the sale of goods, such as adulteration and misrepresentation, became widespread. Dishonest manufacturers offered warranties on products without any intention of discharging their obligations under warranty. As a result, consumers began to perceive a warranty of any sort as an indication of poor product quality.

Associated with these changes was the fact that businesses were becoming larger. In an effort to control the behavior of businesses, the Federal Trade Commission (FTC) was established in 1914 in the USA. The federal government formulated certain codes governing the sale of goods, enacted various Acts, and encouraged all states to adopt them in order to achieve consistency. Under one such act, the Uniform Sales Act, an express warranty is defined as

> *... any affirmation of fact or any promise by the seller relating to the goods ... if the natural tendency of such affirmation or promise is to induce the buyer to purchase the goods, and if the buyer purchases the goods relying thereon.* [2]

This definition illustrates the dual nature of the obligation of express warranty. The statute describes two kinds of express warranty, one that is promissory or

---

[1] [1] Loomba traced the history of the warranty concept from its ancient beginnings to the post-industrial era of consumerism and warranty legislation in the latter part of the twentieth century.

contractual in nature,[2] and a second, which is a non-promissory affirmation of fact.[3] It should be noted, however, that the implied warranties of quality and of title under the Uniform Sales Act were imposed by law and clearly were non-consensual [3]. The involved parties could potentially use their contractual power by means of a disclaimer to destroy a non-consensual warranty, but its creation in no way depends on their intentions [4].

During the twentieth century, consumer movements have had an impact on warranty. There have been three consumer movements. The first began in the early part of the twentieth century in reaction to marketplace excesses, which had their origins in the industrial revolution of the nineteenth century. The major consumer problems related to quality and safety of foods and drugs and came to an end with the onset of World War I.

The second consumer movement began after the end of World War I and the focus was on the shoddy performance of some of the consumer durables on the market. The courts offered very little warranty protection and implied warranties were unknown. This led to the creation of independent product testing organizations to curb such deceitful practices. Two of the most important such organizations were the Good Housekeeping Institute, run by *Good Housekeeping* magazine, which tested household goods; and Consumers' Research, a consumer-sponsored organization, which led to the publication of *Consumer Reports*. Approval from such organizations served as a symbol of acceptable product quality and gave credibility to a manufacturer's warranty. However the movement came to an end with the start of World War II.

The third consumer movement began after the end of World War II and gained momentum in the 1960s, paving the way for the additional consumer legislation mentioned previously. Because of growing concerns for buyers' protection, the notion of express warranty was augmented by another concept, "*implied warranty,*" which basically states that a product must be capable of performing its intended function when used properly and under normal operating conditions. By 1952, every state in the United States except Louisiana adopted what is termed the Uniform Commercial Code (UCC). This code specifies the obligations of manufacturers, distributors, and any other vendors, with regard to both express and implied warranties. Several forms of legislation have been enacted during the past few decades to regulate warranties on various products, the most notable such legislation being the Magnuson-Moss Warranty-Federal Trade Commission Improvement Act of 1975. An excellent discussion of express and implied warranties, the Magnuson-Moss Act and related issues may be found in [5].

---

[2] Analytically speaking, only the promissory express warranty and those affirmations of fact which constitute an implied-in-fact promise are consensual.

[3] Here, an actual agreement to a contract is not essential and the obligation is imposed by law, analogous to the implied-in-law promise.

1.3 Theories of Warranty

Through time, the perceived role of warranty in society has changed. As the notion of warranty became more complex and its use became more widespread, a number of theories of warranty were developed. We look next at three of these.

1.3.1 Exploitative Theory

The exploitative theory had its origins in pre-1950 legal literature on warranty. According to this theory, the terms of a warranty are developed for the manufacturer's benefit, while the consumer has few rights and bears the risks. Buyers who believe this theory often feel that if a product is sold, it should last a certain amount of time. The warranty is seen to serve the manufacturer by adding to the price of the product (i.e., by offering a service that should be provided anyway). These buyers reason that because a warranty is offered the manufacturer does not have confidence in the product.

Before 1975, consumers were still at the mercy of manufacturers. Warranties did not provide notice of consumer rights, disclaimers were couched in legal jargon, administration was confusing and ineffective, remedies for defective items were impractical, and excessive and unjustified claims often resulted from consumer frustration and hostility. The Magnuson-Moss Warranty Act (1975) aimed to provide consumers with information, improve the quality of warranties and provide procedures for consumer remedies. To some degree the Act succeeded. The readability of warranties has improved slightly, however the Act's standard of "simply and readily understood" is still an ideal that, for the most part, remains far from reality [6]. Another aim of the act was to ensure that warranty was a good indicator of the product's reliability, leading to the signal theory of Warranty.

1.3.2 Signal Theory

As products become more complex and less easily evaluated by consumers, warranties are used as signals [7] to indicate the product's performance and reliability. The product performance and warranty terms determine costs incurred by the manufacturer, so it follows that a longer warranty period results in higher costs unless product performance is of a correspondingly higher quality. This theory proposes that if a manufacturer offers a better warranty than a competitor, then the reliability of the product should also be better, to reduce costs associated with warranty claims.

Because of this signaling characteristic, warranty is an important product feature and can be used to promote sales. A market study in the *Journal of Consumer Research* concluded that for the consumer durables and motor vehicle markets "warranties were accurate signals of product reliability" [8]. A second study [9] found that for automobiles and some consumer durables, warranty was better at signaling product reliability after the Magnuson-Moss Warranty Act than before. Other studies have found that warranties were accurate signals both before *and* after the Act [6].

1.3.3 Investment Theory

More recently, warranty has been viewed as both an insurance policy and a repair contract. This gives rise to a third theory of warranty, the investment theory (more on this can be found in [10]). Under this theory, the buyer sees warranty as an investment that reduces the risk of costs due to early failure. Manufacturers are insured against having to rectify problems caused by inappropriate use, while the buyer is covered for repair costs of premature failures. The aim is to extend the useful life of the product by specifying responsibilities of the manufacturer and the buyer. By specifying a repair policy, the manufacturer aims to build a long-term relationship with customers, thereby retaining their business even after the warranty period expires.

1.4 Warranty and Manufacturing

1.4.1 Impact of Warranty

Modern industrial societies are characterized by (i) rapidly changing technologies, (ii) fierce competition between manufacturers whose products are often nearly identical due to common components and technology, and (iii) better educated and more demanding customers. This raises serious challenges for buyers, manufacturers and policy makers at national and regional levels.

The notion of post-sale support is becoming an important feature of most product sales. In this context, warranty (and extended warranty, which the consumer can buy at additional cost as opposed to the base or normal warranty that is an integral part of the sale) is an element of post-sale support and manufacturers need to view it as part of the post-sale service strategy. A warranty of any type, since it involves an additional service associated with a product, will lead to potential costs beyond those associated with the design, manufacture and sale of the product. These costs, in fact, are unpredictable future costs, which have typically ranged from 2% to as much as 15% of net sales [11], depending on the product and the manufacturer. According to D. F. Blumberg, total expenditures for repair and service in the USA is $247 billion, about 10 – 12% (or roughly $25 – 28 billion dollars) for goods under warranty. The market for stand-alone warranty/claims processing solutions in 2002 is $194 million, with another $110 million being spent on Internet-based warranty portals. The overall market, "still in infancy," is experiencing a 19% annual growth rate [12]. In the North American automotive industry, warranty costs were just over $700 million in 1965 and this increased to $5 billion by 1988 [13]; according to Thomas Roehm (SAS Automotive Practice Manager), this figure is currently 8.5 billion dollars. As a result of the substantial costs of administering and servicing claims, warranty has a significant impact on the total profits of a manufacturing business. Similarly, for businesses where new products purchased constitute a major component of the total operating budget, ineffective management of warranties can have a significant impact on total operating costs.

The cost of servicing a warranty depends on the reliability of the product as well as the product usage mode and the maintenance and care exercised by the buyer. Product reliability, in turn, depends on the decisions made during the design and manufacturing of the product. Warranty servicing costs can be reduced through better design and greater control during manufacturing. However, this results in higher unit manufacturing cost. Warranty and price play an important role in determining total sales and the implication of reliability on warranty cost is of great importance to manufacturers.

The normal (or base) warranty is integral to product sale and is factored into the sale price. In contrast, extended warranties are warranties that buyers can purchase by paying an additional amount, so that the item is covered for a period beyond that stated in the base warranty. Extended warranties are not only offered by manufacturers, but also by third parties such as dealers, many insurance companies and some credit card operators (such as American Express). It has been a source of additional revenue to businesses offering extended warranties. Ford recorded profits in excess of $100 million from sales of extended warranties in 1988 despite fierce competition from independent insurers. Sears alone is reputed to have sold over $1 billion worth of extended warranties in 1991 [14]. In the case of home electronics, at least half of the profits at some major appliance stores are due to sales of extended warranties [15].

1.4.2 Warranty Decisions

As mentioned earlier, warranty serves as a promotional tool that allows a manufacturer to differentiate its product from those of its competitors. Offering better warranty terms signals better product quality and greater assurance and this in turn leads to greater sales.

This implies that warranty decisions need to be made in a framework that takes into account the strong link between technical aspects (such as design and manufacturing) and commercial aspects (revenue generated by sales and the manufacturing and warranty servicing costs) from an overall business perspective.

The following is an illustrative sample of some of the decision problems that a manufacturer needs to address:

1. How does product reliability affect claims over the warranty period?
2. What is the impact of poor quality control during production on the expected warranty servicing cost?
3. What is the expected warranty servicing cost as a function of the terms of the warranty policy?
4. What should be the optimal investment in reliability improvement, given the warranty terms?
5. What testing effort should be undertaken to reduce the risk that the warranty cost will not exceed some specified value?
6. What warranty strategy should be used to promote the product?
7. What is the expected number of spares needed to service failures of a non-repairable component over the warranty period?

8. How should one deal with the logistic issues for effective warranty servicing?
9. How should service agents for servicing claims under warranty be selected?
10. How should the contract with the service agent be drafted to provide incentives for honesty and for provision of the best possible service?
11. What kind of data should be collected for effective warranty management?
12. How does one develop an effective warranty management system?
13. How should a manufacturer administer warranties for consumer durables?
14. How should a manufacturer administer warranties that include reliability performance measures?
15. How should a manufacturer respond to changes in warranty legislation?
16. How can a warranty dispute be resolved?

Manufacturing is a complex system involving the following four stages:

- Design and Development
- Production
- Marketing
- Post-sale Support

Warranty decisions must be made taking into account the link between warranty and other decisions at each of these stages. In addition, legal aspects, including the legislative and judicial processes relating to production and sale of products, must be taken into account. Figure 1.1 shows the different key elements that are relevant for solving a variety of warranty decision problems, some of which were discussed earlier. Each of the elements involves several variables and these interact with each other. These interactions need to be taken into account in effective warranty decision-making and will be discussed in more detail in later chapters of the book.

1.4.3 Warranty Management

Management needs to be done at two different levels – strategic and operational. Strategic Management deals with decision-making with regard to all aspects of the product from an overall business viewpoint and over the product life cycle, which encompasses the period from initial conception to manufacture and marketing to product obsolescence. As such, the time frame is long and the decision-making needs to take into account the uncertain nature of the impact of external factors (for example, the economy, competitors actions, etc.) and some internal factors (for example, outcome of research and development). A strategy is a managerial outline for the future. Within a business, there are both long-term strategic objectives and shorter-term operational goals that affect the structure and functionality of business dynamics. Strategic management aims to integrate these into a consistent overall “business strategy” outlining the future direction of the company within a specified planning period (medium to long term). Operational management is responsible for achieving the day-to-day intermediate steps needed to reach the strategic objectives.

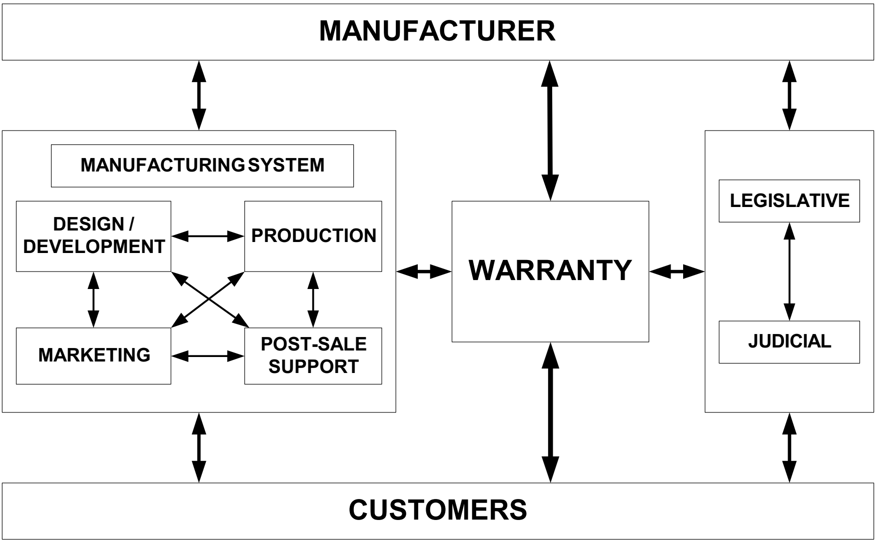


Figure 1.1. Warranty and manufacturing

Organization's strategies are set by top management and influence strategies at lower levels. These include technical/operational strategies such as the following:

- *Technical strategies* – outline goals, expectations and measures by which product performance can be ascertained and improved.
- *Design and development strategy* – concerned with product design, development and testing; developed in response to new product strategy objectives for design and reliability.
- *Manufacturing strategy* – covers the quality and cost aspects of production.
- *Material purchasing strategy* – oversees the selection and quality of materials, parts and components from suppliers, and associated contractual issues.
- *Process control strategy* – concerned with the size of production lots, monitoring methods, the design of the product and process, and the manufacturing cost; outlines procedures for sampling and testing and standards for acceptance, and helps to monitor process quality.
- *Process maintenance strategy* – describes the procedures for maintenance scheduling and aims to minimize unplanned down time and associated costs.

Commercial strategies that are developed in response to corporate strategies to control cost and promotional aspects include the following:

- *Marketing strategy* – involves assessing the potential market to ascertain what product features, price, and warranty terms are in demand, and developing strategies for pricing and for advertising in response to these.

- *Post-sale servicing strategy* – outlines procedures and objectives for warranty terms, extended warranty issues, and repair strategies.
- *Service strategies* – developed to provide benefits to customers and deal with customer dissatisfaction.

1.5 Objectives of the Book

The main objective of the book is to present an approach to strategic warranty management from an overall business point of view. This implies addressing a variety of warranty-related decision problems, taking into account the link between warranty and the different elements of manufacturing. Strategic warranty management requires that the warranty strategy must be formulated in conjunction with other functional (technical and commercial) strategies. Operational strategies then need to be developed to address various issues, taking into account the link between warranty and activities at the different elements of manufacturing.

The book is designed to help managers manage the internal warranty process. Critical to the success of this is the systems approach, involving the use of analysts to execute some of the essential steps. Managers need to understand what analysts need in order to carry out their tasks. One of these is a data collection system. Proper data collection is critical. The different kinds of data generated at each of the four elements of a manufacturing system (shown in Figure 1.1) will be discussed in later chapters and the relevance of these for warranty decision-making will be highlighted throughout the remainder of the book.

In addition, the analyst needs several different tools and techniques for model building, analysis and optimization. We do not discuss this in detail, but do cite appropriates references. As such, the book is a good starting point for analysts who will assist managers responsible for product warranty in a business.

The book deals with a variety of issues relating product warranty and manufacturing. Many of these are illustrated using one or more of the following products.

Product 1: Photocopier
Product 2: Automobile

1.6 Outline of the Book

The book is comprised of 15 chapters. In this section we give a brief outline of each chapter.

Chapter 1. Introduction and Overview
Chapter 1 begins with a brief discussion on the scope and focus of the book. Effective warranty management requires a framework that can integrate the different technical and commercial aspects of manufacturing. These are discussed briefly and the chapter concludes with an outline of the book.

Chapter 2. Products and Product Quality
Chapter 2 begins with a discussion of products and alternate ways of classifying products. It then looks at various measures of product performance.

Chapter 3. Product Warranty
The concept, role and different perspectives on warranty are discussed in Chapter 3. A taxonomy for warranty is presented along with a range of warranty policies.

Chapter 4. Warranty Management
Chapter 4 deals with warranty management at both strategic and operational levels. At the strategic level, warranty strategy must be decided in conjunction with other technical (design, production) and commercial strategies (marketing, servicing). This is done using the concept of a product life cycle consisting of five stages: (i) Front-end, (ii) Design and Development, (iii) Production, (iv) Marketing, and (v) Post-sale Support. At the operational level, decisions regarding several technical issues (such as testing for reliability) and commercial issues (such as inventory levels for effective servicing of claims) are addressed in a manner that ensures that they are compatible with the strategic decisions.

Chapter 5. Systems Approach to Warranty Management
The systems approach is a very general approach for solving many different kinds of problems. It is an important tool for evaluation of alternate options and decision-making with regard to optimal strategies. The key element of the approach is the use of mathematical models. In Chapter 6 we discuss the systems approach and discuss some issues relating to model building.

Chapter 6. The Role and Use of Data in Warranty Management
There are many types of data that are of importance in the context of warranty management. These include test data, economic data, claims data and numerous others. In Chapter 6, we discuss the collection, analysis, interpretation and uses of data for modeling, prediction, and other aspects of warranty management.

Chapter 7. Warranty Cost Analysis
Chapter 7 deals with warranty cost analysis from both manufacturer and buyer perspectives. This involves the use of models to predict warranty claims, taking into account important variables such as product reliability, warranty-servicing actions, customer usage patterns, and so forth.

Chapter 8. Warranty Considerations in Product Design and Development
The reliability of a product depends on the engineering of the product based on decisions made during the design and development stages. The reliability of a product can be improved through better design and development and such an improvement leads to lower warranty costs. Reliability improvement, however, involves additional costs and is worthwhile only if the reduction in warranty costs exceeds these costs. Chapter 8 deals with the interaction between warranty and design and development.

Chapter 9. Implications of Warranty on Production Decisions
Because of variability in production, the quality of items produced varies. In the simplest characterization of this variability, an item is classified as either conforming to design specifications or not. The reliability of nonconforming items is low and results in high warranty costs. Chapter 9 looks at the link between product quality and warranty. There are several strategies for improving product quality. All involve additional costs. Optimal decisions with regard to quality control and improvement take into account the trade-off between the cost of quality and warranty costs.

Chapter 10. The Role of Warranty in Marketing
Warranty in the marketing context serves a dual role. It provides (i) information regarding product reliability and (ii) assurance against product failures over the warranty period. Better warranty terms (such as a longer warranty period) improve sales. This results in higher revenue, but also results in greater warranty costs. This, in turn, impinges on the sale price. Thus the choice of warranty terms, as a marketing strategy, must take into account the interaction between price, warranty terms, and sales. Chapter 10 looks at this issue and at decision-making with regard to marketing strategies, taking into account the interaction between warranty and marketing variables.

Chapter 11. Warranty Logistics
Warranty logistics deals with all of the operations necessary for servicing warranty in the most cost-effective manner. Here we deal with issues such as location of warehouses for spare parts and repair facilities, inventory levels for spares, and warranty servicing strategies. In many cases, a third party carries out the servicing of warranty. This raises several new issues (such as adverse selection, moral hazard, contracts, etc.) that the manufacturer must address. Chapter 11 deals with these issues and with strategies for cost-effective warranty servicing.

Chapter 12. Reliability Improvement Warranties
Reliability Improvement Warranty (RIW) policies are different from standard warranties in that the RIW requires that the manufacturer carry out reliability improvement if the reliability performance falls short of the levels stated in the warranty contract. The management of such warranties poses new challenges and these are discussed in Chapter 12.

Chapter 13. Financial, Societal and Legal Aspects of Warranty
The accounting of warranty for taxation purposes is important because of the dual (promotional and protectional) roles of warranty. In addition, any warranty decision must take into account relevant warranty legislation, much of which has arisen in response to issues pursued by the consumerism movement. Finally, warranty disputes occasionally arise for a variety of reasons. These factors must be taken into account in the overall management of warranty and are briefly discussed in Chapter 13.

Chapter 14. Warranty Management System
Warranty management requires linking warranty decisions with decision-making at the different stages of the product life cycle. This must be done in an integrated manner. The warranty management system needed for accomplishing this is addressed in Chapter 14. The key elements of a warranty management system are (i) a data collection system, (ii) a package of tools and techniques for data analysis and for model building, analysis and optimization, and (iii) a user interface to assist the manufacturer in making proper decisions for effective warranty management.

Chapter 15. Conclusion
Chapter 15 summarizes the salient points of the book in the form of guidelines to assist manufacturers in the strategic management of warranty from an overall business viewpoint.

References

[1] Loomba, A. P. S. (1996), "Historical Perspective on Warranty," Chapter 2 in *Product Warranty Handbook*, W.R. Blischke and D.N.P. Murthy (eds), Marcel Dekker, Inc., New York.

[2] Vold, L. (1959), *Handbook of the Law of Sales, 2nd Edition*, West Pub. Co., St. Paul, MN, p. 427.

[3] Williston, S. (1948), *The Law Governing Sale of Goods at Common Law and Under the Uniform Sales Act*, Baker and Voorhies, New York, p. 420.

[4] Williston, S. (1948), *The Law Governing Sale of Goods at Common Law and Under the Uniform Sales Act*, Baker and Voorhies, New York, pp. 230 and 230a.

[5] "A Businesspersons Guide to Federal Warranty Law," available at http://www.ftc.gov/bcp/conline/buspubs/warranty.htm

[6] Burton, J. R. (1996) "Warranty Protection: A Consumerist Perspective," Chapter 28 in Blischke and Murthy (1996).

[7] Spence, M. (1977), Consumer misperceptions, product failure and producer liability, *Review of Economic Studies* **44**, 561−572. The origin of the signal theory is credited to Spence.

[8] Weiner, J. L. (1985), Are warranties accurate signals of product reliability?, *Journal of Consumer Research* **12**, 245−250.

[9] Kelly, C. A. (1988), An investigation of consumer product warranties as market signals of product reliability, *Journal of the Academy of Marketing Science* **16**, 72−78.

[10] Priest, G. L. (1981), A theory of the consumer product warranty, *Yale Law Journal* **90**, 1297−1352.

[11] McGuire, E. P. (1980), *Industrial Product Warranties: Policies and Practices*, The Conference Board, Inc., New York.

[12] Ericson, J. (2002), The word on warranties, *Line 56, The E-Business Executive Daily*, May 23, 2002. (http://www.line56.com)

[13] Menezes, M. A. J., and Quelch, J. A. (1990), Leverage your warranty program, *Sloan Management Review* **31**, 69−80.

[14] *San Francisco Chronicle*, January, 1992. (Cited in Padmanabhan, V. (1996), “Extended Warranties,” Chapter 18 in Blischke and Murthy (1996).)

[15] *Business Week*, January 14, 1991.

2

Products and Product Quality

2.1 Introduction

Products affect each and every one of us every day of our lives. We use them in many different ways and for many purposes, ranging from eating, wearing and medication, to communication, transport, and energy production, and we are often totally dependent on them. Products are continuously evolving, with new ones replacing earlier ones, thus defining a product life cycle. The rate at which new products have been appearing on the market has been expanding at an exponential rate and the cycle times are becoming shorter. In order to survive and grow in such an environment, manufacturers must continuously produce new products with improved quality. In this chapter, we deal with products and product quality issues.

The outline of the chapter is as follows. In Section 2.2 we look at product classification, decomposition and the bundling of product and service. Section 2.3 deals with product quality and briefly reviews different definitions and notions of quality. An important topic of focus in this section is the connection between product quality and customer satisfaction. Section 2.4 introduces the notion of a product life cycle from the manufacturer and buyer perspectives. The former is used extensively in later chapters. Reliability is one of the quality dimensions and of great importance in the context of warranty costs. This topic is discussed in Section 2.5.

2.2 Products

A narrow definition of products is that they are physical and tangible. This is in contrast to services, which are intangible. The distinction between products (as defined above) and services is becoming blurred and a more commonly accepted definition is that a product generally involves combinations of the tangible and the intangible, for example:

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).[1]

2.2.1 Product Classification

Broadly speaking, products can be categorized into the following four groups:

- **Consumer non-durables**: These are consumed by society at large and include items such as processed food, cosmetics etc. In general these are inexpensive items and often not covered by warranty. However, various health and safety standards cover such items and provide protection to consumers.
- **Consumer durables:** Society at large, as well as commercial enterprises and government agencies are all users of consumer durables (e.g., computers, television sets, furniture, appliances, automobiles), and there are typically many manufacturers competing in the marketplace. Thus this group may be characterized by the large number of consumers for, and manufacturers of, the product. The complexity of the products in this group can vary considerably.
- **Industrial and commercial products:** Industrial and commercial products (e.g., large-scale computers, cutting tools, pumps, X-ray machines, commercial aircraft, hydraulic presses) are characterized 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 aircraft, trucks, pumps, and so forth, or product components needed by a manufacturer, such as large storage batteries, commercial drill bits, electronic modules, turbines, etc.
- **Specialized defense-related and industrial products:** Specialized defense products (for example, military aircraft, ships, rockets) are characterized by one or more consumers (for example, several countries) and a relatively small number of manufacturers. The products are usually complex and expensive and involve "state-of-art" technology with considerable research and development effort required of the manufacturers. 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 specialized industrial products.

Another classification of products is as follows:

- **Standard products:** These are manufactured in anticipation of a subsequent demand. As such, these products are manufactured based on

[1] See ISO9000 [1].

previous experience and the results of market surveys. Products of this type include all consumer durables and most commercial and industrial products.

- **Custom-built products:** These are manufactured in response to a specific request from a customer. Specialized defense and industrial products would be in this category, as would commercial products such as some aircraft, luxury items, and so forth.

Example 2.1 [Photocopier]

The modern photocopier is one of the most common and important pieces of office equipment in the modern workplace and can be found in many homes for personal use as well. The development of the photocopier can be traced back to the early 1800s. The earliest versions were the projection copiers. These included a copy camera and a photostat machine. The copy camera took a photograph of the original negative. The film was then developed using liquid chemicals. This converted the negative into a positive copy that could be either smaller or bigger than the original. A photostat machine operates like a printing machine with the original being a stencil that is coated with ink (a chemical liquid) and then printed on a paper.

The transition from a wet to a dry process was a major technological breakthrough. The dry process was invented in 1938 by Chester F. Carlson (an American physicist) and involved electrostatic photocopying. This type of photocopying is known as “xerography” (a word derived from two Greek words – “xeros” meaning dry and “graphy” meaning writing).

Photocopiers have been continuously evolving and modern versions act as printers for computers and have sophisticated logic built in to do several tasks. There are many manufacturers of photocopiers. Xerox, Canon, Kodak, Mita, Ricoh, Toshiba are few of the well-known brands.

In the USA the sales and rentals of photocopiers has been growing steadily and the revenue generated, at the industry level, is shown in Table 2.1. The total number of units sold in 1999 was 907,470.

Table 2.1. Revenues in the US copier industry (in billion dollars)

Year	1984	1989	1994
Sales	3.9	4.7	4.6
Rentals	3.3	3.8	4.6
Service	3.1	5.4	5.8
Supplies	3.0	4.3	4.9

The process of xerography involves the following steps: [2]

1. The clean surface of a “photoreceptor” drum (or belt) is coated with a light sensitive (photo-conductive) material that acts as an insulator in the dark and as a conductor when exposed to light.

[2] For more details, see http://www.physics.uoguelph.ca/summer/scor/articles/scor54.htm and Bruce and Hunt [2].

2. The photoreceptor material is electrically charged positively through a "corona wire".
3. Light is reflected from the original through a lens on to the drum.
4. The light dissipates the charge on the drum in the areas of the image that are blank. A positively charged image then forms on the light sensitive surface.
5. The negatively charged "toner" (also referred to as "dry ink") is dusted on the drum and sticks to the positively charged image on the drum. This leaves a "toner image" of the original on the drum.
6. A paper charged positively with the corona wire is pressed against the drum so that the toner image is transferred.
7. The "fuser" heats the positively charged paper for a short period so that the toner is permanently attached to the paper.
8. The drum surface is cleaned by "cleaning blade" to remove the remainder of the toner and transferred into a waste bin so that the process can be repeated.

■

Example 2.2 [Automobile]

The automobile is a self-propelled passenger vehicle designed to operate on ordinary roads. The earliest automobile had a steam driven engine and was produced in 1769. The earliest gasoline car appeared in 1855 and since then it has gone through many technical innovations.

Automobiles can be classified into several types based on (i) structure and usage – passenger cars (PC), light trucks (LT), vans, buses, etc., and (ii) the primary energy source – petrol, diesel, electric, hybrid (combinations of petrol and electric) and others such as hydrogen, solar, etc., which are still in the experimental stages. The underlying principle of the gasoline-powered automobile is fairly simple. The chemical energy in fuel (petrol or diesel) is released through combustion in the cylinders of the engine and transmitted to the wheels through a transmission system to achieve the desired motion. In the case of an electric automobile, energy stored in a battery is used to run an electric motor and this in turn is transmitted to the wheels.

Mass production of automobiles started in the early part of the twentieth century with the Model T produced by Ford. Since then, the automotive industry has grown significantly in the USA and many other countries and has a significant impact on the national and global economies. In the USA, the big three companies (General Motors (GM), Ford and Daimler-Chrysler) reported total revenues of over 49, 41 and 18 billion dollars, respectively, for the first quarter of 2003. The automobile has affected the life styles and the social fabric of industrial societies.[3]

The annual unit sales of passenger cars in the USA for the big three (GM, Ford and Chrysler) and others (primarily imports) over the period 1981–2002 are shown

---

[3] There are several books that deal with the economic and social impacts of the automobile. See, for example, Rae [3] and Flink [4].

in Table 2.2. A plot of the annual sales of passenger cars (PC) and light trucks (LT) is shown in Figure 2.1.[4]

Table 2.2. Annual sales of automobiles in the USA (thousands)

	Manufacturer				
Year	**Chrysler**	**Ford**	**GM**	**Others**	**Total**
1981	841	1,413	3,797	2,464	8,515
1982	794	1,346	3,516	2,300	7,956
1983	951	1,571	4,054	3,973	9,149
1984	1,079	1,979	4,601	2,665	10,324
1985	1,245	2,079	4,693	2,962	10,979
1986	1,309	2,081	4,693	3,321	11,404
1987	1,096	2,061	3,728	3,302	10,187
1988	1,191	2,290	3,822	3,240	10,543
1989	1,020	2,178	3,437	3,142	9,777
1990	861	1,936	3,309	3,194	9,300
1991	703	1,636	2,909	2,927	8,175
1992	680	1,778	2,844	2,911	8,213
1993	834	1,964	2,927	2,793	8,518
1994	812	2,036	3,080	3,063	8,991
1995	786	1,898	2,956	2,995	8,635
1996	833	1,844	2,786	3,063	8,526
1997	737	1,720	2,689	3,126	8,272
1998	739	1,660	2,456	3,287	8,142
1999	745	1,733	2,591	3,629	8,698
2000	649	1,687	2,532	3,979	8,847
2001	558	1,495	2,272	4,098	8,423
2002	527	1,326	2,069	4,181	8,103

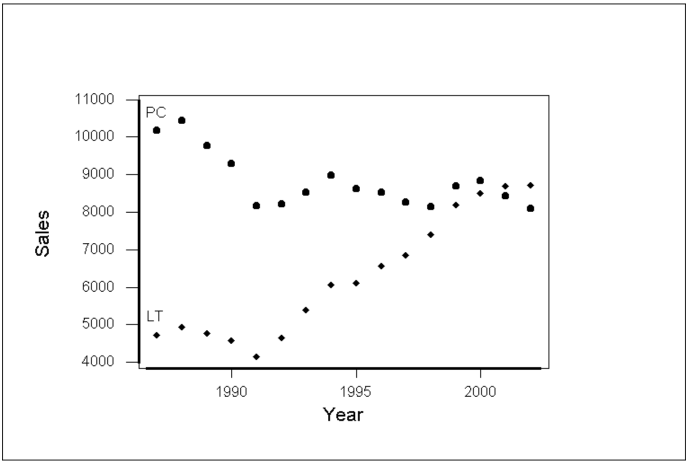


Figure 2.1. Vehicle sales (thousands), by type (1987–2002)

■

[4] The data are from Ward's Communications [5].

2.2.2 Product Decomposition

A product can be viewed as a system that consists of several elements and that 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. The following seven-level description would provide a detailed breakdown:

Level	Characterization
0	System
1	Sub-system
2	Major assembly
3	Assembly
4	Sub-assembly
5	Component
6	Part

Such detailed product characterizations are often necessary because of the increasing complexity of products, due mainly to technological advances. The common farm tractor illustrates this growth in product complexity [6]:

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. The success of the Mariner/Mars spacecraft required the satisfactory performance of some 138,000 components over the nine months of its mission in space [7]. The Boeing 747 has 4.5 million parts [8]. Other very large systems in terms of parts counts are the space shuttle and its launch system, large naval ships such as aircraft carriers, telecommunications systems, and so forth.

Example 2.3 [Photocopier]

The modern photocopier is a complex system consisting of a large number of components. These can be grouped into several sub-systems as follows:

1. Drum: surface
2. Optical: lens, lamp, mirror
3. Electro and chemical: corona wire, toner
4. Heating: fuser
5. Mechanical: feed mechanisms, cleaning arm
6. Electronic control: to perform various control tasks
7. Diagnostics: to detect problems and display on the front panel
8. Environment related: ozone filter, waste bin

■

Example 2.4 [Automobile]
The modern automobile is a complex system comprising of over 15,000 components and can be decomposed into the following sub-systems:[5]

1. Body (passenger compartment)
2. Engine (power source)
3. Chassis (for supporting engine and body)
4. Transmission (for transmitting power from engine to the wheels through shafts and gears)
5. Controls (for accelerating, braking, steering, etc.)
6. Cooling (for cooling the engine, providing comfort to passengers)
7. Electrical (battery, starting motor, lights, logic controllers)
8. Safety (seat belts, air bags, locks)
9. Lubrication
10. Fuel (tank, carburetor, filters, fuel lines)
11. Exhaust system (muffler, catalytic converter)
12. Others (seats, doors, windows, radio, etc.)

Each of these in turn can be decomposed into assemblies, sub-assemblies, and so forth, down to the part level. The components for some of the sub-systems are as follows:
Engine: cylinder block, cylinder head(s), pistons rings, connecting rod, bearings, crankshaft main bearings, camshaft bearings, cam followers, timing chain or belt; timing gears, guides, rocker arms, rocker shaft, rocker bushings, cylinder head valves, valve guides, valve lifters, valve springs, valve seals, valve retainers, valve seats, push rods, water pump, oil pump and oil pump housing, oil pan, intake and exhaust manifolds, valve covers, engine mounts, turbocharger/supercharger housing seals and gaskets
Transmission (Automatic or Standard): transmission case, torque converter, electronic shift control unit, transmission cooler, oil pan; seals and gaskets
Cooling: engine cooling fan and motor, fan clutch, belt, radiator, heater core, thermostat, blower motor, hot water valve
Electrical: alternator, voltage regulator, starter motor, starter solenoid and starter drive, engine compartment wiring harness, computerized timing control unit, electronic ignition module, crank angle sensor, knock sensor, ignition switch, ignition switch lock cylinder, front and rear window wiper motors, washer pump and switch, stop lamp switch, headlamp switch, turn signal switch, heater/air conditioner blower speed switch, manual heater/air conditioner control assembly, and horns
Fuel Delivery: fuel pump, fuel injection pump and injectors, vacuum pump, fuel tank, fuel tank sending unit, metal fuel delivery lines.

■

[5] See http://auto.howstuffworks.com for a discussion of the principles of how these sub-systems work.

2.2.3 Perspectives

One can look at a product from many different perspectives. For our purposes, the key considerations are:

- **Business**: From the business viewpoint, the focus is on the impact of the product on overall business performance.
- **Technical**: The technical aspects deal with the engineering of the product. Here the focus is on technical issues that ensure that the product has the desired characteristics and attributes.
- **Commercial**: The commercial aspects deal with issues such as promotion, sales, pricing, revenue and costs.
- **Customer**: Product-related issues viewed from the customer perspective include cost, operation, maintenance, reliability, useful life, and so forth.
- **Environmental**: Issues dealing with the environmental impact of the new product are of great importance in the context of "green" movements that advocate "environmentally friendly" products and the support for these movements is increasing around the world.
- **Safety and Regulatory**: All products must meet certain requirements regarding safety when used in the intended mode of operation. Failure to do so can result in accidents that can lead to environmental damage, loss of life and economic costs. Most products need to conform to international, national or industry standards.

2.2.4 Product Service Bundling

When making product purchases, customers believe that they are buying more than a physical item. They also have expectation about the level of support service subsequent to the sale of the product. As a result, customers tend to combine product and service attributes together as part of a total package to which they attach some individual perceived value. Most products fall somewhere between pure product and pure service. Manufacturers need to decide which attributes or tangibles are more important than others according to the needs of their customers.

Product support includes installation, documentation, maintenance and repair services (also called field service), user training, and equipment upgrading. Good product support plays a key role in ensuring high customer satisfaction. A majority of dealers for simple domestic appliances perceive product service as a selling point, and good field service can give a competitive edge to technology firms. The importance of post-sale activities in the context of product choice has received a good deal of attention in the literature.[6] Product support service can add value to the tangible product in several ways. Examples of factors that add value to the product from the customer's perspective are:

---

[6] See for example, Lele [9], Lele and Karmarkar [10], Ives and Vitale [11 and 12], and Ritchken, Chandramohan and Tapieor [13]. For a discussion of customer support during the design stage of a new product to ensure high customer satisfaction, see Goffin [14].

- Prompt and proper delivery and installation
- Extending the life of the product
- Direct value in the initial sale and subsequent re-sales
- Comprehensive warranty coverage.

Some of these factors are related. For example, the re-sale value of a used automobile may drop significantly once the warranty expires.

Product support (providing spare parts, extended warranties or service contracts) has a higher profit margin (typically around 30%) as opposed to selling products (typically around 10%) [15]. This implies that product support is a source of significant revenue if manufacturers manage it properly. The product support market (comprised of both the original equipment manufacturer and third parties offering support) has grown at a rate more than 15% during the 1990s.

2.3 Product Quality

Product quality is difficult to define since there are several different notions associated with the concept. A dictionary definition for (product) quality is as follows [16]:

> *Relative nature or kind, distinguishing character; a distinctive property or attribute, that which gives individuality; particular capacity, value or function; particular efficacy, degree of excellence.*

According to the International Standardization Organization [1],

> *Product quality is the totality of features and characteristics of a product that satisfies the stated or implied needs.*

2.3.1 Perspectives

The two important perspectives on quality are those of (i) the manufacturer and (ii) the customer. Manufacturers' criteria may be summarized as "criteria that describe what the manufacturer put into the product," while customers' criteria are "criteria that describe what the consumer gets from the product". As a result, there are several different definitions and notions of product quality.

2.3.2 Definitions of Quality

Five definitions of quality are as follows [17]:

- **Transcendent**: This is synonymous with "innate excellence" and quality indicates an expression of excellence. It is viewed as neither mind nor matter but something different which is difficult to define but easy to recognize.

- **Product-based**: Product quality refers to the various attributes, features or characteristics that are intrinsic to the product. It is an objective, measurable variable, which can be described in terms of technical specifications.
- **User-based**: This is based on the notion that quality "lies in the eye of the beholder" and is very subjective.
- **Manufacturing-based**: Here quality is defined in terms of the product's ability to meet the stated specifications. Greater conformance to the specifications implies quality. Any deviations from specifications would indicate depreciation in quality. The level of conformance depends on the design of the product and the materials and processes used in its production.
- **Value-based**: The concept of value has its roots in the microeconomic tradition. Here the quality of a product is determined in relation to its price and not solely by its own merits.

2.3.3 Notions of Quality

Several different dimensions of product quality have been defined. Reliability is of special importance in the context of product warranty and will be discussed in more detail later in the chapter. We discuss briefly some other notions that are of relevance in the context of warranty management.[7]

- **Performance**: Product performance can be described as the response of a product to external actions in its working environment. This consists, in general, of a multi-dimensional set of variables, each of which is *a measurable property of a product or its elements*. The performance of an item is defined in terms of its functional properties, for example, power, throughput, fuel consumption, etc., in the case of an engine. Product performance is realized through the performance of its constituent components.
- **Conformance**: Due to variability in manufacturing, items produced are not all identical. As a result, the performance of items can vary. Conformance can be defined as the degree to which the performance of an item varies from a pre-specified performance standard. This is the most common accepted notion associated with conformance (or more correctly, with non-conformance). Conformance can be defined as the degree to which a product's design and operating characteristics meet pre-established standards. This definition is broader and includes conformance of the product design to some industry, national, or international standards. The occurrence of nonconforming items is affected by process capability and can be controlled through effective quality control strategies.
- **Durability**: Product durability is a measure of product life. All products deteriorate and degrade with time and/or usage. This can be controlled to

[7] For more on the definition and dimensions of quality, see Chapter 1 of Evans and Lindsay [18].

some extent through proper maintenance. Irrespective of this, the deterioration continues, resulting in the useful life of the product eventually coming to an end.

- **Serviceability**: Serviceability relates to the ease and speed with which a failed item can be restored back to its working state. As such, it is linked to repairability of the product and deals with duration and cost of repairs. Two types of service actions are encountered: (i) anticipated services requiring planning on the part of the buyer (dealing with issues such as installation, training, written instructions, maintenance, and upgrading) and (ii) unanticipated services (dealing with issues such as corrective maintenance to fix failures).
- **Perceived Quality**: Perceived quality is a result of the consumer's (the buyer's) subjective assessment of the quality of a given product. Perceived quality thus differs from objective quality. Objective quality depends on the technical and functional specifications of a product. Subjective quality, on the other hand, is linked to the consumer and her/his perception of the quality of a product.

2.3.4 Product Quality and Customer Satisfaction

From the manufacturer's point of view, customer satisfaction is very important, as indicated by the following statement [19]:

> *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.*

As a result, manufacturers are forced to offer every possible value-added service in order to achieve customer satisfaction and retain those customers who already do business with them. In order to satisfy the consumer, the product and any associated services must meet or exceed his/her expectations and needs.

High customer satisfaction is important for:

- Repeat sales
- Positive word-of-mouth promotion
- Customer loyalty.

A customer is satisfied when his/her perception of the ratio of benefits (from the product and associated services) to the costs paid to obtain the benefits are met or exceeded. This involves (i) perceived product quality, (ii) value-based notion of quality, and (iii) perceived service quality. The benefits customers expect depend primarily on how they perceive product and service quality, and whether or not their perceptions are valid. Customers often tend to use limited knowledge of product and tangible service attributes to assess quality, as many dimensions of quality cannot be observed directly in most cases.

For most products, the product and service attributes can be grouped into two categories: (i) "hygiene" factors and (ii) "satisfiers" or "motivators".[8] Customers expect minimum levels for the hygiene factors (for example, spare parts, service centers). The lack of this level results in dissatisfaction. Any hygiene factors done in excess to what the customers expect will not increase the expected benefits to customers. The satisfiers are those attributes (for example, good service, free consulting) that go beyond the customer's expectations and enable a firm to gain and create a competitive advantage. These go beyond the expected levels of performance and add unexpected value to the bundle of attributes offered to the customer.

If a firm does not provide an adequate number of hygiene factors, this will result in dissatisfied customers. However, having an adequate number of hygiene factors does not help to create customer satisfaction. A firm creates customer satisfaction by using satisfiers. A manufacturer not providing good post-sale service leads to customer dissatisfaction. In this sense it is a hygiene factor.

Customer satisfaction is different from customer loyalty.[9] A satisfied customer will shop anywhere. Satisfaction does not give any indication that the customer will repeat a purchase. A loyal customer is a satisfied customer who not only continues to be loyal in terms of repeat purchases, but also proactively promotes the product through word-of-mouth. In the automobile industry, in which 85% to 95% of the customers reported that they felt satisfied, only 30% to 40% return to buy the same make or model of car [22]. Loyalty can be viewed as the highest form of customer satisfaction.

In order to ensure a high level of customer satisfaction, manufacturers must have a quality product. Without a quality product or service, there is no chance to achieve satisfaction.

For consumer durables, customer satisfaction and customers' perception of product quality is a complicated issue. Different individuals may have different views on a product's quality for the same product. 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 determine, for example, how easy it is for a customer to operate a product), on individual experiences and preferences (a customer having had a bad experience with a manufacturer's product will consider another manufacturer), and on basic functional needs (which can vary from one to another). In order to produce a product that meets customer expectations, the manufacturer needs to ensure that these are well understood and properly defined. Often, customer expectations are expressed as vague statements. This is particularly true for consumer durables.

Example 2.5 [Automobile]

The following is a list of customers' comments on what constitutes a reliable automobile [23]:

---

[8] This was first proposed by Nauman and Jackson [20].

[9] This topic is dealt with in some detail by Gitmore [21].

- Last for a long time
- Starts every morning
- A well-made car
- No breakdown
- Consistent performance
- Hassle-free during ownership
- Dependable
- Maintenance free.

■

Customer satisfaction in the context of industrial products is different from that of consumer durables. For consumer durables, the individual consumer is the unit of analysis for satisfaction. In business-to-business transactions, the customer is no longer a passive buyer but an active partner, and the relationship between the customer and manufacturer is long-term in nature and complex.[10]

2.4 Product Life Cycle

New products are appearing on the market at an ever-increasing pace, mainly as replacements for existing products. This leads to the concept of product life cycle. There are a number of approaches to this concept. 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. 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.

2.4.1 Manufacturer's Point of View

We consider two approaches, the first based on a marketing perspective and the second on a production perspective. From the marketing perspective, the product life cycle is defined as the curve that represents the unit sales for some product extending from the time it is first entered into the marketplace until it is removed. In this traditional form, the product life cycle describes sales over time and is usually characterized in terms of the following four phases:

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

A typical plot of the life cycle is shown in Figure 2.2.

---

[10] Customer satisfaction in the context of industrial products has received very little attention relative to that for consumer products. For a more detailed overview of customer satisfaction for consumer products, see Oliver [24] and Homburg and Rudolph [25].

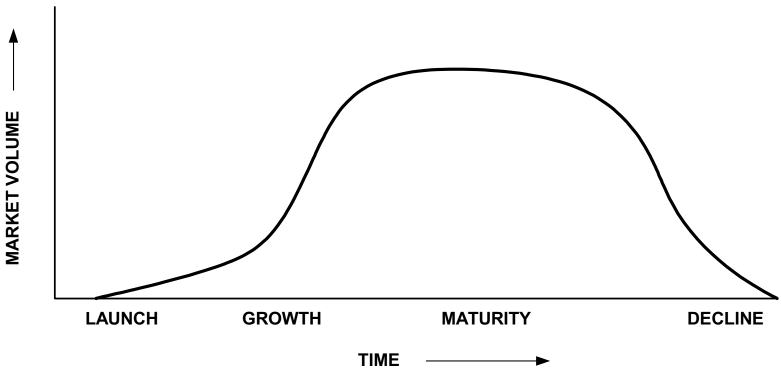


Figure 2.2. Product life cycle

From a 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 (comprising of three phases) and post-launch (comprising of two phases). 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. The five phases occur sequentially and are as follows:

- **Phase 1** [Front-end]: Evaluation of an initial product idea, identification of target characteristics and pricing, and a feasibility study leading to a go/no-go decision.
- **Phase 2** [Design and development]: Development of non-physical product solutions and construction of a prototype.
- **Phase 3** [Production]: Coordination of materials, processes and other resources necessary to produce the product.
- **Phase 4** [Marketing]: Distribution and promotion.
- **Phase 5**: [Post-sale servicing] All the activities needed to ensure satisfactory performance of the product over its useful life.

Note that the marketing phase can be divided into four sub-phases, as indicated above.

2.4.2 Buyer's Point of View

From the buyer's viewpoint, the product life cycle is the time from the purchase of an item to its discarding at the end of its useful life or its replacement for any of a number of reasons (obsolescence, maintenance cost, lack of efficiency, etc.). The life cycle for the buyer involves three phases, namely

- **Phase 1**: Acquisition,

- **Phase 2**: Operation and maintenance, and
- **Phase 3**: Discard and replacement by new one.

2.4.3 Product Performance

Here we consider the product life cycle from the production perspective. The first two phases constitute the pre-launch stage, and the last three phases, the post-launch stage. In this structure, three notions of product performance are useful: (i) desired performance, (ii) predicted performance, and (iii) actual performance. These are indicated in Figure 2.3 and discussed below. They are of particular importance in the context of new product development.

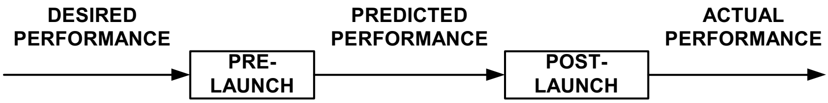


Figure 2.3. Performance and product life cycle

- **Desired performance** may be defined as *a statement about which performance is desired from an object, i.e. 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. The manufacturer’s 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 (such as total sales, profits, etc.). The degree to which the manufacturer succeeds in fulfilling these expectations determines the customer satisfaction. Desired performance may be defined as a range, a minimum or maximum value, or an absolute value.
- **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 performance goals. This forms the basis for decisions during the various phases of the product life cycle.
- **Actual performance** may be defined as *observed performance of a prototype of an object during development or over its operating life*. Actual performance will differ from the desired performance. The more the actual and desired performances differ, the greater is the probability that the object will not satisfy the manufacturer’s and/or customers’ expectations.

2.4.4 Product Cost

2.4.4.1. Manufacturer’s Perspective

From the manufacturer’s perspective, two costs of importance in the design of a product are *design to cost* (DTC) and *life cycle cost* (LCC).

In the design to cost 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 life cycle cost 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 defense and industrial products. Buyers of such products often require a cost analysis from the manufacturer as a part of the acquisition process.

2.4.4.2. Buyer's Perspective

From the buyer's perspective, the costs of importance are the initial acquisition cost, the average operating cost per unit time and life cycle cost. Product performance and cost are closely linked. The value-based notion of quality defined previously deals with this issue.

2.5 Product Reliability

2.5.1 Definition

Reliability of a product conveys the concept of dependability, successful operation or performance, and the absence of failures.

Example 2.6 [Automobile]

A crude way of characterizing the reliability of a product is through the number of problems encountered by customers over some specified time period subsequent to the sale. Consumer organizations carry out such studies and report the results as a guide to readers of consumer magazines. Table 2.3 is a report of one such study. We will discuss more comprehensive characterizations of reliability in later chapters.

Table 2.3. Automobile reliability (problems per 100 vehicles)

Brand	Problems
Toyota	10
Honda	11
Hyundai	11
Subaru	13
Nissan	15
BMW	20
Mazda	20
Volkswagen	20
General Motors	21
Mercedes-Benz	22
Ford Motors	23

■

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:

The *reliability* of a product 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.

Reliability theory deals with the interdisciplinary use of probability, statistics and stochastic modeling, combined with engineering insights into the design and the scientific understanding of the failure mechanisms, to study the various aspects of reliability. As such, it encompasses issues such as (i) reliability modeling, (ii) reliability analysis and optimization, (iii) reliability engineering, (iv) reliability science, (v) reliability technology and (vi) reliability management.

Reliability modeling deals with model building to obtain solutions to problems in predicting, estimating and optimizing the survival or performance of an unreliable system, the impact of unreliability, and actions to mitigate this impact.

Reliability analysis can be divided into two broad categories: (i) qualitative and (ii) quantitative. The former is intended to verify the various failure modes and causes that contribute to the unreliability of a product or system. The latter uses real failure data in conjunction with suitable mathematical models to produce quantitative estimates of product or system reliability.

Reliability engineering deals with the design and construction of systems and products, taking into account the unreliability of its parts and components. It also includes testing and programs to improve reliability. Good engineering results in a more reliable end product.

Reliability science is concerned with the properties of materials and the causes for deterioration leading to part and component failures. It also deals with the effect of manufacturing processes (e.g. casting, annealing) on the reliability of the part or component produced.

Reliability management deals with the various management issues in the context of managing the design, manufacture and/or operation of reliable products and systems. Here the emphasis is on the business viewpoint, as unreliability has consequences in cost, time wasted, and, in certain cases, the welfare of an individual or even the security of a nation.

2.5.2 Product Life Cycle Perspective

The reliability of a product over its life cycle varies considerably. A typical scenario is shown in Figure 2.4.[11] A feasibility study is carried out using the specified target value for product reliability. During the design stage, product reliability is assessed in terms of part and component reliabilities. Product reliability increases as the design is improved. However, this improvement has an upper limit. If the target value is below this limit, then the design using available parts and components achieves the desired target value. If not, then a development program to improve the reliability through test-fix-test cycles is necessary. Here the prototype is tested until a failure occurs and the causes of the failure are

[11] Adapted from Court [26].

analyzed. Based on this, design and/or manufacturing changes are introduced to overcome the identified failure causes. This process is continued until the reliability target is achieved.

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 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.

The reliability of an item in use deteriorates with age. This deterioration is affected by several factors, including environment, operating conditions and maintenance. The rate of deterioration can be controlled through maintenance efforts, as shown in Figure 2.4.

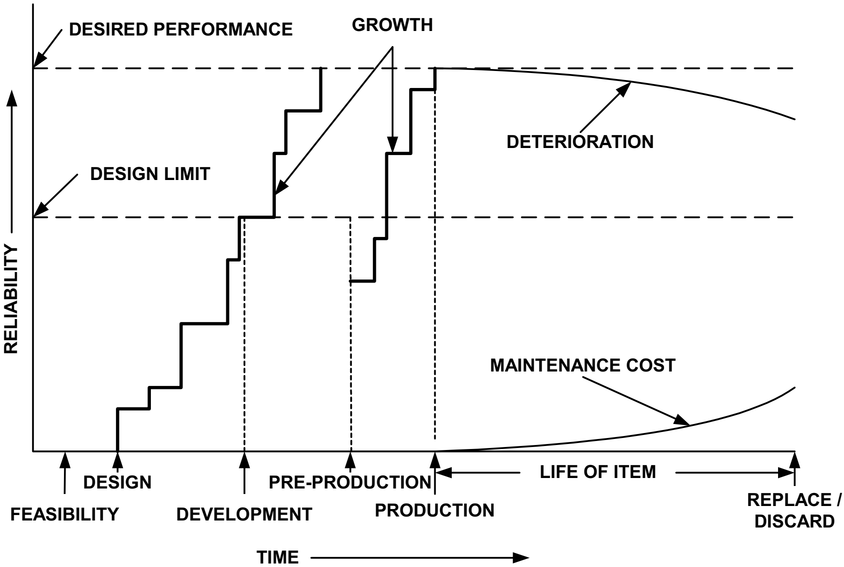


Figure 2.4. Product reliability (product life cycle perspective)

It is worth noting that if the reliability target values are too high, they might not be achievable with development. In this case, the manufacturer must revise the target value and start with a new feasibility study before proceeding further.

References

[1] ISO9000 (2000), *Quality Management and Assurance – Vocabulary*, International Standardization Organization, Geneva, Switzerland.

[2] Bruce, N. and Hunt, J. (1984), "How the photocopier works," *The Science Corner*, http://www.physics.uoguelph.ca/summer/scor/articles/scor54.htm.

[3] Rae, J. B. (1971), *The Road and the Car in the American Life*, MIT Press, Cambridge, MA.

[4] Flink, J. J. (1970), *America Adopts the Automobile, 1895–1910*, MIT Press, Cambridge, MA.

[5] *Ward's Automotive Yearbook*, 1978–1998, Detroit.

[6] Kececioglu, D. (1991). *Reliability Engineering Handbook – Vol. 1*, Prentice Hall, Englewoods Cliffs, NJ.

[7] *Engineering Opportunities*, October 1964, pp. 14–15.

[8] Appel, F.C. (1970). "The 747 ushers in a new era," *The American Way (magazine of the American Airlines Corp.)*, March 25–29.

[9] Lele, M. M. (1983), "How to protect your unguarded battlefield," *Business Marketing,* June, 69–76.

[10] Lele, M. M., and Karmarkar, U. S. (1983), "Good product support is smart marketing," *Harvard Business Review* **61**, 124–132.

[11] Ives, B., and Vitale, M. R. (1988), "After the sale: Leveraging maintenance policy over a warranty period," *Microelectronic Reliability* **34**, 529–534.

[12] Ives, B., and Vitale, M. R. (1988), "After the sale: Leveraging maintenance with information technology," *MIS Quarterly* **12**, 7–21.

[13] Ritchken, P. H., Chandramohan, J., and Tapieor, C. S. (1989), "Servicing, quality design and control," *IIE Transactions* **21**, 213–220.

[14] Goffin, K. (1988), "Evaluating customer support needs during new product development – An exploratory study," *Journal of Product Innovation Management* **15**, 42–56.

[15] Blumberg, D. F. (1991), *Managing Service as a Strategic Profit Center*, McGraw Hill Inc., New York.

[16] Hayward, A. L. and Sparkes, J. J. (1984), *The Concise English Dictionary*, Omega Books, London.

[17] Garvin, D. A. (1988). *Managing Quality*, Free Press, New York.

[18] Evans, J. R., and Lindsay, W. M. (1999), *The Management and Control of Quality, 4th Edition*, Southwestern College Publishing, Cincinnati.

[19] Wang, C. J. (1990), "Concept of durability index in product assurance planning," *Proceedings Annual Reliability and Maintainability Symposium*, 221–227.

[20] Nauman, E., and Jackson, D. W., Jr. (1999), "One more time: How do you satisfy customers? *Business Horizons* **42.3**: 71–76.

[21] Gitmore, J. (1998), *Customer Satisfaction is Worthless: Customer Loyalty is Priceless*, Bard Press, Austin, TX.

[22] Reichland, F. F. (1996), *The Loyalty Effect*, Harvard Business School Press, Boston.

[23] Archer, N. P. and Wesolowsky, G. O. (1996), "Consumer response to service and product quality: A study of motor vehicle owners," *Journal of Operations Management*, **14**, 103–118.

[24] Oliver, R. L. (1996), *Satisfaction: A Behavioral Perspective*, McGraw-Hill, New York.

[25] Homburg, C., and Rudolph, B. (2001), "Customer satisfaction in industrial markets: dimensional and multiple role issues," *Journal of Business Research* **52**, 15–33.

[26] Court, E. T. (1981). "To specify reliability requirement does not ensure its achievement," *Reliability Engineering* **2**: 243–258.

3

Product Warranty

3.1 Introduction

In Chapter 1, the concept and uses of warranty were introduced. Here we look more carefully at the warranty concept and list some warranty policies. Some of these are common, frequently used consumer warranties. Others are less frequently used or, indeed, new types of policies that a manager might consider in selecting a warranty strategy. Our focus is on warranties associated with physical goods (such as consumer durables, industrial and commercial products, and special defense products). As such, we do not deal with software warranties,[1] warranties associated with food products, livestock and veterinary sales[2] and similar items, warranties associated with construction,[3] the service industry,[4] features of the infrastructure (such as power plants, roads, bridges, etc.),[5] or assorted other special applications.[6]

The outline of the chapter is as follows. In Section 3.2, we look at the basic concept of warranty and some of the regulations that govern its use in the U. S. The role of warranty from the perspectives of manufacturer, buyer, and society as a whole are discussed in Section 3.3. Details of a variety of warranty policies are given in Section 3.4. In Section 3.5, we discuss a scheme to classify the many different types of warranty policies for new products. In Section 3.6, we look at extended warranties and we conclude with a brief discussion on the study of warranties in Section 3.7.

---

[1] Information on warranties on software can be found in Gomuldiewicz [1], Zhang and Pham [2], Kimura, Toyota, and Yamada [3], Pham and Zhang [4], and Sahin and Zahedi [5].

[2] For warranties related to livestock and veterinary sales, see Emswiller [6] and Hannah [7].

[3] Warranties relating to building construction can be found in Ong [8].

[4] For a discussion of approaches in the service sector, see McDougall, Levesque and VanderPlaat [9].

[5] Some relevant ideas may be found in Dornan [10].

[6] There are a number of others. Examples are (1) commercial leases, discussed in Vlatas [11] and warranty in the designing of an accounting system, discussed in Yost and Rasch [12].

3.2 Warranty Concept

A warranty is a written and/or oral 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) that is entered into upon sale of the product or service. The contract specifies product performance, buyer responsibilities, and what the warrantor (generally the manufacturer) will do if an item purchased fails to meet the stated performance. A warranty may be implicit or it may be explicitly stated.

The terms warranty and guarantee are often used synonymously. The distinction is that a guarantee is defined to be a pledge or assurance of something; a warranty is a particular type of guarantee, namely a guarantee concerning goods or services provided by a seller to a buyer. Another related concept is that of a service contract or "extended warranty". The difference between a warranty and a service contract is that the latter is entered into voluntarily and is purchased separately – the buyer may even have a choice of terms – whereas the basic warranty is a part of the product purchase and is an integral part of the sale.

In the USA, the Uniform Commercial Code (UCC) covers express and implied warranties. Table 3.1 summarizes the sections of the Uniform Commercial Code that pertain to warranties.

Table 3.1. Sections of the Uniform Commercial Code[7]

Section	Content
2-312	Warranty of Title and Against Infringement: Buyer's Obligation Against Infringement
2-313	Express Warranty by affirmation, Promise, Description, and Sample
2-314	Implied Warranty of Merchantability
2-315	Implied Warranty of Fitness
2-316	Exclusion or Modification of Warranties
2-317	Conflict of Express or Implied Warranties
2-318	Third Party Beneficiaries of Express or Implied Warranties

Implied Warranties

Implied warranties are unspoken, unwritten promises, created by state law. Implied warranties are based upon the common law principle of "fair value for money spent." There are two types of implied warranties that occur in consumer product transactions.

1. The *implied warranty of merchantability* is a merchant's basic promise that the goods sold will do what they are supposed to do and that there is nothing significantly wrong with them. In other words, it is an implied promise that the goods are fit to be sold.
2. The *implied warranty of fitness* is a promise that a product can be used for a particular purpose and is applicable when the customer relies on the manufacturer or seller's advice that this is the case.

Implied warranties are promises about the condition of products at the time they are sold, but they do not assure that a product will last for any specific length

[7] See White and Summers [13] for details.

of time. (The normal durability of a product is, of course, one aspect of a product's merchantability or its fitness for a particular purpose.) There is no specified duration for implied warranties under state laws.

In order to disclaim implied warranties, the manufacturer must inform consumers in a conspicuous manner, and generally in writing, that the manufacturer will not be responsible if the product malfunctions or is defective. It must be clear to consumers that the entire product risk falls on them. Some states do not allow the sale of consumer products "as is." In those states, sellers have implied warranty obligations that cannot be avoided.

Express Warranties

Section 2-313 of the UCC covers the various actions that a seller may take to create an express warranty. Specifically, Section 2-313 states [13]:

Express warranties by the seller are created as follows:

> (a) Any affirmation of fact or promise made by the seller to the buyer which relates to the goods and becomes part of the basis of the bargain creates an express warranty that the goods shall conform to the affirmation or promise.
>
> (b) Any description of the goods which is made part of the basis of the bargain creates an express warranty that the goods shall conform to the description.
>
> (c) Any sample or model which is made part of the basis of the bargain creates an express warranty that the whole of the goods shall conform to the sample or model.

For more details of the remaining sections of the UCC, see Kelly [14].

Congress enacted the Magnuson-Moss Warranty and Federal Trade Commission Improvement Act of 1975 to overcome some of the confusion resulting from the uniform Commercial Code and a number of problems concerning consumer products. These included excessive use of disclaimers, inadequate warranty coverage, consumer difficulty in obtaining warranty service, and complex warranty language.

The Magnuson-Moss Warranty Act does not require a seller to provide a warranty. It only applies to sellers that offer a written warranty on consumer products. In addition, the act applies only to the sale of goods. The Magnuson-Moss Warranty Act defines a written warranty as:

A. A written affirmation of fact or written promise made in connection with the sale of a consumer product by supplier to a buyer which relates to the nature of the material or workmanship and affirms or promises that such material or workmanship is defect free or will meet a specified level of performance over a specified period of time; or
B. Any undertaking in writing in connection with the sale by a supplier of a consumer product to refund, repair, replace or take other remedial action with respect to such product in the event that such product fails to meet the specifications set forth in the undertaking.

Every written warranty must contain the following sentence: "This warranty gives you specific legal rights, and you may also have other rights which vary from state to state." In addition, the rules that govern consumer product warranties promulgated by the Federal Trade Commission after the act was passed require the warranty to include the following information:

1. Who can enforce the warranty
2. A clear description and identification of the products, parts, and components covered by or excluded from the warranty
3. What the seller will and will not do
4. The starting date and duration of the warranty
5. An explanation of the process the consumer needs to follow to obtain service or other warranty performance
6. Information concerning any informal dispute settlement procedure
7. Any limitations of the duration of implied warranties
8. Any exclusions or limitations on relief .

The Magnuson-Moss Warranty Act contains several sections (2301–2312), with contents as listed in Table 3.2. A key section of the Act requires the terms and conditions of a warranty to be disclosed in “simple and readily understood language” and be made available to the consumer prior to the sale of any product with retail price of $15 or more. A seller may select one or more of the following methods to make their warranty available to a consumer prior to a purchase. The seller may elect to

1. Display the text of the warranty with the product
2. Display the warranty on the package of the product
3. Place signs disclosing the warranty terms “in close proximity” to the product
4. Maintain a binder or series of binders with copies of the warranties of the products sold in each department where the product is sold.

For further discussion of warranty legislation and references to additional sources, see Kelly [14].

Note that this discussion has been concerned mainly with warranties on consumer goods. Legislation has also dealt with warranties on goods and materiel sold to the military, particularly the Reliability Improvement Warranty (RIW; to be discussed in some detail later in the chapter). RIW was first used in military acquisition in the early 1970s. This and other warranties were covered by a number of legislative actions, culminating in the period 1983 to 1985 with the passage of blanket legislation requiring warranties on all weapons systems and components.[8]

[8] For additional information on the history of RIW and related legislation, see Blischke and Murthy [15], Chapter 7.

Table 3.2: Sections of the Magnuson-Moss Warranty Act of 1975
(*Source:* U.S.C.A. Sections 2301–2312 (1992))

Section	Content
2301	Definitions of consumer product, consumer, supplier, warrantor, written warranty, implied warranty, and other terms.
2302	Rules governing contents of warranties.
	(a) Full and conspicuous disclosure of warranty terms and conditions.
	(b) Availability of warranty terms to the consumer; methods for presenting and displaying information and duration of a written warranty.
	(c) Prohibition on conditions for written or implied warranties.
	(d) Detailed substantive warranty provisions.
	(e) Applicability of the act to consumer products costing more than $15.00.
2303	Designation of written warranties.
	(a) Full or limited warranty.
	(b) Applicability of requirements, standards to representations or statements of customer satisfaction.
	(c) Exemptions by the Federal Trade Commission.
	(d) Applicability of the act to consumer products costing more than $15.00 and not designated as full warranties.
2304	Federal minimum standards for warranties.
	(a) Remedies under written warranty; duration of implied warranty; exclusion or limitation on consequential damages for breach of written or implied warranty; election of refund or replacement.
	(b) Duties and conditions imposed on the consumer by the warrantor.
	(c) Waiver of standards.
	(d) Remedy with charge.
	(e) Incorporation of standards to products designated with full warranty for purposes of judicial actions.
2305	Full and limited warranties.
2306	Service contracts; rules for full, clear, and conscious disclosure of terms and conditions.
2307	Designation of representatives by warrantor to perform duties under a written or implied warranty.
2308	Implied warranties.
	(a) Restrictions on disclaimers or modifications.
	(b) Limitation on duration.
	(c) Effectiveness of disclaimers, modifications, or limitations. Procedures applicable to promulgation of rules by the Federal Trade Commission.
2309	Procedures applicable to promulgation of rules by the Federal Trade Commission.
2310	Remedies in consumer disputes.
	(a) Informal dispute settlement procedures.
	(b) Prohibited acts.
	(c) Injunction proceedings by Attorney General or Federal Trade Commission.
	(d) Civil action by consumer for damages; jurisdiction; recovery of costs and expenses.
	(e) Warrantors subject to enforcement of remedies.
2311	Applicability to other laws.
	(a) Federal Trade Commission Act.
	(b) Rights, remedies, and liabilities.
	(c) State warranty laws.
	(d) Other federal warranty laws.
2312	Effective dates

Many complex industrial products (e.g., boilers, locomotives) are custom built and statements relating to reliability performance are often contained in the contracts that require the manufacturer to make design changes if the performance targets are not met. These contracts can be viewed as RIW policies.

3.3 Role of Warranty

Warranties are an integral part of nearly all commercial and many government transactions that involve product purchases. The buyer (individual, corporation, or government agency) point of view of a warranty is different from that of the manufacturer (or distributor, retailer, and so forth). Another perspective is the societal point of view, including legislators, consumer affairs groups, the courts, and public policy decision-makers.

3.3.1 Buyer's Viewpoint

From the buyer's point of view, the main role of a warranty in product purchase transactions is protectional – it provides a means of redress if the item, when properly used, fails to perform as intended or as specified by the seller. Specifically, the warranty assures the buyer that a faulty item will either be repaired or replaced at no cost or at reduced cost. A second role is informational. Many buyers infer that a product with a relatively longer warranty period is more reliable and longer lasting than one with a shorter warranty period.

3.3.2 Manufacturer's Viewpoint

One of the main roles of warranty from the manufacturer's point of view is also protectional. Warranty terms may, and often do, specify the use and conditions of use for which the product is intended and provide for limited coverage or no coverage at all in the event of misuse of the product. The manufacturer may be provided further protection by specification of requirements for care and maintenance of the product. A second important purpose of warranties for the manufacturer is promotional. Since buyers often infer a more reliable product when a long warranty is offered, this has been used as an effective advertising tool. This is often particularly important when marketing new and innovative products, which may be viewed with a degree of uncertainty by many potential consumers. In addition, warranty has become an instrument, similar to product performance and price, used in competition with other manufacturers in the marketplace.

3.3.3 Warranty in Government Contracting

In simple transactions involving consumer or commercial goods, a government agency may be dealt with in basically the same way as any other customer, obtaining the standard product warranty for the purchased item. Often, however, the government, as a large entity wielding substantial power as well as a very large consumer, will be dealt with considerably differently, with warranty terms negotiated at the time of purchase rather than specified unilaterally by the seller. The role of warranty in these transactions is usually primarily protectional for both parties.

In some instances, particularly in the procurement of complex military equipment, RIW policies are used. These play a very different and important role, that of an incentive to the seller to increase the reliability of the items after they are put into service. This is accomplished by requiring that the contractor service the items in the field and make design changes as failures are observed and analyzed. The incentive is an increased fee paid to the contractor if it can be demonstrated that the reliability of the items has, in fact, been increased.

3.3.4 Societal Viewpoint

Civilized society has always taken a dim view of the damage suffered by its members that is caused by someone or some activity, and has demanded a remedy or retribution for offences against it. Consequently, manufacturers are required to provide compensation for any damages resulting from failures of an object. This has serious implications for manufacturers of engineered objects. Products-liability laws and warranty legislation are signs of society's desire to ensure fitness of products for their intended use and compensation for failures.

In the USA, Congress' intentions in passing the Magnuson-Moss Warranty Act were the following:[9]

1. Congress wished to ensure that consumers could get complete information about warranty terms and conditions. By providing consumers with a way of learning what warranty coverage is offered on a product before it is purchased, the Act gives consumers a way of knowing what to expect if something goes wrong, and thus helps to increase customer satisfaction.
2. Congress wished to ensure that consumers are able to compare warranty coverage before buying. Consumers can then choose a product with the best combination of price, features, and warranty coverage to meet their individual needs.
3. Congress intended to promote competition on the basis of warranty coverage. By assuring that consumers can obtain warranty information, the Act encourages sales promotion on the basis of warranty coverage and competition among companies to meet consumer preferences.
4. Congress wished to strengthen existing incentives for companies to perform their warranty obligations in a timely and thorough manner and to resolve any disputes with a minimum of delay and expense to consumers. Thus, the Act makes it easier for consumers to pursue a remedy for breach of warranty in the courts, but it also creates a framework for companies to set up procedures for resolving disputes inexpensively and informally, without litigation.

3.4 Description of Warranty Policies

There are a large number of possible warranties. A list of over 30 is given in *Warranty Cost Analysis*,[10] and there are innumerable variations of many of these.

---

[9] See *A Businessperson's Guide to Federal Warranty Law*. The document may be obtained from http://www.ftc.gov/bcp/conline/buspubs/warranty.htm

[10] Blischke and Murthy [15]. Many others are discussed in Blischke and Murthy [16 and 17].

To illustrate the breadth of possibilities, a variety of warranty policies will now be described. Typical products sold with some of these warranties will be indicated.

In listing the warranties, we categorize them by *dimension*, that is, the number of variables on which the warranty is based. For example, a warranty based on calendar time alone would be one-dimensional; one based on time and usage would be two-dimensional, and so forth. It is also necessary to specify whether or not the warranty is *renewing*. For renewing policies, the warranty period begins anew with each replacement or repair, while for non-renewing policies, the repaired or replacement item is covered under warranty for the time remaining in the original warranty period.

For ease of description of the warranty policies, some symbols are required. We use the following notation:

W = length of warranty period
C = selling price of the item (cost to buyer)
X = time to failure (lifetime) of an item.

3.4.1 One-dimensional Policies

3.4.1.1 Basic Standard Consumer Warranties

The most commonly used consumer warranties are variations of the basic Free Replacement Warranty (FRW), Pro Rata Warranty (PRW) and rebate policies. The basic FRW and rebate warranties are:

Policy 1

NON-RENEWING FREE-REPLACEMENT POLICY: The seller agrees to repair or provide replacements for failed items free of charge up to a time W from the time of the initial purchase. The warranty expires at time W after purchase.

Policy 2

BASIC REBATE WARRANTY POLICY: The seller agrees to refund an amount αC, where $0 < \alpha < 1$, if the item fails prior to time W from the time of purchase.

The warranty of Policy 1 is non-renewing since repaired or replaced items are not warrantied for another period of length W, but only for the time remaining in the original warranty period. Thus, in the case of nonrepairable items, should a failure occur at age X (with $X < W$), then the replaced item has a warranty for a period $(W - X)$ – the remaining duration of the original warranty. Should additional failures occur, this process is repeated until the total service time of the original item and its replacements is at least W. In the case of repairable items, repairs are made free of charge until the total service time of the item is at least W.

Policy 2 is similar to an FRW, but involves a cash refund rather than a repair or replacement item. The cash refund could be used toward the purchase of a replacement. Here α is the proportion of the purchase price that is refunded. If $\alpha =$ 1, this is the classical “Money Back Guarantee,” and is analogous to Policy 1, with cash provided rather than a refund. Note that this policy may be much more costly to the manufacturer, since the rectification is based on the selling price rather than the cost of producing the item. Typical applications of these warranties are consumer products, ranging from inexpensive items such as photographic film to relatively expensive repairable items such as automobiles, refrigerators, large screen color TVs, and so forth, and on expensive nonrepairable items such as microchips and other electronic components as well.

The most commonly used PRW is a renewing warranty. The basic renewing PRW is:

Policy 3

RENEWING PRO-RATA POLICY: Under this policy, the manufacturer agrees to provide a replacement item, with warranty, at prorated cost $[1 - X/W]C$, for any item (including the item originally purchased and any replacements made under warranty) which fails to achieve a lifetime of at least W.

Here the cost of a replacement item is discounted by the amount of service provided by the item it replaces. Note that this is equivalent to linear proration. In fact, the proration can theoretically be either a linear or nonlinear function of the remaining time $W - X$, with $X < W$, although the linear form is almost always used. Depending on the proration function, this defines a family of pro-rata policies. Non-linear forms, though seldom, if ever, used, would allow for greater flexibility in selecting a warranty policy, One could select policies, for example, that would feature increasing (or decreasing) the prorated cost of a replacement more rapidly in the early part of the warranty period.

Under this warranty, replacement items are warrantied anew, and in analysis of the policy (e.g., in formulating cost models) it is usually assumed that the warranty terms are the same as those of the warranty under which the product was originally sold. In practice, the replacement is provided with whatever is the then current warranty.

Many nonrepairable items are sold with this type of policy or a combination having this, following an initial FRW period. Most auto tires and batteries are sold under renewing PRW, the buyer being offered a replacement for a failed item at a reduced price, without a cash rebate option.

The most common combination policy is a non-renewing combination of the FRW and PRW. This has some advantages in that, as we shall see, cost wise it is a compromise for both seller and buyer. The policy is

Policy 4

COMBINATION FRW/PRW: The seller agrees to provide a replacement or repair free of charge up to time W_1 from the initial purchase; any failure in the interval W_1 to W (where $W_1 < W$) results in a prorated refund. The warranty does not renew.

As before, the proration in the PRW portion of the warranty can be either linear or nonlinear. Again, depending on the form of the proration cost function, we have a family of combined free-replacement and pro-rata policies similar to that for the PRW.

As stated, Policy 4 is not renewing, i.e., replacements for items that fail before W_1 assume the remaining coverage in the warranty period and a failure after W_1 leads to a rebate. A renewing version of this is also used occasionally. Other versions, called *partially renewing warranties*, provide for renewing of the warranty in either the first or second portion of the warranty period. In fact, there are many warranties offered with terms that change one or more times during the course of the warranty policy.

Warranties of this type are sometimes used to cover replacement parts or components where the original warranty covers an entire system. They are also widely used in sales of consumer products.

3.4.1.2 Some Variations

As we have already noted, there are a very large number of possible warranty policies. Here we look at a few additional variations of the FRW, PRW and rebate policies.

Policy 5

> *PRO-RATA REBATE POLICY*: The seller agrees to refund a fraction of the purchase price should the item fail before time W from the time of the initial purchase. The buyer is not constrained to buy a replacement item.

The refund provided under Policy 5 depends on the age of the item at failure and as before, it can theoretically be either a linear or nonlinear function of $W - X$, the remaining time in the warranty period. The amount of the rebate depends on the form of the refund function. For a linear pro-rata relate policy, the refund is $\alpha[1 - X/W]$, which will give a fully prorated refund if $\alpha = 1$, and a lesser amount if $\alpha < 1$.

Policies such as this are sometimes offered on relatively inexpensive nonrepairable products such as batteries, tires, ceramics, and so on. Figure 3.1 is a plot of the refund to a buyer (cost to the seller) for an item that fails during the warranty period under PRW Policy 5 with linear proration and $\alpha = 1$ and $\alpha = 0.7$. The refund is plotted as a function of the failure time of the item, assuming that the cost of a new item was C. The plot also shows a plot for a nonlinear rebate function, in this case a quadratic function of the lifetime of the item. Note that for this, the rebate decreases rapidly early on in the warranty period.

The combination FRW/PRW of Policy 4 is a two-stage policy. Multistage warranties such as the following are also used in some applications:

Policy 6

> *NON-RENEWING THREE-STAGE WARRANTY*: The seller agrees to provide replacements or repairs of failed items free of charge up to time W_1 after initial purchase, at cost C_1 if the failure time X is between W_1 and W_2, and at cost C_2 if X is between W_2 and W, where $0 < W_1 < W_2 < W$ and $C_1 < C_2$. The warranty expires at time W after purchase.

Here the warranty period is divided into three portions, with the amount of compensation declining as the warranty period progresses. Cost to both manufacturer and buyer of repair/replacement of an item that fails when covered by Policy 6 are shown in Figure 3.2. Examples of products often covered by warranties that are basically of this type are television sets or appliances for which full coverage is provided for an initial period and only partial coverage (e.g., some parts and/or labor) in later periods. Policy 6 can be generalized so that it has more than three stages.

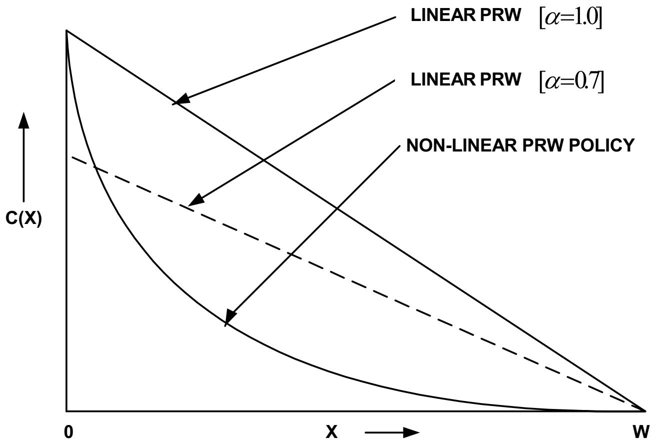


Figure 3.1. Rebate functions for FRW policies

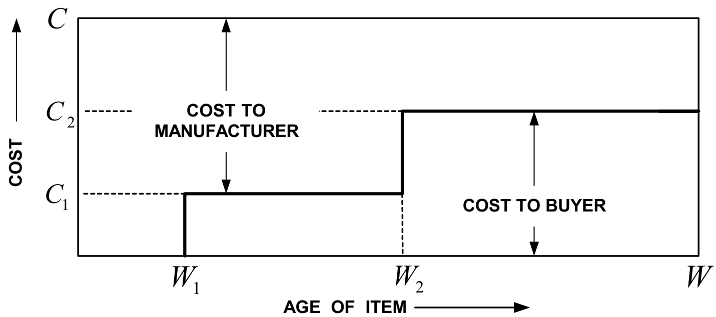


Figure 3.2. Repair/replacement costs under a three-stage warranty, Policy 6

Another version of this is combination lump-sum rebate warranty, under which a refund which is a declining proportion of the original purchase price is given rather than a replacement item or a repair. An example of such a policy is that offered by the manufacturer of a stand-alone fireplace that is warrantied for 25 years with declining rebates over four periods.[11]

Occasionally, a renewing FRW such as the following is offered:

Policy 7

RENEWING FRW: Under this policy, the manufacturer agrees to either repair or provide a replacement free of charge up to time W from the initial purchase. Whenever there is a replacement, the failed item is replaced by a new one with a new warranty whose terms are identical to those of the original warranty.

Under this policy, the buyer is assured of one item that operates for a period W without failure.

[11] This is discussed in Blischke and Murthy [15], Chapters 1 and 2.

This type of policy is usually offered with inexpensive electrical, electronic, and mechanical products such as coffee grinders, alarm clocks, tools, and so forth, for which the warranty is contained inside the item package. Upon failure, the item is returned to the seller, who merely replaces it with an identical package. If the buyer simply returns the new warranty card, new warranty coverage results with each replacement.

Example 3.1 [Photocopier]

Most copiers carried a 30 days warranty (industry practice) up to the late 1980s. Since 1990, the warranty periods have increased and some copiers now have warranties of three years or longer. Copiers are basically commercial goods and, as such, have warranties that are more complex than warranties on consumer products. In practice, the warranty provided to the buyer or lessee includes the original manufacturer's warranty plus additional terms that are covered by the seller/lessor. Exhibit 3.1 of the Appendix to this chapter is an example of a typical warranty/purchase agreement on a standard commercial copier. Note that the warranty is a full FRW, including parts and labor, for the first 60 days, and covers all major malfunctions under FRW for two years, except that in both cases the buyer must pay shipping costs. A number of additional terms and conditions are stated in the warranty.

■

Example 3.2 [Automobile Battery]

A battery is one of several components of an automobile that comes with a separate warranty, that is, it is not covered under the basic warranty provided by the manufacturer of the automobile. A typical battery warranty, covering several models, is shown in the Appendix in Exhibit 3.2. Note that this is a combination FRW/PRW policy, with the free-replacement portion and the total length of the warranty depending on the specific model purchased. The warranty also specifies limitations, conditions of use, and buyer responsibilities.

Another set of components that are commonly covered separately are automobile tires. The tire manufacturer ordinarily covers these under a pro-rata warranty based on mileage.[12]

■

3.4.2 Two-dimensional Policies

In the one-dimensional case, a policy is characterized by an interval, called the warranty period, which is defined in terms of a single variable – for example, time, age, or usage. In the case of two-dimensional warranties, a warranty is characterized by a region in a two-dimensional plane, usually with one axis representing time or age and the other representing item usage. As a result, many different types of warranties, based on the shape of the warranty coverage region, may be defined.

Three possibilities with regard to the region of coverage are shown in Figure 3.3. The first of these, shown in Figure 3.3(a), is the usual warranty region with independent limits on time and usage. In Figure 3.3(b), the warranty coverage is

[12] For an example, see www.michelinman.com.

such that the buyer is assured a minimum time of coverage *and* a minimum usage. The region in (a) tends to favor the manufacturer because it limits both the maximum time and the maximum usage for the buyer. For a buyer who is a heavy user, the warranty expires before time W because usage has reached U. Similarly, for a buyer who is a light user, the warranty expires at time W with total usage below U. In contrast, the region shown in (b) favors the buyer. Here, a heavy user is covered for a time period W, by which time the usage may have well exceeded the limit U, and a light user is covered well beyond W, for the policy expires only when the total usage reaches U.

The region shown in Figure 3.3(c) is a compromise between (a) and (b). In this case, the buyer is provided warranty coverage for a minimum time period W_1 and for a minimum usage U_1. At the same time, the manufacturer is obliged to cover the item for a maximum time period W_2 and for a maximum usage U_2. Although all two-dimensional warranties of which we are aware are based on region (a), (c) may be an attractive alternative in some markets.

The standard version of the FRW based on the region shown in Figure 3.3(a) is:

Policy 8

TWO-DIMENSIONAL NONRENEWING FRW: The seller agrees to repair or provide a replacement for failed items free of charge up to a time W or up to a usage U, whichever occurs first, from the time of the initial purchase. W is called the warranty period and U the usage limit. The warranty region is the rectangle shown in Figure 3.3(a).

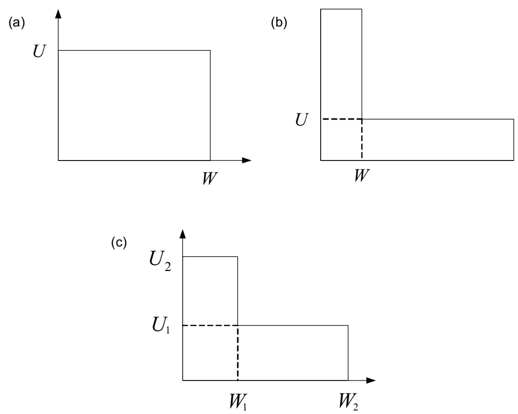


Figure 3.3. Two-dimensional warranty regions – usage versus time

As noted, under this policy, the buyer is provided warranty coverage for a maximum time period W and a maximum usage U. If the usage is heavy, the warranty can expire well before W, and if the usage is very light, then the warranty can expire well before the limit U is reached. Should a failure occur at age X with usage Y, it is covered by warranty only if X is less than W *and* Y is less than U. If the failed item is replaced by a new item, the replacement item is warrantied for a time period $W - X$ and for usage $U - Y$. Nearly all auto manufacturers offer this type of policy, with usage corresponding to distance driven.

Two-dimensional PRW and combination FRW/PRW are also easily defined, as are renewing versions of all of these.[13] The following is an example of such a warranty:

Policy 9

TWO-DIMENSIONAL COMBINATION FRW/PRW: The seller agrees to provide replacements for failed items free of charge up to a time W_1 from the time of the initial purchase provided the total usage at failure is below U_1. Any failure, with time at failure greater than W_1 but less than W_2 and/or usage at failure greater than U_1 but less than U_2, is replaced at a prorated cost. Failures with time greater than W_2 or usage greater than U_2 are not covered by warranty.

The proration in Policy 9 can be either a linear or nonlinear function of the warranty parameters and the age and usage at failure. The coverage area is identified in Figure 3.3(c). Many other such policies are possible. In managing warranty, it is useful to be aware of the many possibilities beyond the simplest basic policies.

Two-dimensional versions of many other one-dimensional policies may be defined similarly.

Example 3.3 [Automobile]

All new automobiles are sold with Policy 8. The warranty for the whole automobile (called bumper-to-bumper) covers all parts of the automobile. Warranty coverage varies from manufacturer to manufacturer and by brand of the car. The power train (which includes the engine, transmission and other parts of the drive train only) is usually covered by a longer warranty. Warranty terms have changed significantly over time. The following is a brief history:

- Until 1960: Basic warranty was 3 months and 4000 miles. Exhibit 3.3 in the Appendix gives a typical warranty circa 1930. As can be seen, this is a one-dimensional FRW policy with no mention about usage limit. Some of the components (tires, battery) are covered by separate warranties provided by the component manufacturers. Note particularly that the warranty contains exclusion clauses and the owner incurs some costs.
- 1960: Increased to 1 year and 12,000 miles.
- 1967: Increased to 2 years and 24,000 miles.
- 1970: Auto industry reduced warranty to 1 year and 12,000 miles and an additional warranty on power train (which includes engine, transmission and other parts of the drive train) made optional.
- 1981: Power train warranty increased to 2 years and 24,000 miles. Chrysler increased it to 5 years and 50,000 miles.
- 1987: GM increased power train warranty from 3 years and unlimited miles to 6 years and 60,000 miles and corrosion warranty from 3 years unlimited miles to 6 years and 100,000 miles.
- 2003: Table 3.3 gives the warranty coverage for 2003 model automobiles sold at the New York Exhibition in 2003. As can be seen, the variation in

[13] See Blischke and Murthy [15] for definition and discussion of a number of such policies.

the bumper-to-bumper coverage is small whereas that for the power train is large. This has been used as a marketing tool to promote the product. Both Hyundai and Suzuki claim to offer the "best" warranty.[14]

Table 3.3. Warranties for automobiles sold in the USA
[Source: *Warranty Week*, April 22, 2003]

		Power train		**Bumper to bumper**	
Make	**Model**	**Years**	**Mi (000)**	**Years**	**Mi (000)**
Hyundai	Tiburon	10	100	5	60
Kia	Amanti	10	100	5	60
Suzuki	Forenza	7	100	3	36
Isuzu	Ascender	7	75	3	50
Chrysler	Sebring	7	70	3	36
Dodge	Intrepid	7	70	3	36
Jeep	Wrangler	7	70	3	36
Infiniti	Q45	6	70	4	60
Lexus	LX	6	70	4	50
Volkswagen	Beetle	5	60	4	50
Mitsubishi	Endeavor	5	60	3	36
Nissan	Z Roadster	5	60	3	36
Subaru	Baja	5	60	3	36
Toyota	Prius	5	60	3	36
Acura	RSX	4	50	4	50
Audi	A3	4	50	4	50
BMW	525i	4	50	4	50
Cadillac	Escalade	4	50	4	50
Jaguar	XK8	4	50	4	50
Land Rover	Range Rover	4	50	4	50
Lincoln	Navigator	4	50	4	50
Mazda	RX-8	4	50	4	50
Merc.-Benz	S500	4	50	4	50
Mini	Cooper S	4	50	4	50
Porsche	911 GT2	4	50	4	50
Saab	9-5 Aero	4	50	4	50
Volvo	XC90	4	50	4	50
Buick	Rendezvous	3	36	3	36
Chevrolet	TrailBlazer	3	36	3	36
Ford	Focus	3	36	3	36
GMC	Envoy	3	36	3	36
Honda	Odyssey	3	36	3	36
Hummer	H2	3	36	3	36
Mercury	Sable	3	36	3	36
Oldsmobile	Alero	3	36	3	36
Pontiac	Grand Prix	3	36	3	36
Saturn	VUE	3	36	3	36
Average new auto warranty		4.7	55	3.5	44

[14] For an interesting discussion from both sides, see *Warranty Week*, April 22, 2003.

Exhibit 3.4 is a partial description of warranty coverage on a 2004 General Motors Pontiac copied from a warranty booklet obtained on purchase of a new car. The GM warranty is a two-dimensional FRW policy with some components (such as the battery, as discussed in Example 3.2) being covered separately by a different policy provided by the component manufacturer. Exhibit 3.4 is the Table of Contents of the 30-page warranty booklet provided to a purchaser of a new automobile. The basic automobile warranty provides coverage for three years or 36,000 miles, whichever occurs first. The warranty covers a number of models of cars and light trucks and coverage varies to some extent by model. In one instance, (a diesel engine), the warranty is actually three-dimensional, specifying age, mileage and hours of operation. The complete booklet includes detailed information on what is and what is not covered by GM, how to obtain warranty service, buyer's responsibilities, required maintenance, and so forth.

■

3.4.3 Cumulative Warranties

In certain types of applications, it may be desirable to provide warranty coverage for groups of items. Such warranties are called cumulative warranties and are applicable only when items are sold as a single lot of n items and the warranty refers to the lot as a whole. The policies are conceptually straightforward extensions of the nonrenewing free-replacement and pro-rata warranties discussed previously. Under a cumulative warranty, the lot of n items is warrantied for a total time of nW, with no specific service time guarantee for any individual item.

Cumulative warranties are appropriate only for commercial and governmental transactions, since individual consumers rarely purchase items by lot. In fact, warranties of this type have been proposed in the United States for use in acquisition of military equipment.

The rationale for such a policy is as follows. The advantage to the buyer is that multiple-item purchases can be dealt with as a unit rather than having to deal with each item individually under a separate warranty contract. The advantage to the seller is that fewer warranty claims may be expected because longer-lived items can offset early failures.

We illustrate the concept by looking at two cumulative FRWs. The notation used in expressing the terms of these policies is as above with the additional term S_n = total service life of n items. The policies are:[15]

Policy 10

CUMULATIVE FRW: A lot of n items is warranted for a total (aggregate) period nW. The n items in the lot are used one at a time. If $S_n < nW$, free-replacement items are supplied, also one at a time, until the first instant when the total lifetimes of all failed items plus the service time of the item then in use is at least nW.

This type of policy is applicable to components of industrial and commercial equipment bought in lots as spares and used one at a time as items fail. Examples of possible applications are mechanical components such as bearings and drill bits.

[15] These and a number of other cumulative examples are from Guin [18].

The policy would also be appropriate for military or commercial airline equipment such as mechanical or electronic modules in airborne units.

In the following, it is assumed that more than one item is in use at a given time:

Policy 11

CUMULATIVE FRW: A lot of n items is warranted under cumulative warranty for a total period of nW. Of these, k ($< n$) are put into use simultaneously, with the remaining $n - k$ items being retained as spares. Spares are used one at a time as failures occur. Upon failure of the nth item, free replacements are supplied as necessary until a total service time of nW is achieved.

There are some conceptual and practical difficulties in implementing cumulative warranties and they have not been widely used.[16] There could be considerable cost savings, however, and managers of warranty in commercial and government transactions should be aware of the many possibilities offered by warranties of this type. In applications of these, warranty terms must be carefully specified and will usually be negotiated.

3.4.4 Reliability Improvement Warranties

The basic idea of a reliability improvement warranty (RIW) is to extend the notion of a basic consumer warranty (usually the FRW) to include guarantees on the reliability of the item and not just on its immediate or short-term performance. This is particularly appropriate in the purchase of complex, repairable equipment that is intended for relatively long use. The intent of reliability improvement warranties is to negotiate warranty terms that will motivate a manufacturer to continue improvements in reliability after a product is delivered.

Under RIW, the contractor's fee is based on his ability to meet the warranty reliability requirements. These often include a guaranteed MTBF (mean time between failures) as a part of the warranty contract.[17] The following will illustrate the concept:

Policy 12

RELIABILITY IMPROVEMENT WARRANTY: Under this policy, the manufacturer agrees to repair or provide replacements free of charge for any failed parts or units until time W after purchase. In addition, the manufacturer guarantees the MTBF of the purchased item to be at least M. If the computed MTBF is less than M, the manufacturer will provide, at no cost to the buyer, (1) engineering analysis to determine the cause of failure to meet the guaranteed MTBF requirement, (2) engineering change proposals, (3) modification of all existing units in accordance with approved engineering changes, and (4) consignment spares for buyer use until such time as it is shown that the MTBF is at least M.[18]

---

[16] See Blischke and Murthy [15], Chapter 6.
[17] Ibid., Chapter 7.
[18] This warranty is one of the early versions of RIW. It is discussed in Gandara and Rich [19].

Many variations of the RIW have been used. Applications have included purchase of aircraft and electronics by airlines and military procurement. Some examples of alternate versions of RIW are (i) a warranty that provides for an initial period during which no MTBF guarantee is in effect, followed by successive periods in which specific improvements in MTBF are required [20], and (ii) a variation of this that allows the manufacturer some "free" failures at the outset [21].

3.5 Classification of Warranties

Because of the wide variety of products covered, company objectives, and market conditions, a large number of different warranties are offered, as illustrated in the previous section. Here we look at a scheme for classification of the many types of warranties. This will provide a framework for selection of a warranty policy in any particular application. The taxonomy of warranties that resulted from our approach to classification is given in Figure 3.4.

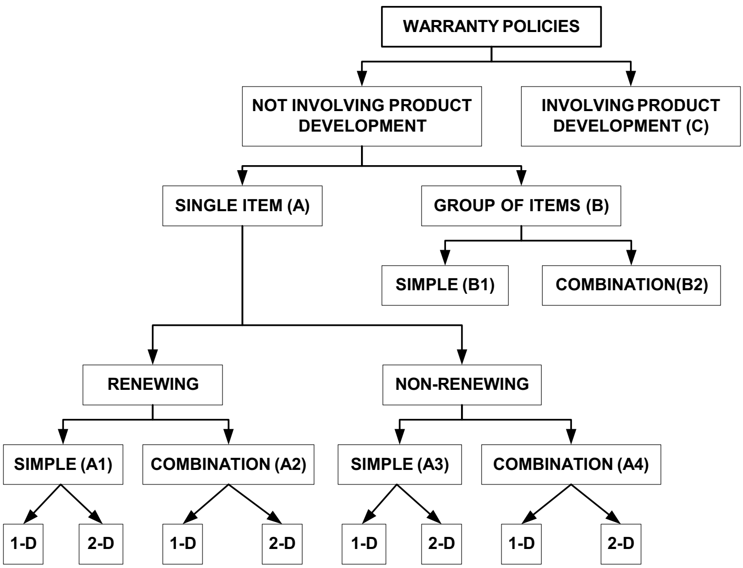


Figure 3.4. Taxonomy of warranty policies

As shown in Figure 3.4, the first criterion for classification of warranties is whether or not the manufacturer is required to carry out further product development (for example, to improve product reliability) subsequent to the sale of the product as part of the warranty contract. Policies which do not involve such further product development can be further divided into two groups – Group A, consisting of policies applicable for single item sales, and Group B, policies used in the sale of groups of items (called lot or batch sales).

Policies in Group A are divided into two sub-groups, based on whether the policy is renewing or nonrenewing. A further subdivision comes about in that warranties may be simple or combination. As noted, the basic FRW and PRW policies discussed in the previous section are simple policies. A combination policy is a simple policy combined with some additional features or a policy that combines the terms of two or more simple policies. The resulting four different types of policies under category A are labeled A1–A4 in Figure 3.4. Each of these four groupings can be further subdivided into two sub-groups based on whether the policy is one-dimensional or two- (or more) dimensional. Policies belonging to Group B can also be sub-divided into two categories based on whether the policy is simple or combination. These are labeled B1 and B2 in Figure 3.4. As in grouping A, B1 and B2 can be further subdivided based on whether the policy is one-dimensional or two-dimensional.

Finally, policies that involve product development subsequent to the sale are labeled Group C. Warranties of this type are typically part of a service maintenance contract and are used principally in commercial applications and government acquisition of large, complex items – for example, aircraft or military equipment. Nearly all such warranties involve time and/or some function of time as well as a number of characteristics that may not involve time, for example, fuel efficiency.

A classification of the policies listed in the previous section in the taxonomy of Figure 3.4 is given in Table 3.4. Note that our list of policies includes examples of all categories except A4 and B2. Both of these groups are policies that are conceptually simple extensions of some of the policies listed and note has been made of this in the discussion of the previous section.

The taxonomy given in Figure 3.4 is for new products. Many other types of warranty coverage have been offered. These include second-hand products,[19] notably automobiles, on which some of the same types of warranties discussed here have been offered. Such warranties usually include additional features such as exclusions, deductibles, cost limits, and so forth. The taxonomy also does not include extended warranties. We deal with this topic briefly in the next section.

Table 3.4. Classification of warranty policies 1–12

Policy	Group	Dimension	Policy	Group	Dimension
1	A1	1	7	A3	1
2	A1	1	8	A1	2
3	A3	1	9	A2	2
4	A2	1	10	B1	1
5	A1	1	11	B1	1
6	A2	1	12	C	1

[19] For information on management and analysis of warranties on second-hand products see Chattopadhyay [22], Chattopadhyay and Murthy [23 and 24].

3.6 Extended Warranties

An extended warranty (which is also sometimes referred to as a "service contract") is a related concept. The difference between a warranty and a service contract is that the latter is entered into voluntarily and is purchased separately – the buyer may even have a choice of terms, whereas a warranty is part of product purchase and integral to the sale. The terms of an extended warranty can be the same as those for the base warranty (provided by the manufacturer for a new product at no additional cost to the buyer) or may differ in the sense that it may include features such as (i) exclusions (labor cost to be borne by the buyer), (ii) limits (on individual claim and total claim under warranty) and (iii) deductibles.

Extended warranties are very popular and are commonly offered by major retailers of consumer goods, as well as on electronics and automobiles. They are a major source of revenue for many manufacturers and retailers. Over ten years ago, Sears reported in excess of $1 billion in revenues from extended warranties alone[20] and they accounted for over 50% of profits for some major appliance store chains.[21]

Marketing and administration of extended warranties is approached in various ways, involving manufacturers, retailers, and/or third parties. Over the past decade or so, the role of independent providers has grown considerably, and competition has increased accordingly.[22] A good deal of market research is being done in this area.

If the extended warranty is of length L, then for nonrenewing warranties the total amount of warranty coverage is $W + L$. The period from W to $W + L$ is called the extended warranty period.

The following are a few policies that contain the additional features of an extended warranty:

Policy 13

SPECIFIED PARTS EXCLUDED: Under this policy, the dealer rectifies failures of components belonging to a specified set of components of the product at no cost to the buyer over the extended warranty period. The costs of rectifying failures of the remaining components are borne by the buyer.

Policy 14

LIMIT ON INDIVIDUAL COST: Under this policy, all claims under warranty during the extended warranty period are rectified by the dealer. If the cost of a rectification is below a specified limit, then it is borne completely by the dealer and the buyer pays nothing. If the cost of a rectification exceeds this limit, then the buyer pays the excess cost and the warranty terminates.

---

[20] *San Francisco Chronicle*, January, 1992.

[21] *Business Week*, January 14, 1991.

[22] A thorough discussion of extended warranties, customer behavior in this regard, and implications for warranty policy is given in [25].

Policy 15

LIMIT ON TOTAL COST: Under this policy, the dealer's obligation ceases when the total repair cost over the warranty period exceeds a specified limit or at the end of the extended warranty period, whichever comes first.

Again, there are a large number of additional possibilities.

Example 3.4 [Automobile]

Most automobile manufacturers as well as third parties (such as insurance companies and retailers) offer a wide variety of extended warranty policies. In most cases, the customer is offered a choice for (i) the limits on the time and usage and (ii) the items covered under the policy.

The Ford Motor Company offers four different types of warranties, namely:

- ESP-1: ESP PowertrainCare [Major coverage for budget minded]
- ESP-2: ESP BaseCare [Recommended for moderately equipped vehicles]
- ESP-3: ESP ExtraCare [Recommended for well-equipped vehicles]
- ESP-4: ESP PremiumCare [Recommended for the most high-tech vehicles].

The number of components covered under extended warranty is as follows:

- ESP-1: 29 components
- ESP-2: 84 components
- ESP-3: 113 components
- ESP-4: 500 components.[23]

The four policies also include coverage for a rental car of up to $35/day and towing reimbursements of up to $100. The price for the extended warranty depends on the type of coverage and the limits on time and usage.

■

3.7 Study of Warranty

Because of the diversity of purpose and application, product warranty has received the attention of researchers from many diverse disciplines.[24] As a result, warranty issues have been considered from many perspectives, as illustrated in the following tabulation [16]:

1. Historical: origin and use of the notion
2. Legal: court action, dispute resolution, product liability

---

[23] The specific components covered under each of the four warranty policies can be found at http://www.fordwarrantys.com/plans.cfm

[24] See Djamaludin *et al.* [26] for a bibliography listing over 1500 papers through 1996. Reviews of the more recent literature on warranty can be found in Thomas and Rao [27], and Murthy and Djamaludin [28].

3. Legislative: Magnusson-Moss Act; Federal Trade Commission, Warranty requirements in government acquisition (particularly military) in the USA and the latest EU legislation
4. Economic: market equilibrium, social welfare
5. Behavioral: buyer reaction, influence on purchase decision, perceived role of warranty, claims behavior
6. Consumerist: product information, consumer protection
7. Engineering: design, manufacturing, quality control, testing
8. Statistics: data acquisition and analysis, data-based reliability analysis
9. Operations Research: cost modeling, optimization
10. Accounting: tracking of costs, time of accrual
11. Marketing: assessment of consumer attitudes, assessment of the marketplace, use of warranty as a marketing tool, warranty and sales
12. Management: integration of many of the previous items, determination of warranty policy, warranty servicing decisions
13. Societal: public policy issues

As a consequence, the literature on warranty is very large. In attempting to organize this literature and integrate the many different issues that have been addressed [16], it was found that most analyses deal with technical and/or cost issues.

In contrast, the management of warranty has received very little attention, at least as far as consumer products are concerned. Some management issues that have been addressed are:

- Administration of warranties in the context of government acquisition [29]
- The use of warranty as offensive and defensive marketing strategies [30]
- The strategic management of warranty [31].

In the remainder of this book, we deal in depth with these and many related management issues.

Appendix. Selected Warranty Policies

Exhibit 3.1. Warranty Policy for a Photocopier[25]

Warranty Information and Purchase Agreement

American Copier Corp. may choose to cover additional elements or situations involving a customer's machine beyond those warranties contained below.

1 Two year replacement guarantee on all copiers. American Copier Corp. warrantees the main unit to be free from major malfunction for a period of 2 years from date of purchase. This includes all circuit boards, sorter/finisher and document feeder. American Copier will ship replacement major components promptly. If the copier is deemed irreparable by two (2) separate service companies (1 company in

[25] Offered by American Copier. For further information, see sales@American-copier.com

written approval) American Copier Corp. will replace the machine with an equal or better copier at the discretion of American Copier Corp. at no charge to customer with exception of shipping.
2 60 Day 100% Parts and Labor for all copiers.
3 Drum Warranty comes with a 6 month, 60,000 maximum copy drum (photoreceptor) warranty. This warranty is in effect up until 60,000 copies or the number of copies rated for the photoreceptor by the copier manufacturer, which ever is lower.
4 This warranty does not cover consumables.
5 American Copier Corp. guarantees that unless otherwise stated, all copiers will be operable or made operable upon receipt by customer. Should the copier arrive damaged it is the responsibility of the customer to call American Copier Service Tech. Any repairs needed to make by American Copier Corp. must be approved first by management.
6 Return Policy. Customer may return copiers which do not function to the manufacturers specifications with prior written approval from American Copier Corp. Management. Customer must allow repair attempt prior to return authorization. Remember your copier was just transported and the most common time for the machine to need fine tuning is after shipment. Customer is responsible for any and all shipping cost including insurance. Restocking fee of 15% applies to all returns. If customer rejects shipment of any time subsequent to placing order and within 30 days of placing order customer agrees to pay all shipping and restocking fees. American Copier Corp. will when return is approved arrange for return shipping at our discount rate with usual shipping of agent or agents of customer choosing so long as set shipper provides air ride, padded transportation. Customer will receive full refund for all the equipment accessories, and supplies including used toner in original packing. Equipment return request must be made to American-Copier.com within 30 days of original purchase date.
7 This agreement shall not apply to any equipment which ceases to be at the original customer shipping destination location or is damaged through accident, abuse, misuse, theft, neglect acts of third party, fire water, war, casualty or other natural forces.
8 Specifications, changes, alterations or attachments may require a change in warranty. Such changes should become effective upon notice to Customer by American Copier Corp. American Copier Corp. also reserves the right to terminate this agreement by notice to customer if American Copier Corp. determines that such change in alteration, or attachment make it impractical for American Copier Corp. to continue to warrantee the equipment.
9 American Copier Corp. should have the consequential damages by any reason of non-performance of this agreement. Customer agrees to resolve any disputes regarding credit card charges through legal means other than Credit Card Company or issuing bank. This is, such disputes are to be resolved through legal channels or agreed upon terms. American Copier should be entitled to consequential damage, including but limited to attorney fees arising out of customer's non-performance of this purchase agreement. .
10 Customer accepts this agreement as binding under those terms described herein and herby authorized payment for the same. 05% monthly late charges will be applied to unpaid balances.

Exhibit 3.2: Warranty Policy for an Automobile Battery[26]

LIMITED WARRANTY

IMPORTANT: Keep this and sales receipt in glove compartment or wallet.

Interstate Battery System of America, Inc. ("IBSA") warrants only to the original purchaser that: 1) this battery is free of defects in material and workmanship for the number of months indicated on the label, and 2) prior to installation or use, the state of charge of this battery has been maintained at a level equal to or greater than the minimum level considered adequate under industry standards for batteries to perform effectively upon their use or installation. If adjustment is necessary due to a defect in material or workmanship, or state of charge below minimum industry standards prior to installation or use, and the battery is NOT MERELY DISCHARGED after installation or use, then upon return of the battery to an authorized dealer:

[26] Information obtained from off-the-shelf battery manufactured by Interstate Battery System of America, Inc., and displayed for sale in October of 2003. For additional information, access www.ibsa.com.

a. Within eighteen (18) months from the date of original purchase, all batteries designed for passenger cars, and types: C24-XHD, C24F-XHD, D27-XJD. C27F-XHD, C50-XHD, C65-XHD, C74-XHD, C75DT-XHD, C78DT-XHD, and group sizes 29H and 31, will be replaced free of charge (except for taxes, where applicable).*
b. Within twelve (12) months from the date of original purchase, all batteries of the following types: HD24-DP, 24M-H, 24M-RD, 24M-XHD, SRM-24, SRM-27, SRM-29, will be replaced free of charge (except for taxes, where applicable).
c. Within six (6) months from the date of original purchase, all other batteries will be replaced free of charge (except for taxes, where applicable).
d. After the free replacement described in paragraphs (a), (b), or (c) above, whichever applies, and for the remaining period of months of designated warranty period, the original purchaser may obtain a replacement battery of similar size upon payment of a prorated charge based upon the then current published cost per month of the battery multiplied by the number of full months elapsed since the date of original purchase. *

* When a passenger car battery is used in a diesel vehicle (not including passenger automobiles), commercial service, truck over one ton, marine service, recreational vehicle, lawn tractor, snowmobile, etc., and is defective in material or workmanship, it will be replaced free of charge (except for taxes, where applicable), within six (6) months from date of original purchase. The length of the prorated warranty is one half that indicated on the battery label. Any battery used in electric vehicle service has a twelve month prorated warranty.

FOR WARRANTY SERVICE, RETURN THE BATTERY TO THE IBSA DEALER WHERE THE BATTERY WAS PURCHASED OR CALL THE TOLL FREE NUMBER LOCATED ON YOUR BATTERY FOR THE NEAREST DEALER LOCATION. ALL BATTERIES ARE DESIGNED TO MEET CERTAIN PERFORMANCE SPECIFICATIONS, SUCH AS COLD CRANKING AMPS AND RESERVE CAPACITY, BUT DUE TO VARYING USES AND OPERATING CONDITIONS, IT IS IMPOSSIBLE TO ANTICIPATE THE USEFUL LIFE OF THIS BATTERY, OR ANY OTHER BATTERY. IF THIS BATTERY SHOULD MATERIALLY FAIL DURING THE WARRANTY PERIOD, THIS LIMITED WARRANTY SHALL CONTROL THE TERMS FOR ADJUSTMENT.

ISBA'S LIABILITY IS LIMITED TO REPLACEMENT OF THE BATTERY IN ACCORDANCE WITH THE TERMS STATED ABOVE. IBSA WILL NOT BE RESPONSIBLE FOR ANY EXPENSE FOR INSTALLATION, TOWING, ELECTRICAL SYSTEM TESTS, CHARGING A BATTERY, LOSS OF TIME, OR OTHER EXPENSES WHICH WOULD BE CONSIDERED AS INCIDENTAL OR CONSEQUENTIAL DAMAGES. THIS WARRANTY DOES NOT COVER DAMAGE TO THE BATTERY CAUSED BY ABUSE OR NEGLECT, A FAILURE TO KEEP THE BATTEERY PROPERLY CHARGED OR MAINTAINED, FIRE, COLLISION, EXPLOSION, FREEZING, THEFT, OVERCHARGING, OR DAMAGE CAUSED BY USE OF SPECIAL ADDITIVES.

THE WARRANTY DESCRIBED IN THIS PARAGRAPH SHALL BE IN LIEU OF ANY OTHER WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE.

NOTE: SOME STATES DO NOT ALLOW LIMITATIONS ON HOW LONG AN IMPLIED WARRANTY LASTS, OR THE EXCLUSION OR LIMITATION OF INCIDENTAL OR CONSEQUENTIAL DAMAGES, SO THE ABOVE LIMITATIONS MAY NOT APPLY TO YOU.

This warranty gives you specific legal rights, and you may also have other rights which may vary from state to state.

Exhibit 3.3. The Standard Automobile Warranty (Circa 1930) [32]

Warrant each new motor vehicle manufactured by us, whether passenger or commercial vehicle, to be free from defects in material and workmanship, under normal use and service, our obligation under warranty being limited to making good at our factory any part or parts thereof which shall, within ninety (90) days after delivery of such vehicle to the original purchaser, be returned to us with transportation charges prepaid, and which our examination will disclose to our satisfaction to have been thus defective; this warranty being expressly in lieu of other warranties expressed or implied and of all other obligations or liabilities on our part, and we neither assume nor authorize any person to assume for us any other liability in connection with the sale of our vehicles.

The warranty shall not apply to any vehicle which shall have been repaired or altered outside our factory in any way or so as, in our judgment, to affect its stability, or reliability, nor which has been subjected to misuse, negligence or accident, nor to any commercial vehicle made by us which shall have been operated at a speed exceeding the factory rated speed, or loaded beyond the factory rated load capacity.

We make no warranty whatever in respect to tires, rims, ignition apparatus, horns or other signaling devices, generators, batteries, speedometers or other trade accessories in as much as they are usually warranted separately by their respective manufacturers.

Exhibit 3.4. Warranty for 2004 Pontiac (Table of Contents)[27]

2004 Pontiac Warranty and Owner Assistance Information

References

[1] Gomuldiewicz, R. W. (1998), "The implied warranty of merchantability in software contracts: A warranty no one dares to give and how to change that," *John Marshall Journal of Computer and Information Law* **16**, 393–402.

[2] Zhang, X. M., and Pham, H. (1998), "A software cost model with warranty cost, error removal times and risk costs," *IIE Transactions* **30**, 1135–1142.

[3] Kimura, M., Toyota, T., and Yamada, S. (1999), "Economic analysis of software release problems with warranty cost and reliability requirement," *Reliability Engineering and System Safety* **69**, 49–55.

[4] Pham, H. and Zhang, X. M. (1999), "A software cost model with warranty and risk costs," *IEEE Transactions on Computers* **48**, 71–75.

[5] Sahin, I., and Zahedi, F. M. (2001), "Control limit policies for warranty, maintenance and upgrade of software systems," *IIE Transactions* **33**, 729–745.

[6] Emswiller, B. B. (1994), "Veterinary sales and purchases of goods and the warranties that affect them," *Journal of the American Veterinary Medical Association* **204**, 433–438.

[7] Hannah, H. W. (1999), "Livestock sales and the Uniform Commercial Code – What warranties are there?" *Journal of the American Veterinary Medical Association* **214**, 1013–1014.

[8] Ong, S. E. (1997), "Building defects, warranties and project financing from pre-completion marketing," *Journal of Property Finance* **8**, 35–51.

[9] McDougall, G. H. G., Levesque, T., and VanderPlaat, P. (1998), "Designing the service guarantee: unconditional or specific?" *Journal of Services Marketing* **12,** 278–293.

[10] Dornan, D. L. (1992), "Asset management: remedy for addressing the fiscal challenges facing highway infrastructure," *International Journal of Transport Management* **1**, 41–54.

[11] Vlatas, A. J. (1994), "An economic analysis of implied warranties of fitness in commercial leases," *Columbia Law Review* **94**, 658–709.

[12] Yost, J. A., and Rasch, R. H. (2000), "Optimal warranty arrangements for the design of accounting information systems," *International Journal of Accounting Information Systems* **1**, 135–152.

[13] White, J. J., and Summers, R. S. (1972), *Uniform Commercial Code*, West Publishing Company, St. Paul, MN.

[14] Kelley, C. A. (1996), "Warranty legislation," in Blischke, W. R., and Murthy, D. N. P. (Editors), *Product Warranty Handbook*, Marcel Dekker, Inc., New York, Chapter 4.

[15] Blischke, W. R., and Murthy, D. N. P. (1994), *Warranty Cost Analysis*. Marcel Dekker, Inc., New York.

---

[27] Reproduced from the basic 2004 Pontiac warranty document as provided to owners. More information may be obtained from a Pontiac dealer.

[16] Blischke, W. R., and Murthy, D. N. P. (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[17] Blischke, W. R., and Murthy, D. N. P. (1992), “Product Warranty Management – I: A taxonomy for warranty policies,” *European Journal of Operational Research* **62**: 127–148.

[18] Guin, L. (1984), *Cumulative Warranties: Conceptualization and Analysis*, doctoral dissertation, University of Southern California, Los Angeles, CA.

[19] Gandara, A., and Rich, M. D. (1977), *Reliability Improvement Warranties for Military Procurement*, Report No. R-2264-AF, RAND Corp., Santa Monica, CA.

[20] Balaban, H. S. (1975), “Guaranteed MTBF for Military Procurement,” *Proceedings 10th International Logistics Symposium*, SOLE.

[21] Kruvand, D. H. (1987), “Army aviation warranty concepts,” *1987 Proceedings Annual Reliability and Maintainability Symposium*, 392-394.

[22] Chattopadhyay, G. N. (1999), *Modelling and Analysis of Warranty Costs for Second-hand Products*, doctoral dissertation, The University of Queensland, Australia.

[23] Chattopadhyay, G. N., and Murthy, D. N. P. (2000), “Warranty cost analysis for second-hand products,” *Journal of Mathematical and Computer Modelling*, **31**, 81–88.

[24] Chattopadhyay, G. N., and Murthy, D. N. P. (2001), “Warranty cost sharing policies for second-hand products,” *International Transactions in Operational Research* **8**, 47–60.

[25] Padmanabhan, V. (1996), “Extended warranties,” in [16], Chapter 4.

[26] Djamaludin, I., Murthy, D. N. P., and Blischke, W. R., “Bibliography on warranties,” in [16].

[27] Thomas, M. U., and Rao, S. S. (1999), “Warranty economic decision models: A summary and some suggested directions for future research,” *Operations Research*, **47**, 807–820.

[28] Murthy, D. N. P., and Djamaludin, I. (2002), “Product warranty – A review,” *International Journal of Production Economics* **79**, 231–260.

[29] Brennan, J. R. (1994), *Warranties. Planning, Analysis and Implementation*, McGraw-Hill, New York.

[30] Menezes, M. A. J., and Quelch, J. A. (1990), “Leveraging your warranty program,” *Sloan Management Review* **31**, 69–80.

[31] Murthy, D. N. P., and Blischke, W. R. (2000), “Strategic Warranty Management – A life cycle approach,” *IEEE Transactions on Engineering Management* **47**, 40–54.

[32] Bogart, G. G., and Fink, E. E. (1930), Business practice regarding warranties in the sale of goods, *Illinois Law Review*, **25**, 400–417.

4

Warranty Management

4.1 Introduction

Many companies have failed to recognize the importance of warranties, to say nothing of warranty strategy, and have, in fact, reduced factory warranties and attempted to maximize profits by selling extended warranties, instead. In a discussion of this phenomenon, Cope and Pellitier [1] state that “American business, in other words, has divorced the warranty from the product, making it just another saleable item. Sadly, this only reinforces the impression that U. S. companies have no confidence in their products.” In the long run, this strategy will not work.

Historically, poor warranty management has had serious financial consequences. In 1960, Ford expanded its warranty from 90 days/4000 miles to one-year/12,000 miles. The automobile industry saw warranty as a marketing strategy and other manufacturers followed this lead. By 1962, Chrysler decided to offer a five-year/50,000 mile warranty as means of reversing its sagging market share. By the late 1960s, manufacturers discovered the consequences of this action. The warranty servicing costs ($300 million for Ford, $580 million for General Motors and $200 million for Chrysler in 1969) had increased significantly because product reliability and quality were not good enough to support the longer warranty. In particular, the warranty strategy was not linked properly to product development strategy, and as a result, it was not recognized that product reliability was not adequate to keep the warranty costs low. In the late 1960s, manufacturers reversed their strategy and began decreasing warranty coverage, resulting in ill feelings among consumers [2].

An interesting case study of U.S. and Japanese air conditioners [3, p. 201] looked at the service call rates per 100 units in the first year of warranty coverage. The median and range for the two are:

	USA	Japan
Median	10.5	0.6
Range	5.3 – 26.5	0.04 – 2.0

As can be seen, the warranty costs for the U.S. manufacturers are significantly higher than those for the Japanese. According to Garvin, the author of the study, “In both countries the stages of the design procedures were similar but in Japan the pre-testing and experimentation was far more extensive. In the USA, often only a single prototype was built and tested before moving to pilot production. In contrast, the Japanese often repeated the process three or four times.” [3, p.208] This indicates that the design and development strategies were not well integrated with warranty strategy.

How, then, does one deal with warranties, or, more specifically, with warranty management in a strategic sense? Warranty has been recognized for some time as being of increasing importance in the marketing of products in the context of both product assurance and product differentiation. What is needed is a coherent, well thought out policy for dealing with warranty issues.

For most companies, warranty costs are a closely guarded secret, as evidenced by the fact that very little warranty data is available in the public domain. These costs are, of course, related to product quality. Bergstrom [4] emphatically makes this point (in the context of a high quality John Deere product for which warranty costs have been significantly reduced), stating that, “... what will contain some meaning (for a customer) is an examination of the manufacturer's warranty costs. If warranty costs are high, then product quality is more likely to be low, in an inverse proportionate sense.”

Because of the importance of warranties, organizations supplying goods or services with warranty need to develop effective approaches to managing warranties. This chapter deals with a strategic approach to warranty management. It discusses decision-making with regard to all aspects of warranty from an overall business viewpoint and over the product life cycle. This involves formulating a warranty strategy that is coherent and well integrated with other strategies of the organization because warranty strategy formulation must take into account the impact of warranty on the activities of the various sections of the organization, and vice versa.

Strategic warranty management means more than simply avoiding claims during the warranty period. It means that companies learn from customer experience and reconcile what they want with what engineers can reasonably design and build. Failure to develop a warranty strategy can have an adverse effect on overall business performance.

An appropriate warranty strategy depends on the type of product, the type of customer, and the overall business strategy. It also depends on a number of external factors, especially competition and competitors' strategies. Most importantly, it must link both technical and commercial issues over the product life cycle, since technical issues (for example, design) affect warranty cost and this in turn affects commercial issues (for example, pricing) and, finally, overall business performance.

In addressing the strategic management of warranty from the manufacturer's perspective, we are concerned with the following questions: What are the issues that need to be addressed in formulating a warranty strategy? How should these issues be managed in the product life cycle context? A framework for addressing these issues is discussed in the next section.[1]

The outline of the chapter is as follows: In Section 4.2, we look at warranty strategy in the context of overall company strategies, considering both technical and commercial issues and the relationships between these. Strategies over the life cycle of the product are considered. These are discussed in detail in Sections 4.3–4.5, which deal, respectively, with strategies for the pre-launch, launch, and post-launch stages of the life cycle.

4.2 Framework for Strategic Warranty Management

A warranty of any type, since it involves an additional service associated with a product, will lead to potential costs beyond those associated with the design, manufacture and sale of the product. These costs, in fact, are unpredictable future costs. Management of these costs is important. Warranty strategies based solely on minimizing this cost can be called "defensive" strategies. In contrast, "offensive" strategies view warranty in a different light. Better warranty terms lead to greater sales (market share) and revenue. However, this increases the warranty servicing costs. Warranty servicing costs can be reduced by improving reliability (through product development) and better quality control. These in turn involve additional costs. These must be integrated in the formulation of a warranty strategy. The goal of strategic warranty management should be to achieve the stated business objectives, which can include one or more of the following – return on investment, revenue, market share, customer loyalty and profits. This can be achieved only when all the different strategies (including warranty strategy) are effectively integrated from an overall business viewpoint.

Effective warranty management must take into consideration both the commercial and technical aspects of warranty. To be effective and successful, a warranty manager must have a good understanding of the issues involved in both the commercial and technical areas and the interrelationships amongst these issues so as to craft the warranty strategy in the context of an overall business strategy.[2]

Periodic re-evaluation and revision of warranty strategy is necessary for several reasons. The main reason is that products (and services) are changing rapidly as a result of emerging new technologies, as discussed in Chapter 2. These changes often lead to significant and relatively rapidly occurring changes in the marketplace, in turn requiring that the various strategies, including that for warranty, be dynamic in order to respond to new conditions adequately.

Figure 4.1 is a schematic showing a hierarchy of strategies, beginning with the overall business strategy of the organization. Typically a company in its long-range planning will be considering a number of possible new products or product lines as

---

[1] This was first proposed in Murthy and Blischke [5].

[2] There are many books dealing with strategic management. See, for example, Thompson and Strickland [6]. Technology management is a key aspect of strategic warranty management. For more on this topic, see Betz [7].

a part of its overall business strategy. From this will emerge a set of goals with regard to new product development and a strategy for achieving these goals. Goals may be quite broad, but will ordinarily include market share, profit objectives, per-unit production cost, and so forth.

In planning to achieve these goals, strategies for addressing the technological issues, as shown on the left side of Figure 4.1, and the commercial issues, shown on the right side, must be developed. From the point of view of warranty strategy, technology issues include the engineering aspects of product design and manufacturing. Commercial issues in this context involve marketing and servicing aspects. To be effective, these strategies must be coherent and integrated.

Failure to address both sets of issues adequately can seriously affect profitability of the product. In particular, lack of attention to technological issues can lead to inadequate product reliability and quality and hence to excessive warranty claims. Excessive claims can also occur as a result of inappropriate warranty terms as illustrated by the automobile industry case discussed in Section 4.1.

Excessive claims, in turn, will lead to an increase in warranty costs and in the number of dissatisfied customers. The consequence of this dissatisfaction is loss of sales for both this and future products. Increased warranty costs and customer dissatisfaction can also result from improper warranty servicing by either the company or its agents. Undue delays, hidden costs to the customer, improper repairs, and inconvenience in obtaining service will adversely affect both costs and level of dissatisfaction. The end result is declining profits.

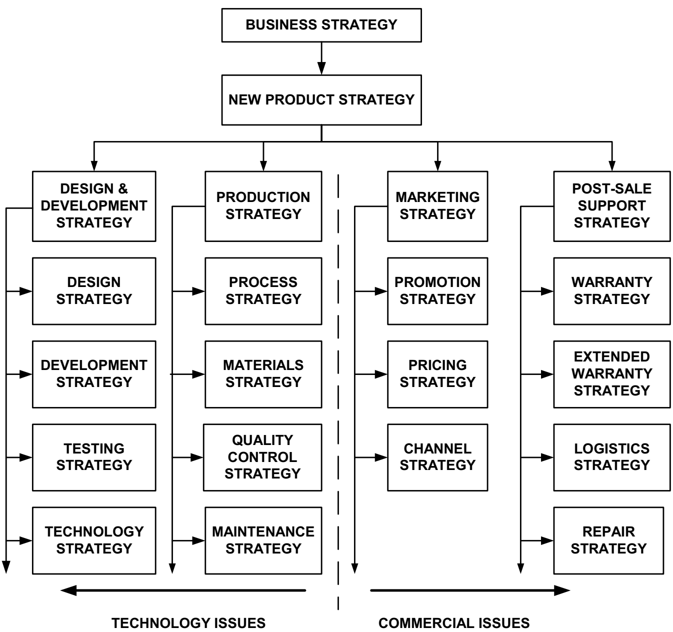


Figure 4.1. Strategy hierarchy for new products

The first step in strategic warranty management is an understanding of the technical and commercial issues involved and their interactions, in the context of the different stages of the product life cycle. In this way, warranty strategy addresses all decision problems relating to warranty from a business viewpoint. In the remainder of the section we discuss these issues.

4.2.1 Technical Issues

The principal determinants of direct warranty cost are the terms of the warranty and the reliability of the items produced. Product reliability is determined primarily by design and production choices and includes many characteristics of product performance as well as reliability and related measures. Technological issues in this context are those concerned with reliability, including conformance to design, methods for testing, prediction of expected numbers and types of product failures, and the probable cost of repair or replacement associated with each type of failure.

The technological issues for product and process design are listed in broad terms in the first two columns of Figure 4.1. The design and development strategy is developed in response to the basic design and reliability goals specified in the new product strategy. From this, the strategy for building and testing prototypes follows. This, in turn, leads to development of the final product design. A production strategy also needs to be developed at the outset. This includes selection of raw materials, suppliers of raw materials and out-sourced parts and components, and a process strategy. Finally, a quality control strategy for proper monitoring of the manufacturing process, including sampling procedures, testing schemes, acceptance standards, and so forth, also needs to be developed.

To assure high quality in the long run, attention must be paid to this beginning early in the product design process. Methods for reliability prediction play an important role. Predictions are based on past experience with similar products, by analysis of various design trade-offs, use of engineering judgment, and so forth. These predictions are refined throughout the research and development phase, as prototypes are built, testing is done, redesign is undertaken, and the final version of the product evolves. The extent and cost of this process depends on the type of product and the context. It may be a relatively straightforward process for a simple product based on existing technology, or quite costly and time consuming if new technologies are involved.

Development of an effective and efficient production process deals with the issue of producibility – process designs that minimize unit production cost while maximizing the fraction of non-defective units produced. Feedback in both directions between product design and production greatly enhances the chances of achieving the goals of producibility and design effectiveness.

Ideally, the analysis and testing of both product and process should lead to a reasonable prediction of product failure rates as a function of age. This is important information in evaluating warranty costs.

Other issues related to reliability include maintainability, availability, repairability, and many aspects of product performance that may, under certain circumstances, be covered under warranty. In this case, technical issues also include the development of methods for assessing these characteristics and application of these methods to the product being designed.

In some applications, certain performance measures may also be guaranteed under warranty. For example, jet engine manufacturers may guarantee thrust, fuel efficiency and low noise levels of their product. For complex systems, particularly in military applications, the list of performance characteristics may be quite extensive.

Clearly, not all of these issues related to reliability are applicable in every application. In order to predict warranty costs, it is necessary to decide early on what the probable warranty terms are to be. Several possibilities may be under consideration. If the customer is specifying the warranty terms or they are being negotiated (under a government contract, for example), this information must be taken into consideration by the design team.

We will discuss the link between warranty and design and development in more detail in Chapter 8 and between warranty and production in Chapter 9.

4.2.2 Commercial Issues

Commercial issues include marketing, post-sale support, accounting and related areas, and deal with pricing, selection of warranty terms, promotion, and warranty service. Actions of competitors and the marketplace into which the product is to be introduced are also important factors. Strategies in this area that should be developed at the same time as the technology strategies listed in the right-hand two columns of Figure 4.1.

The two major areas that directly or indirectly involve warranty are marketing and post-sale service. Until relatively recently, the latter has received far too little attention, especially in the early planning stages. For the most part, warranty remains in this category. To be effective, strategies in these areas need to be developed concurrently, with frequent feedback from one to the other.

In developing a new product strategy, it is essential to assess the marketplace at an early stage. From this, a marketing strategy for the new product will evolve. A proposed advertising strategy will be a part of the marketing strategy. Assessment of the market and the overall marketing objectives will also lead to setting of goals with regard to pricing of the product and warranty terms to be offered.

Prediction of warranty costs is an important consideration in product pricing, since warranty and price are key elements of the marketing strategy. If the strategy is to convince the potential customer that the product is highly reliable by offering a longer warranty than that of the competition, this will almost always have the effect of increasing warranty costs.

Chapter 10 deals with the link between warranty and marketing and looks at several issues ranging from the effect of warranty on the consumer choice process to market outcome. Chapter 11 looks at various logistical issues related to warranty servicing. These include strategic issues such as location of warehouses, manufacturer–dealer contracts, transportation of spares, etc., as well as operational issues such as inventory levels, reordering policies, repair versus replace decisions, and so forth.

4.2.3 Interaction of Technological and Commercial Issues

Commercial and technical issues tend to interact strongly in determining the profitability of a product. This needs to be taken into account in selecting and evaluating warranty policy. Longer warranties require higher reliability in order to control warranty costs. There is a trade-off between design and production costs to improve reliability and the cost of servicing a warranty. As one increases, the other decreases. The difficult problem is to find the optimal cost allocation, i.e., the balance between design and production cost and future warranty costs that minimizes the total cost per item. In seeking such an optimum, close cooperation among design, production, marketing, and warranty servicing groups is essential. Interactions among many groups within a company as well as with suppliers are required in formulating a warranty strategy.[3]

Recognition of the importance of the linkage between technological and commercial issues has developed slowly over the past few decades. The development of the linkages between design and development (D & D), production, marketing and post-sale service is shown in Figure 4.2.

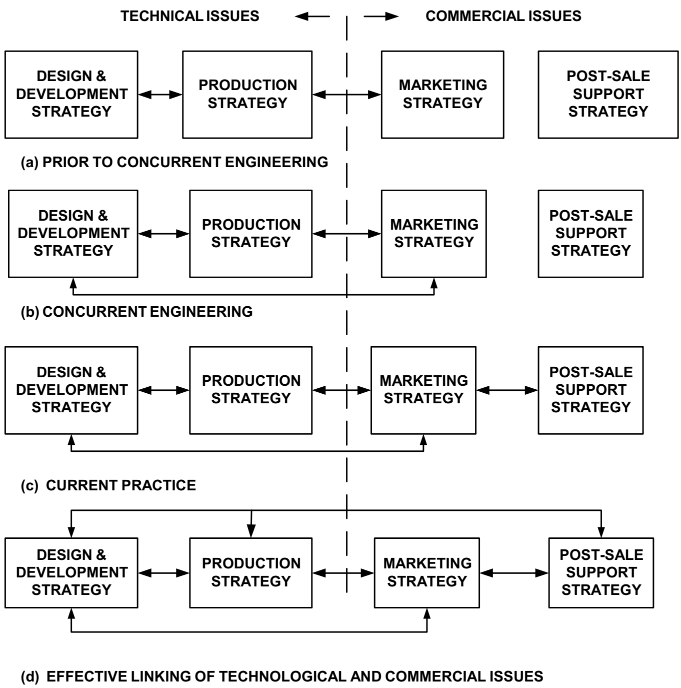


Figure 4.2. Evolution in the linking of technological and commercial issues

[3] This is discussed in the context of government procurement of aircraft and aircraft components by Hadel and Lakey [8].

Prior to the notion of concurrent engineering (Figure 4.2(a)), product development began with D & D and proceeded through a sequence of steps, including prototype construction and testing, to the final design configuration. The project was then taken over by the production section. Once the necessary tooling, production line set-up, and so forth were completed and other decisions necessary to the production process were made, the marketing section took on the activities of advertising, product distribution, and related activities. Typically little feedback between these sections took place and little thought was given to warranty (except to make sure that it was conservative) and post-sale service.

With the advent of concurrent engineering (Figure 4.2(b)), D & D and production decisions were made jointly and many activities in these two areas began to take place simultaneously. This allowed for important feedback between D & D and production to take place, and marketing was included in this loop as well. This significantly shortened the time required to bring a new product to market. It also provided a mechanism for various trade-offs, for example, between product and process design, that could greatly enhance producibility and reduce costs. All in all, the concurrent engineering approach to product development led to a much more effective and efficient organization. Warranty and other post-sale considerations, however, remained more or less an after-thought and played little, if any, role in these decisions.

As discussed in Chapter 2, post-sale service is now recognized as an important element in the market place. The current situation (Figure 4.2(c)) is that this activity is undertaken early in product development, with input primarily from marketing. Thus warranty terms and decisions regarding extended warranties are made in the context of the overall marketing strategy, with little feedback and inadequate or no interaction with the technological side.

For effective strategic management of warranty, all four of these areas must interact with each other as shown in Figure 4.2(d). Design and production choices affect product reliability and quality and hence warranty cost. Conversely, warranty decisions require compatibility with product reliability and quality to control costs and hence impact on design, process and quality control, and there are many other areas of interaction between technology and business.

4.2.4 Product Life Cycle Approach to Warranty Management

For the strategic management of warranty, we view the life cycle as comprised of two stages (defined as the pre- and post-launch stages in Chapter 2) separated by the launch window, as indicated in Figure 4.3. The pre-launch stage includes all aspects of product definition, product and process design, preparation of marketing plans, and specification of warranty alternatives and covers the first three phases of the product life cycle from the production perspective, as discussed in Section 2.4.1.

The launch window includes all activities just prior to and just after product launch. The focal point of the launch window is the target launch date. The launch window may be expanded in either or both directions as the project unfolds. If a competitor announces an earlier launch date or a similar product, the target date may be advanced. If unavoidable delays in achieving pre-launch goals are incurred, the target date may be pushed back. Both of these actions may have considerable impact on both pre-launch and post-launch activities.

Finally, the post-launch stage includes marketing, post-sale service, feedback to design, manufacturing and marketing and any revisions in these areas that might become necessary for the duration of the product life cycle. As such, it covers the last two phases of the product life cycle from the production perspective, which is discussed in Section 2.4.1.

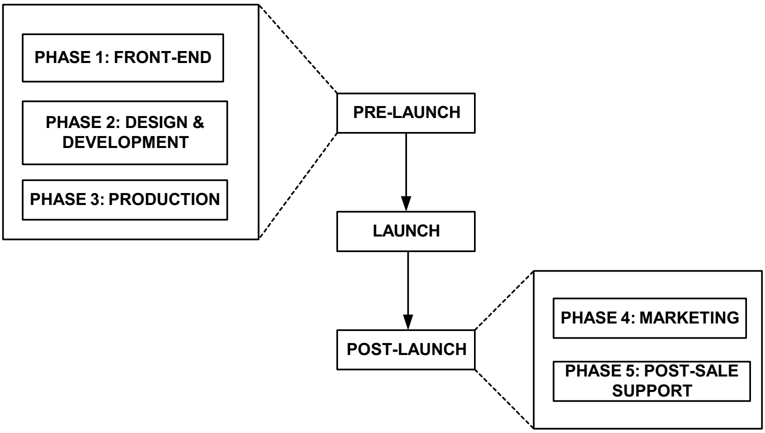


Figure 4.3. Product life cycle – warranty perspective

4.2.5 Formulation of Warranty Strategy

Warranty costs depend primarily on two factors: the performance of the product and the terms of the warranty. Product performance is determined by many factors: engineering design of the product, design of the manufacturing process, raw materials selection, quality of parts or components received from outside sources, quality control, distribution, pre-sale servicing (if any), use and maintenance of the product by the buyer. Warranty should be an important consideration in many of these areas.

A key aspect of strategic warranty management is that decisions with regard to warranty must begin at a very early stage in the product life cycle and not as an afterthought just prior to the launch stage. The technical and commercial targets at the Front End phase influence the various strategies (see Figure 4.3) for the next four phases (Design and Development, Production, Marketing, and Post-sale), and decisions regarding the target values must take this into account.

Figure 4.4 is a schematic representation of the setting of technical and commercial target values in the Front End phase. These then lead to a hierarchy of targets for defining strategies as one proceeds into the various sub-phases of each of the next four phases. The outcome of the strategy formulation process is the overall business strategy, in which all the lower level strategies are cohesive and well integrated.

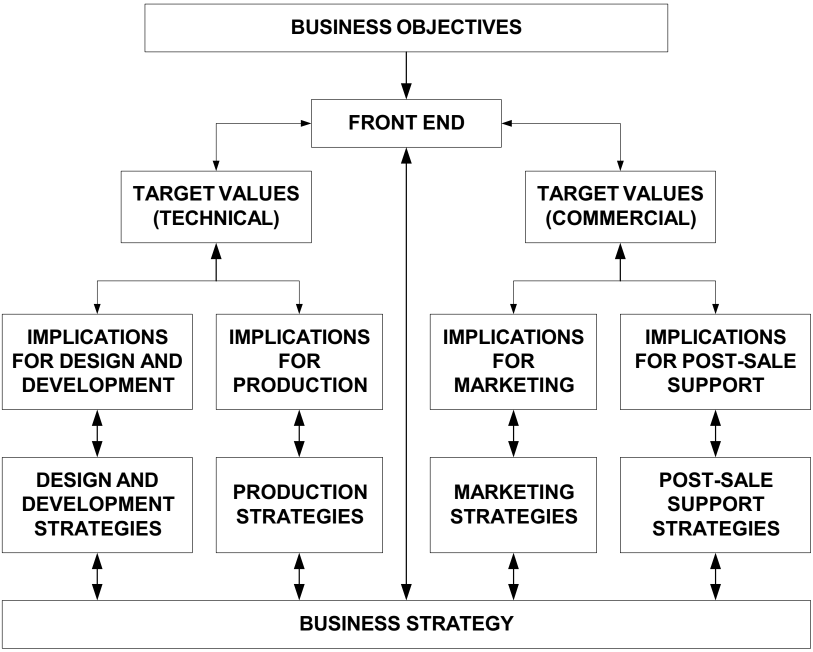


Figure 4.4. Strategy formulation

4.2.6 Strategy Implementation

Strategy formulation (done in the Front End phase) is only the first step in the strategic management of new products. Once the strategies have been formulated, they need to be implemented and this involves executing a variety of tasks in each of the next four phases. As the implementation proceeds, new information is obtained and this is used for making changes to the strategy, as necessary.

One important source of new information is the warranty data. This provides valuable information regarding the performance of the product in the field, ability to meet customer needs, and customer satisfaction. This information is used in making periodic revisions to the various strategies over the life cycle of the product. This is shown schematically in Figure 4.5.

In the following sections, we discuss these and highlight the link between warranty and the various activities at each phase.

4.3 Pre-Launch Stage

4.3.1 Front-End [Pre-Design or Feasibility] Phase

New products are developed in response to market forces. By the conventional approach, during the pre-design phase, the need for a particular product is perceived and customer expectations with regard to the product are measured. Management then sets target values for the product regarding

- Desired functional features
- Desired cost per unit
- Desired sale price.

Potential sales are assessed and a budget for development and manufacturing is determined. Based on this analysis, a GO/NO GO decision is made regarding the product concerned. In the case of a GO decision, the target values, along with a target launch date, become the basis for defining strategies for R&D, manufacturing and marketing.

In this approach, the linking between the commercial and technical issues is as shown in Figure 4.2(c). Post-sale service (warranty and extended warranty) is not viewed in a strategic framework. The warranty costs are simply viewed as a percentage of the sale price in the cost analysis.

Because of the role and importance of warranty, a more desirable approach is to define a preliminary warranty policy, in conjunction with the target values, at the pre-design phase. This constitutes the warranty strategy element for the pre-launch stage and leads to a linking between the commercial and technical issues as shown in Figure 4.2(d).

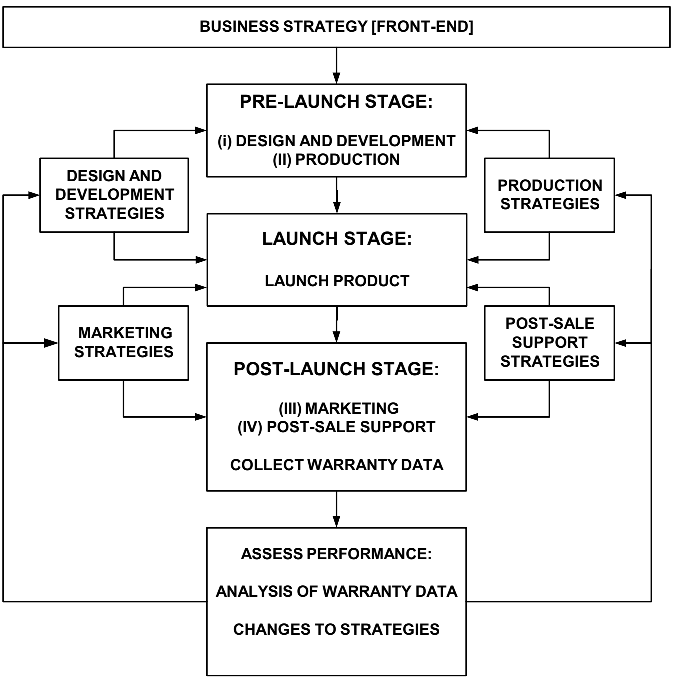


Figure 4.5. Strategy implementation

As shown in Figure 4.4, the most important strategic decisions regarding warranty in the pre-launch stage are those involving preliminary selection of a warranty policy, i.e., setting target values for warranty terms, and selection of target values for related commercial and technical variables. These must take into consideration the following:

1. Warranties serve many purposes.
2. Customers may have certain minimum expectations regarding warranty.
3. The warranty must be competitive.
4. Design and production decisions have a significant impact on product reliability and hence on future warranty and other support costs.
5. These costs can have a significant impact on profits.

Determination of customer expectations regarding basic functional features and performance of the product may require some effort, but these expectations are easily measurable, for example, by surveys and other market research techniques. Customer reactions to possible alternative warranty policies may also be obtained in this way. Customer expectations with regard to other areas of support, e.g., reliability, availability, and so forth, may be more difficult to measure. Furthermore, they may be nonlinear functions of time, e.g., downtime of four hours may be much more costly than twice the cost of a downtime of two hours.

As a result, in the pre-design phase, issues relating to the warranty are the planned use of warranty in advertising, a tentative decision regarding extended warranties, and so forth. The warranty strategy that evolves is an initial specification of the warranty policy that is to be offered. This can undergo revisions in the later phases of the pre-launch stage.

4.3.2 Design and Development Phase

This phase is comprised of two sub-phases – Conceptual Design and Detailed Design and Development.

4.3.2.1 Conceptual Design

The principal goal in the design phase is to determine the feasibility of achieving the objectives put forth in the pre-design phase and to initiate the engineering activities for accomplishing them. This will usually involve theoretical studies, analysis of capabilities, engineering judgment, and use of information on past similar products and/or components.

The initial product functional features and warranty policy defined during the pre-design phase has a considerable impact on the design phase. We focus our discussion on the warranty related issues. The design issues that become critical are the following product features:

- Product reliability (defined through various measures, such as the failure pattern of the item, failure rates, mean time to failure, etc.)

- Other features such as serviceability (defined through mean time to repair, cost of repair, etc.).

These define target values for product reliability and other features. These in turn have an impact on R&D and manufacturing. R&D is needed when available technologies (processes and materials) are not adequate to achieve the defined target values for product performance.

As a result, the costs associated with manufacturing and warranty servicing become important. It is estimated that 80% of all of the future costs associated with a product are determined in the design stage [7]. To reduce future warranty costs, it is necessary either to increase product reliability and conformance quality, incurring an immediate cost, or reduce the warranty coverage, which may be noncompetitive. There are many potential trade-offs that may be considered in the design phase. It is also necessary to determine at this point if the targets set at the pre-design stage are achievable and, if they are, what actions (by R&D and production) are needed to achieve them. If they are not achievable, the target values must be revised.

In the design stage one also needs to look at other issues that can reduce warranty costs. Depending on the type of product, these may include:

- Use of modular designs (to facilitate repair)
- Building diagnostic features so that on failure an item either can self-correct or the user is guided to appropriate corrective actions.

All of these lead to an increase in the design and production costs. The increases in these costs are traded against the decrease in the warranty cost. Finally, there are diminishing returns for increased effort in many cases; for example, increasing reliability beyond a certain point will have limited impact. The optimal decisions regarding product reliability are discussed in Chapter 8.

4.3.2.2 Detailed Design and Development

Once a tentative conceptual product design is selected, the project proceeds through the usual steps of detailed design, building prototypes, testing and improving the design and evaluating product performance in the context of the specified goals. As test results become available, updated reliability assessments are made and design revisions are undertaken if reliability improvement is necessary.

With regard to warranty, it is essential at this point to carefully evaluate product quality in as many dimensions as possible and to input the results into appropriate warranty cost models in order to predict and ultimately control future costs. Any cost models previously analyzed should be updated using the more complete and accurate information subsequently available.

4.3.3 Production Phase

Planning for production involves defining various elements of the manufacturing strategy. Two important issues are (i) producibility – the ease of manufacturing the product in large numbers, and (ii) quality of manufacturing. The latter refers to whether or not an item produced conforms to design specifications.

A noncomforming, or defective, item has performance characteristics that are inferior to those of a conforming item. This implies that the warranty cost for such items is usually very much higher than that for conforming items. The quality of production is affected by various factors, a few of which are:

- Process design and process capability
- Input materials and components
- Quality control practices
- Skill level of the workforce.

This implies that many strategies determined in this phase need to be integrated with the revised versions of the warranty and other strategies defined in the pre-design phase.

4.3.4 Formulating Warranty Strategy in the Pre-Launch Stage

The point has been made that for strategic management of warranty, a preliminary selection of warranty policy (for example, free replacement for a period of one year) should be made early in the pre-launch stage. Warranty policy should be evaluated, and changed as necessary, during the subsequent phases of the pre-launch stage. A schematic representation of this process is given in Figure 4.6.

In an initial evaluation of the proposed warranty, information is needed from marketing as to whether or not the warranty is competitive. If it is determined not to be, a decision has to be made regarding whether or not it can be improved. This will ordinarily require a re-evaluation of the cost models with alternative terms.

If it is found that the warranty cannot be made competitive, then other actions must be considered. Other actions that might be available include:

- Reducing the price of the product to offset the lesser warranty
- Accepting a lower profit objective and changing the warranty to meet the competition (return to “Business Objective” in Figure 4.6)
- Moving the launch date forward to beat the competition
- Cutting costs in other areas
- Abandoning the project.

If it is found that the warranty is competitive or that it can be improved to make it competitive, the next step is to evaluate product reliability. If it is found to be inadequate, determine if it can be improved and, if it cannot, proceed to take other action. If product reliability can be improved, it is the responsibility of Research and Development to make the necessary changes.

Once an acceptable level of reliability has been achieved, production costs for the redesigned product and/or process are re-evaluated. If they are not acceptable and cannot be reduced, again consider other actions. If these costs can be reduced, the necessary changes are made.

Finally, expected warranty costs are estimated and compared with the target value. If these expected costs are acceptable, the go-ahead for commencement of production is given. If not, changes to warranty terms or R&D are considered or other actions are taken.

Note that many of the decisions made in the analysis just described will be quite tentative in that they are necessarily based on incomplete or otherwise uncertain information. This will ordinarily be true, for example, of reliability predictions. In any such cases, whenever more reliable information is obtained, the analysis should be appropriately updated.

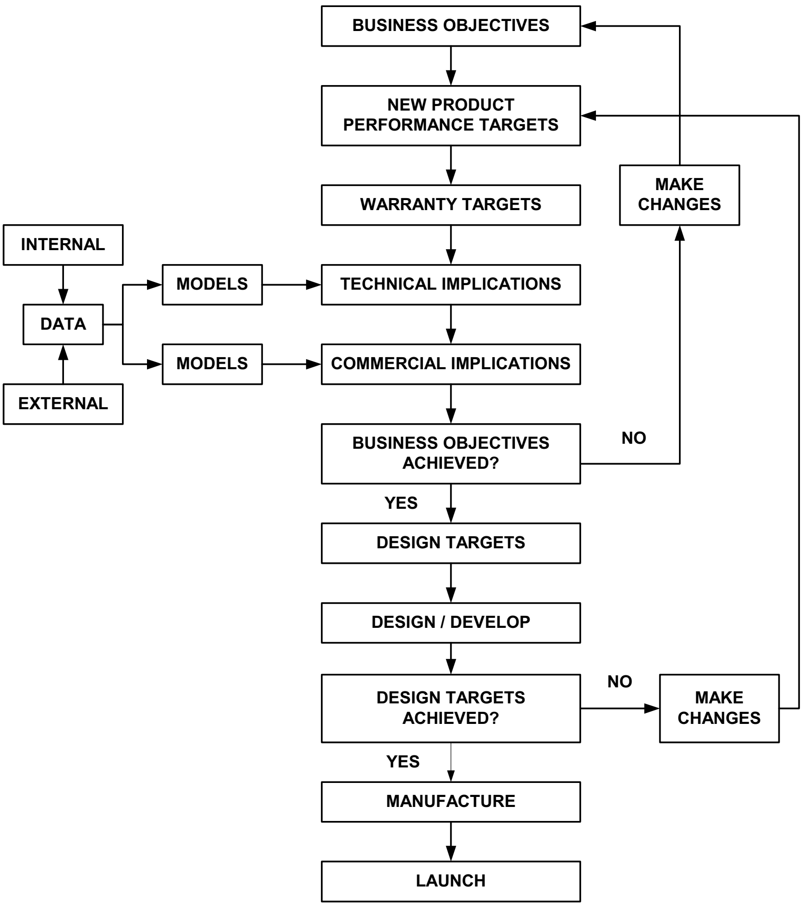


Figure 4.6. Pre-launch stage

4.4 Launch Window

The final decision to launch depends on many factors, both internal and external. Again both technological and commercial considerations are involved in the decision process. The principal concerns are (1) whether or not the project is on schedule, and (2) action of the competition. How these affect the launch decision is shown schematically in Figure 4.7.

If pre-launch activities have gone on as scheduled and it is determined that targets regarding design, production and unit costs have been reasonably satisfied, product release into the market will go on as per plan. If a decision is made to release the product prematurely (for reasons discussed in the previous section), the actual performance and/or quality may be below and/or the cost of production of the item may be above the targeted values. In this case, it should be anticipated that further design or process modifications after product release may be necessary and provision should be made for this possibility.

In any case, final decisions concerning warranty policy and price must be made at this point. These are made, in part, by analysis of some of the trade-offs previously discussed. Other issues that are related to warranty and need to be addressed are the use of warranty as a promotional tool and the servicing of the warranty. These are phases of the post-launch stage and are discussed in the next section.

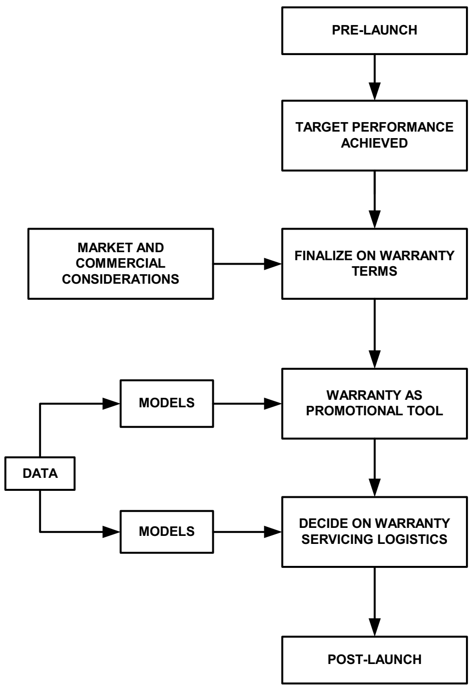


Figure 4.7. Launch stage

4. 5 Post-Launch Stage

4.5.1 Warranty as a Marketing Strategy

As a marketing tool, warranty plays many roles. One of the most important of these is that it provides the buyer with a degree of assurance against uncertainty. Strategic warranty decisions depend on whether the company is a leader or a follower with the product being introduced and the warranty being offered, i.e., whether an offensive or a defensive warranty strategy is being pursued. If the uncertainties are considered to be too great, a defensive stance will be taken, even if the action is proactive.

Warranty is viewed as an offensive tool when it is used as a signal of reliability. Better warranty terms imply higher product quality and that the manufacturer will stand behind the product. A longer warranty requires higher reliability for cost control, but higher reliability gives a competitive advantage (as long as the customer is convinced that the product is, in fact, more highly reliable). Producers of lower quality products cannot meet the competition or can do so only at substantially higher cost. Warranty in this situation is an offensive marketing tool in that the manufacturer is able to take a proactive stance in setting warranty terms.

If, instead, the manufacturer is reacting to the competition, warranty will be used as a defensive tool. The objective here is (1) to meet competition to avoid losing sales, (2) to correct possible consumer misperceptions concerning the quality of the item, and (3) to limit liability.

The FRW is sometimes thought of as an offensive strategy, while the PRW is defensive [9]. In this context, a combination FRW/PRW would be a reasonable compromise between these two strategies. On the other hand, these warranties also tend to be appropriate for specific types of products.

4.5.2 Warranty Servicing Strategy

In the analysis of predicted warranty costs, information will have been obtained concerning the number of warranty repairs or replacements that might be anticipated. This information is also useful in planning for warranty servicing. The quality of warranty service is an important product support activity. It can impact on customer good will and future sales.

Decisions must be made concerning who does the servicing and where. Servicing of failed products may be done by

- the manufacturer,
- dealers (retailers) handling the product, or
- a third party.

If done by the manufacturer, service facilities will typically already be in place for servicing other products, either at its production facilities or at dispersed locations, and it should be a straightforward matter to stock up spare items or parts and prepare service technicians for dealing with the new product. The same is basically true of dealer service. In the auto industry, for example, dealers provide most of the warranty service and are quite accustomed to the yearly change-over to new models. For radically new products, much more preparation will obviously be required. If service centers are to be set up and operated by a third party, contractual arrangements will have to be completed in addition to the other preparations.

In the case where service is to be provided by a dealer or a third party, mechanisms must be put in place to guard against the following undesirable actions on the part of agents or dealers:

- providing poor quality of service
- overcharging (either the manufacturer or, in case of less than full warranty coverage, the customer).

4.5.3 Other Issues

Several other activities are involved in the post-launch stage as shown in Figure 4.8. The decisions can vary from no change in strategy to changes in the marketing mix (changes to warranty policy and/or price) to product improvements through design and manufacturing improvements and to the final decision to discontinue the product line. Again, the warranty decisions must be done in a framework that incorporates other technical and commercial aspects.

4.5.4 Warranty Related Data

After product launch, the warranty servicing organization is put into operation. This organization is the prime source of information on product performance and quality in the post-launch period as well as information on customers' reactions. It is very important, at least initially, that this data be forwarded to the manufacturer for immediate analysis. The importance of this activity is highlighted by the following statement: "Warranties and service contracts are well known examples of the use of information to augment a product. By enhancing the effectiveness of such agreements, [information technology] can help reduce consumer risk. Sears uses an extensive information system to track product warranties." [10]

Another important source of information, obtained by the manufacturer directly, is the customer information on the warranty registration card included with most products. If analyzed properly and at regular intervals, this enables the manufacturer to prepare customer profiles and provides other information of use in marketing.

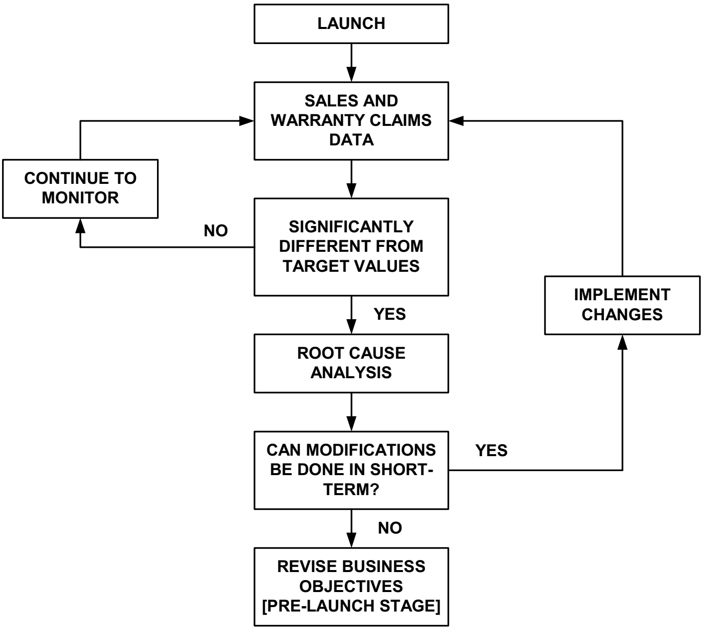


Figure 4.8. Post-launch stage

4.5.5 Use of Warranty Claims Data

Of most immediate use are the warranty claims and repair data. One very important use of these data is in updating the warranty cost models and prediction of future warranty claims.[4]

Other very important uses of the claims information are as feedback to:

- Engineering – Types and frequency of failures must be evaluated in relation to product design. If unanticipated failures occur or certain failures occur relatively frequently, design changes may be necessary.[5]
- Production – Failures are analyzed to determine if any are process induced. Changes in raw materials, suppliers, or the production process may be necessary.
- Quality Control – The QC operation must determine whether too many defective items are passing through undetected. The sampling, inspection or testing procedures may require modification.

---

[4] This is examined in the context of motorcycle warranty data from Indonesia in Iskandar and Blischke [11]. Sander *et al.*, [12] look at warranty data to assess reliability of CD players and DVDs at Philips.

[5] Two interesting case studies illustrating this in the context of automobiles are Majeske *et al*. [13], which deals with improvements in wheel bearings at Ford, and Amasaka and Osaki [14], which deals with oil seal for transaxle at Toyota.

- Warranty Management – If claims are excessive, changes in warranty policy may have to be considered.
- General Management – Top management must be aware of all of the above activities and their potential cost implications and should be involved in these decisions.

This topic is discussed further in Chapter 10.

4.5.6 Modifications to Warranty Policy

If warranty costs are predicted to become unacceptably high, changes in warranty policy, for example to a more conservative type warranty (PRW or combination instead of FRW) or to a shorter warranty period may be considered as a cost control measure. Caution must be used in such situations, however, because such changes, if they become widely known in the market, send an extremely negative message to the potential customer and can have a very adverse impact on sales. It is always better, when feasible, to correct design flaws and deal with production or quality control problems to reduce warranty service costs.

Other changes in warranty policy that may be considered are changes in the opposite direction, i.e., to more generous warranties. There are two situations in which this might be considered. The first is in reaction to competition, if one or more competitors introduces a product with a better warranty or changes the warranty in that direction on an existing product. A careful cost analysis must be undertaken prior to such action.

A second situation in which a better warranty may be considered occurs when the product is ultimately found to be of higher quality than anticipated. If initial warranty service costs are lower than expected and are predicted to remain so, a proactive strategy, increasing warranty coverage, may be considered. With proper marketing, this can send a very powerful positive message to the consumer.

Note that warranty strategy is only one aspect of support system strategy. Customer goodwill increases significantly by improving product service in other areas. These include convenience of service centers, quick response time, faster repairs, and so forth.

4.5.7 Dealing with Customer Dissatisfaction

It is only human nature that even in the case of excellent products and customer service, some customer dissatisfaction will be encountered. Considerations of customer goodwill and future sales demand that consumer complaints be handled as fairly and expeditiously as possible.

There are a number of modes of expression of customer complaints, ranging up to legal action, and a number of ways of dealing with them. These are discussed in Chapter 9. If possible, it is highly desirable that a complaint be resolved on a personal level, through correspondence or a personal call.

Warranty complaints that reach the stage of legal action can be very costly, both in direct legal costs and in negative publicity and loss of customer goodwill.

This is particularly true if a company is found to violate the laws covering warranty, and it is essential that management be aware of the legal requirements for both explicit and implicit warranties.

A related concern is how to deal with invalid claims. There are a number of ways invalid claims can occur. The most common are failures that occur after the end of the warranty period, claims on items that, in fact, have not failed, failures due to customer misuse of the product, and those due to the customer failing to maintain the product properly. It is necessary to have a consistent and reasonable strategy for handling these. For relatively inexpensive items or repairs, many companies simply do the replacement or repair regardless, except in the most blatant cases, having concluded that the resultant goodwill is worth the cost. If the cost is significant, however, this is not acceptable, and dispute resolution along the lines discussed above will have to be undertaken.

Finally, it is worth noting that some consumers express dissatisfaction through external organizations such as consumer affairs bureaus, the Better Business Bureau, or political action groups. Many of these organizations will forward this information to companies, asking for action, or will publish a listing of complaints, particularly if a sufficient number of similar problems are encountered. A number of other consumer organizations may be involved as well. For example, *Consumer Reports* regularly reports tests of small samples of many types of products and also reports on warranties. It is important to monitor all of these groups in order to be aware of negative publicity and to be in a position to respond.

4.5.8 Warranty Administration

To manage warranty effectively from a strategic viewpoint, the manufacturer needs to have a separate unit responsible for warranty. This unit can be a full-fledged department in the case of a large manufacturer or a small unit attached to the CEO in the case of a small manufacturer. This unit must be responsible for managing all aspects of warranty over the life cycle of the product.

The manager of such a unit must have a multi-disciplinary background as he/she would need to interact closely with different sections of the business and in a mode that requires the interlinking of technical and commercial issues.

The unit must set up a proper data-collection system and ensure that only credible data are collected. In addition, it must have the competencies (either in-house or through external consultants) to carry out proper analysis and interpretation of the data in the context of the technical and commercial issues involved. Any decision relating to warranty or warranty-related issues must be based on such analysis. Failure to set up such a unit can lead to poor management of warranty, in turn affecting the overall business performance.

Chapter 14 deals with a warranty management system to administer and manage warranty.

4.6 Conclusions

In this chapter we have looked at warranty management. The key elements of effective management are:

- Proper understanding of the multiple roles of warranty discussed in Chapter 3.
- Recognition that warranty is affected by technological decisions made prior to product launch that affect the commercial outcomes subsequent to the launch.
- Proper linkage of warranty strategy to other strategies in the manufacturing of a new product. This is discussed further in Chapter 8 (Warranty Considerations in Product Design and Development), Chapter 9 (Implications of Warranty on Production Decisions), Chapter 10 (The Role of Warranty in Marketing) and Chapter 11 (Warranty Logistics).
- Recognition of the importance of other issues, such as resolution of disputes, accounting and warranty legislations. These are discussed in Chapter 13.
- Effective administration of the warranty management process through use of a proper warranty management system. This is discussed in Chapter 14.

Another key issue, one that will be dealt with later, is the use of models in strategy formulation. Figures 4.5 – 4.7 indicate this explicitly. Models are needed for evaluating alternate options and for choosing the best option. Building models is an analytical effort and may require various kinds of data, depending on the context. We discuss the data issue in more detail in Chapters 7 – 12. Again, the model building, data analysis, and related activities will ordinarily be done by analysts for use by managers. It is most helpful, however, for the manager to be aware of both the power and the limitations of these important tools, and we discuss this in the chapters that follow.

References

[1] Cope, S. D., and R. Pellitier (1991), "Whipping the warranty factor," *Sales and Marketing Management*, April, pp. 105–106.

[2] *Business Week* (1970), "Can FTC put a governor on Detroit? Proposed automobile quality act," February 28, pp. 31–33.

[3] Garvin, D.A. (1988), *Managing Quality*, The Free Press, New York.

[4] Bergstrom, R. P. (1989), "Why nothing runs like a Deere," *Production* **101**:70–74.

[5] Murthy, D. N. P., and W. R. Blischke (2000), "Strategic warranty management – A life cycle approach," *IEEE Transactions on Engineering Management*, **47**, 50–54.

[6] Thompson, A. A., and Strickland, A. J. (1990), *Strategic Management: Concepts and Cases*, BPI Irwin, Homewood, IL.

[7] Betz, F., *Strategic Technology Management*, McGraw-Hill, Inc., New York (1993).

[8] Hadel, J. J., and Lakey, M. J. (1993), "A structured approach to warranty preparation and risk assessment," *1993 Proceedings Annual Reliability and Maintainability Symposium*, pp. 298–303.

[9] Menezes, M. A. J., and Quelch, J. A. (1990), "Leverage your warranty program," *Sloan Management Review* **31**, No. 4, 69–80.

[10] Ives, B., and Vitale, M. R. (1988), "After the sale: Leveraging maintenance with information technology," *MIS Quarterly* **12**, 7–20.

[11] Iskandar, B.P., and Blischke, W. R. (2003), "Reliability and Warranty Analysis of a Motorcycle Based on Claims Data," Chapter 27 in Blischke, W. R., and Murthy, D. N. P. (Editors), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[12] Sander, P. C., Toscano, L. M., Luitjens, S., Petkova, V. T., Huijben, A., and Brombacher, A. C. (2003), "Warranty Data Analysis for Assessing Product Reliability," Chapter 26 in Blischke, W. R., and Murthy, D. N. P. (Editors), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[13] Majeske, K. D., Riches, M. D., and Annadi, H. P. (2003), "Ford's Reliability Improvement Process – A Case Study on Automotive Wheel Bearings," Chapter 24 in Blischke, W. R., and Murthy, D. N. P. (Editors), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[14] Amasaka, A., and Osaki, S. (2003), "Reliabilty of Oil Seal for Transaxle – A Science SQC Approach at Toyota," Chapter 25 in Blischke, W. R., and Murthy, D. N. P. (Editors), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

5

Systems Approach to Warranty Management

5.1 Introduction

In most companies, problem solving (at least for large problems) is typically approached somewhat as follows: Managers define the problem (technical, commercial or managerial) for investigation. Analysts then come up with several alternate solutions for consideration by senior managers. Managers then proceed to select a solution and implement it. The systems approach is ideally suited for this purpose. It is a very general approach that can be used for solving many problems in an effective manner.

At each of the five phases of the product life cycle discussed in Chapter 2, the systems approach is useful in obtaining solutions to a range of decision problems that need to be solved as part of strategic warranty management. In this chapter we focus our attention on the use of the systems approach to solving decision problems in the front-end phase (Phase 1) of the product life cycle. Chapters 7–12 deal with problems in the later phases of the product life cycle.

We start with a brief overview of the system approach in Section 5.2. The systems approach involves six steps. Following this, we discuss the modeling of uncertainty in Section 5.3. In Section 5.4, we discuss the systems approach for solving decision problems in the front-end phase. In Section 5.5, we look at the systems approach to warranty cost analysis and present two different characterizations. Finally, in Section 5.6 we look at the modeling of product failures.

5.2 The Systems Approach

The systems approach views the real world relevant to the problem under consideration as a complex system comprising of many interacting variables.[1] The

[1] There are several books on the systems approach and mathematical modeling. In Murthy *et al.* [1], various issues involved in mathematical modeling are discussed at an introductory

approach involves six steps (Steps 1–6) as shown in Figure 5.1. The execution of each step requires a good understanding of concepts and techniques from many disciplines. It is worth noting that managers carry out Steps 1, 5 and 6, whilst analysts carry out Steps 2, 3 and 4.

5.2.1 Step 1: Define the Objective

This involves clearly defining the problem to be solved. Managers do this, with the subsequent detailed study carried out by analysts. Strategy formulation involves carrying out studies that address a variety of questions. The questions can be broadly grouped into two categories:

a. What is the consequence of a particular decision? For example, how much will the expected warranty servicing cost increase if the warranty period is increased?
b. What is the optimal decision? For example, what should be the optimal reliability development plan and warranty terms to maximize total profits?

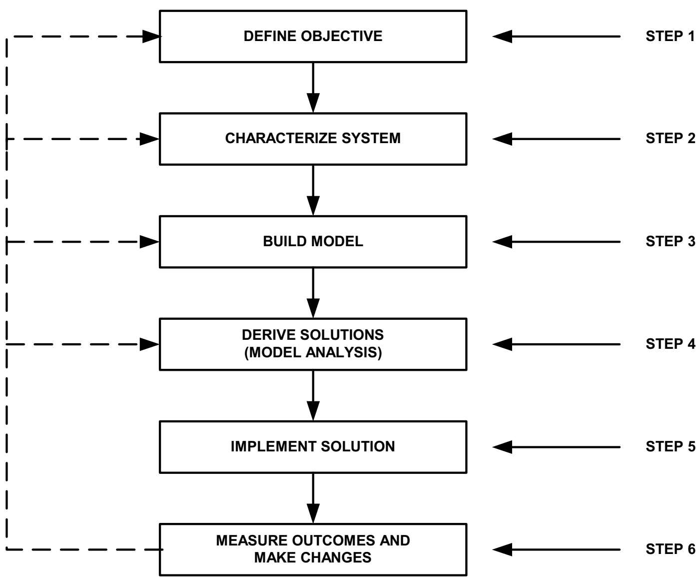


Figure 5.1. The systems approach

---

level. This source also contains an annotated literature review of books on mathematical modeling.

5.2.2 Step 2: System Characterization

Characterization of a system details the salient features of the system that are relevant to the problem being addressed so that they become apparent. As such, this involves a process of simplification. The variables used in the system characterization and the relationships between them are problem dependent. If the problem were to understand product failures, then the system characterization would involve reliability theory; if the problem were to study the impact of warranty on sales, then one would use theories from marketing; and so forth. The characterization of the cause–effect relationship between the variables is best done using diagrams with nodes representing variables and directed arcs indicating the cause–effect relationships.

Figures 4.5 – 4.8, discussed in the previous chapter, can be viewed as system characterizations of the processes involved in the formulation of strategies for the last four phases of the product life cycle.

5.2.3 Step 3: Build Model

A model is a representation of the real world relevant to the strategy formulation. A descriptive model highlights the interactions between different variables either using language or some diagrammatic representation. A mathematical model links the descriptive model to an appropriate mathematical formulation. The type of formulations needed depends on the nature of the variables and the interactions between them. If some of the variables change with time (for example, sales rate increasing or reliability improving as a result of engineering changes) then dynamic formulations are appropriate. If uncertainty is a significant feature (for example, items failing in an uncertain manner, uncertainty of development outcome) then one needs more complex probabilistic and stochastic formulations. This topic is covered in Section 5.3.

Model building is an art as well as a science. It involves the following three sub-steps:

1. **Model selection**: In the empirical (black-box) approach, model selection is based solely on the data available. In the physics-based (white-box) approach, model selection is based on relevant theories (for example, the different theories for component failures).
2. **Parameter estimation**: The model will involve one or more unknown parameters, and numerical values for these are needed. These are obtained by means of a statistical methodology called parameter estimation and the approach used depends on the type and amount of data available.
3. **Model validation**: This involves testing whether or not the model selected (along with the assigned parameter values) adequately models the real world relevant for strategy formulation.

Many different kinds of data are involved in building models for effective warranty management. This is discussed in Chapter 6, along with issues relating to data collection and analysis, parameter estimation, model validation, and related issues. It is important to ensure that the model used is adequate for solving the problem at hand and that relevant data can be obtained to build and validate the model. If not, then the model will yield results that are of limited use for solving the problem. In general, obtaining an adequate model requires an iterative approach, wherein changes to the system characterization and/or the mathematical formulation are made in a systematic manner until an adequate model is obtained.

5.2.4 Step 4: Derive Solutions

Once an adequate model is developed, techniques from statistics, probability theory and stochastic processes and optimization theory are used to carry out the analysis and derive solutions to the problem. In some instances, analytical solutions that allow one to study the effect of model parameters on the solution can be obtained. If this is not possible, computer analysis, based either on numerical methods or direct simulation of the underlying processes, is used to generate approximate solutions. When uncertainty is significant, the simulation is replicated as many times as necessary to obtain reasonable approximations of the solution.

5.2.5 Step 5: Implement Solution

Managers carry out this step, based on the results of Steps 2–4. In doing so, it must be kept in mind that a model is a simplified representation of the real world and must be viewed as a tool to assist in decision-making. As such, intuitive judgment combined with the results from model analysis form the basis for implementation.

5.2.6 Step 6: Measure Outcomes and Implement Modifications

It is important to note that the data and information available for the execution of Steps 2–4 is often limited. As a result the actual outcomes resulting from the implementation in Step 5 will differ from the values predicted by the model in Step 4. This is to be expected. By comparing the two, information can be fed back (see Figure 5.1) to initiate actions to improve the predictive accuracy (and the usefulness) of the model.

Later in the chapter, we will look at the initial steps in the systems approach in two applications, decision making in the front-end phase, and warranty cost analysis. First we look at an important aspect of the analysis in nearly all applications, dealing with uncertainty.

5.3 Characterizing Uncertainty

An event is said to be uncertain if its outcome cannot be predicted with certainty. Once the event has occurred, however, the uncertainty disappears and the outcome is known exactly. Uncertainty basically means non-repeatability – we will not always get the same outcome.[2] That leads to the concept of variability, which will be discussed in more detail in Chapter 6.

Warranty management requires dealing with uncertainty in nearly all decision problems. Some illustrative examples are the following:

i. The outcome of research and development is uncertain in the sense that it can result in either a successful (goals achieved) or a failed (goals not achieved) outcome. To characterize this, we use a binary-valued variable X that takes a value 1 or 0 depending on whether the outcome is a success or a failure.
ii. The life of a new item is uncertain before it is put into use. Once it is put into operation and operated until failure, the uncertainty in the time to failure disappears. The time until failure of the item can be characterized through a continuous-valued variable that can take any positive value in the interval zero to infinity. (The latter is to avoid nominating an upper limit and facing the embarrassing situation where the item survives its upper limit.)
iii. When two physical objects rub against each other, a wear mechanism is in operation. The wear on a component (for example, an automobile tire) is a function of usage, which in turn can be a function of age. As a result, the wear on a new tire as a function of the age, changes in an uncertain manner so that it is not possible to predict its exact value at any future time instant.

Note that in (i) the variable X is discrete and is not a function of time whereas the variable indicating the wear in (ii) is a function of time and is continuous. When time plays no role, then we have a static situation and when it plays a role we have a dynamic situation.

When the variable is not a function of time, it can be modeled by a probability distribution. This indicates the likelihood of the variable being less than a specified value. The distribution is defined over an interval with the end points representing the minimum and maximum values that the variables can assume. The probability distribution is discrete if the variable assumes values from a discrete set. In this case the probability distribution is a staircase function as shown in Figure 5.2(a). The distribution is non-decreasing, starting with a value zero (implying that the variable cannot assume a value lower than the minimum) and reaching a value 1 (implying that the variable must always assume a value less than the maximum). The jumps indicate the probability of the variable assuming the different values in the interval. The probability distribution is continuous if the variables can assume any value within an interval and in this case the distribution is a smooth function (non-decreasing with value zero at one end and one at the other end) as shown in Figure 5.2(b).

When the variable is a function of time, then one needs different kinds of processes (called stochastic processes) to model the variable. These can be classified into four types depending on whether time is treated as discrete or

---

[2] Most introductory books on statistics and on probability deal with uncertainty. See, for example, Moore and McCabe [2].

continuous and whether the values assumed by the variables are discrete or continuous. Note that time is always continuous but is sometimes discretized. Table 5.1 indicates the four cases with illustrative applications of relevance in the context of warranty management.

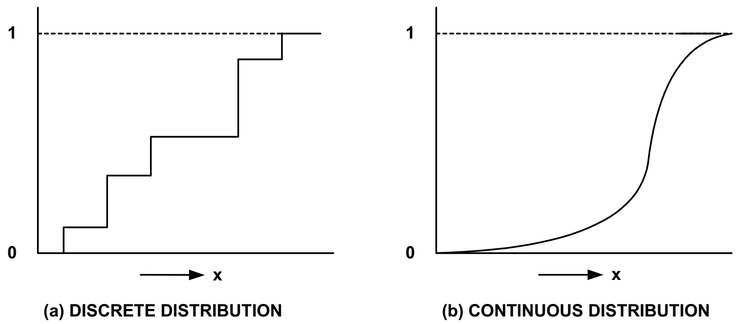


Figure 5.2. Probability distributions

Table 5.1. Different types of stochastic processes

Time (*t*)	Values of *X(t)*	Examples
Discrete	Discrete	Count of the number of automobiles returned for repairs under warranty each week
Discrete	Continuous	Wear of item measured on a weekly basis
Continuous	Discrete	Time to failure for a component in continuous use
Continuous	Continuous	Wear of item monitored continuously

5.4 Decision-making in the Front-end Phase

To illustrate the systems approach, we look at the first three steps of the process – objectives, system characterization, and modeling – in the context of the decision problems that are typically encountered in the front-end phase of the product life cycle. At this point, modeling aspects are discussed conceptually.

5.4.1 Define Objective

The front-end phase deals with what a new product 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, acquisition of new technologies, investment for opening new markets, etc.) and the associated costs determine whether one proceeds with the development of the new product or not. If the decision is to proceed, then one executes the subsequent phases of the NPD process.

The business objectives are typically stated in terms one or more of the following goals:

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

It is important that the statements be consistent and compatible. For example, achieving a certain level of sales might require that the price be below some specified value that might not be adequate to ensure that the profits exceed some specified value.

The impact of product performance and price have on market share is shown in Figure 5.3. The left curve in Figure 5.3 represents combinations of performance and price that yield a 70% share of the market. Market share can be increased either by lowering 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 the figure.

The stated business objectives can be achieved through several new product options. Each option is characterized by a set of specifications that serves as the input for the next phase (Design and Development) of the product life cycle. The identification of the different options is a creative process and many techniques, such as for example brainstorming, are useful in assisting the process. Each option is described in terms of targets for product performance, marketing, etc. that need to be met to achieve the business objectives.

We next look at the system characterization when the objective is to maximize profits.

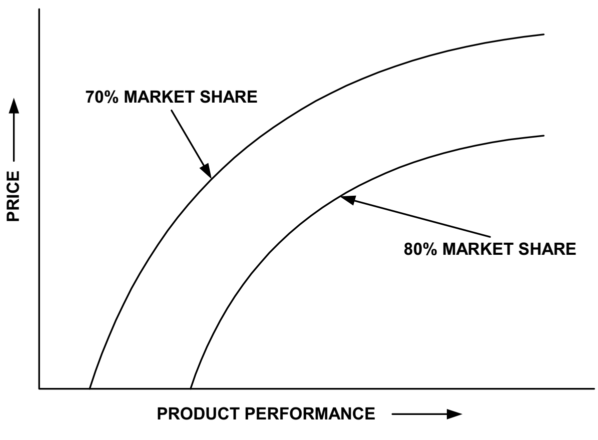


Figure 5.3. Influence of price–product performance on market share

5.4.2 System Characterization

Profit depends on sales, which in turn, is influenced by how attractive the manufacturer's product is, compared with the competitors' products, in terms of one or more of the following:

- Technical features
- Unit sale price
- Warranty period
- Life cycle cost
- Other product characteristics.

The costs to the manufacturer are comprised of:

- Production costs
- Marketing costs
- Distribution costs
- Warranty costs
- Miscellaneous other costs.

Figure 5.4 is a simplified system characterization for determining the target values at the front-end phase. It highlights the key elements involved in the warranty process and the interactions between them. As can be seen, product reliability depends on the decisions made during the design of the product and the production process. Product quality depends on the input materials and the quality program used. All of these factors impinge on production costs. Warranty terms affect sales, which in turn affect the revenue generated. Warranty servicing costs depend on the warranty terms and product reliability. As such, effective management of warranty needs to take into account the strong link between warranty and reliability. Finally, the manufacturer is interested in the overall profits and these depend on the revenue generated and the production and warranty servicing costs. Each of the elements can be described in more detail, leading to more refined system characterizations. This is done in later chapters in the context of studying specific decision problems.

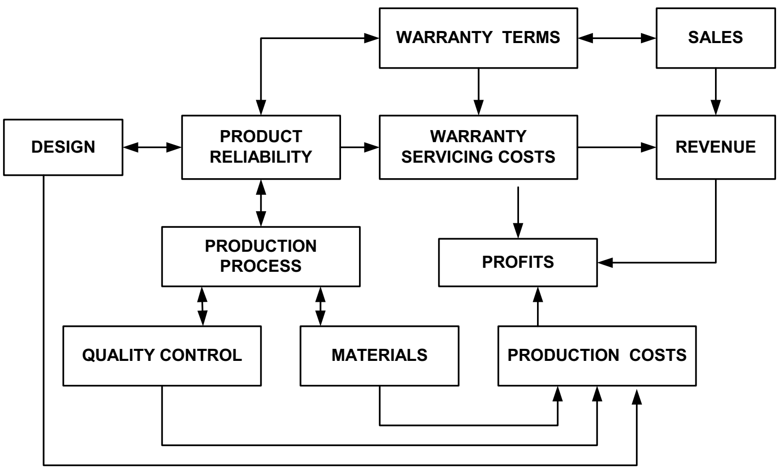


Figure 5.4. System characterization of strategy formulation in front end

If the variables are aggregates, such as total sales, total development cost, total warranty cost, and so on, then time plays no role and a static formulation would be appropriate. In contrast, if some of the variables represent annual values, such as annual sales, annual costs, etc., then a discrete dynamic model is needed.

5.4.3 Modeling

Decision making at the front-end involves linking the business objectives to targets for one or more of the variables defined above. These targets become the inputs for the later phases of the new product development. Models are used (implicitly or explicitly) to express the linkages. Some of the issues that need consideration in this context are [3]:

- **Customers**: Targeting new customer groups/markets is far more time consuming and costly than marketing to 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, so 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 have cost implications.
- **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 influences time and cost significantly.

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

The decision-making process must take into account constraints on the following variables:

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

Models play an important role is determining whether the specifications defining an option can achieve the business objectives without violating the constraints. Several different models are needed, including the following:

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

Many different kinds of data and information are needed to build and use the models. They can be grouped into the following four categories:

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

Figure 5.5 shows schematically the decision-making process at the front-end based on the systems approach.

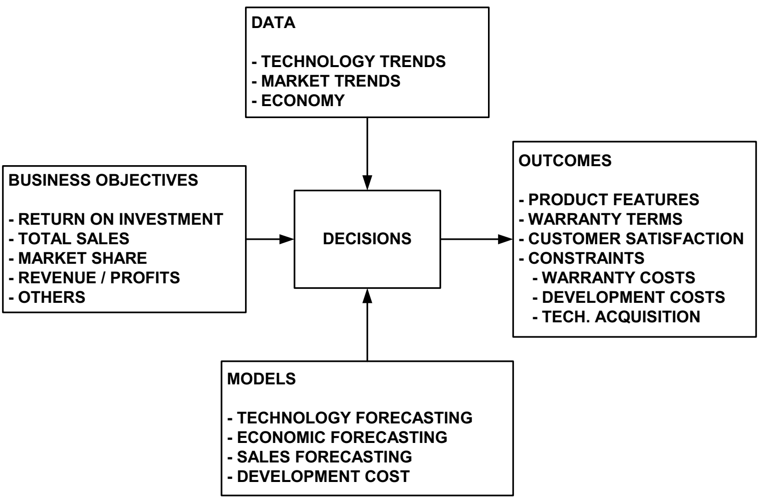


Figure 5.5. Decision-making at the front-end

5.5 Systems Approach to Warranty Cost Analysis

As a second illustration of the systems approach, we look at the first two steps in the process in analyzing warranty costs. We will return to this analysis in Chapter 7, where explicit models of warranty costs are discussed in detail.

5.5.1 Define Objective

When a product is sold with warranty, the manufacturer incurs additional costs resulting from the servicing of claims under warranty. The expected cost depends on several factors and these include the warranty terms, warranty duration, product reliability etc. This cost is important in the context of product development, pricing, warranty servicing strategy, and so forth, as will be discussed in later chapters.

5.5.2 System Characterization

We present two system characterizations – one simple and the other detailed.[3]

5.5.2.1 Simple Characterization
A simple system characterization for warranty cost analysis is shown in Figure 5.6. The manufacturer produces and sells products to consumers with a warranty policy. Product performance depends on the interaction between product characteristics (influenced by the design and production decisions) and product usage (influenced by the consumer). If the product performance is not satisfactory at some time during the warranty period, then a warranty claim may result. The manufacturer then has to service the claim, and this results in warranty cost.

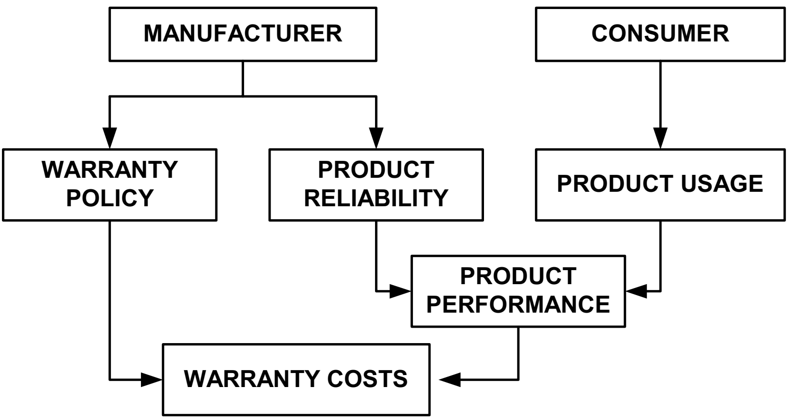


Figure 5.6. Simplified system characterization for cost analysis

[3] The simple system characterization is from Blischke and Murthy [4]. The detailed characterization is from Murthy, Lyons, and Blischke [5].

The characterization of each of the elements in Figure 5.6 can involve many variables, depending on the degree of detail desired. The simplest case is as follows.

1. All consumers are alike in their usage. One can relax this assumption by dividing consumers into several groups based on the intensity of usage. In the simplest case, this would involve two groups, corresponding to high and low usage intensities.
2. All items are statistically similar, that is, any observed differences are due simply to chance and not to any changes in design or in the manufacturing process. One can relax this assumption to include two types of items (conforming and non-conforming) to reflect quality variations in manufacturing.
3. The performance of the product is characterized through a binary variable to indicate the two states – working or failed.
4. Failed items are either repaired or replaced or the consumer is refunded a fraction of the sale price.
5. All claims are exercised and valid. One can relax the assumption to include the possibility that some valid claims are not made and that some of the claims made are not valid.

5.5.2.2 Detailed System Characterization

A detailed characterization needed for life cycle cost analysis from the manufacturer's perspective is given in Figure 5.7. Boxes with heavy outline represent the major elements of manufacturing. Boxes with light outline indicate the key elements within each major category, and, as with the simple characterization, each of the elements may involve one or more variables in its characterization.

The number of claims during the warranty period per item sold is a function of many more variables than is the case in the simple system characterization. These include product reliability, production quality, usage intensity, repair quality (in the case of repairable items) and the proportions of warranty claims that are valid and are executed. The warranty cost per item sold depends on the claims per item and the cost of servicing the warranty for each claim. From this, one obtains the life cycle cost (from the manufacturer's perspective), taking into account the sales rate (sales per unit time).

5.6 Modeling Product Failures

Warranty claims result from product failures over the warranty period. Hence, modeling of failures is important. We focus our attention on this and look at alternate approaches to modeling product failures.[4]

---

[4] There are many reliability books that deal with the modeling of product failures. See, for example, Meeker and Escobar [6] and Blischke and Murthy [7].

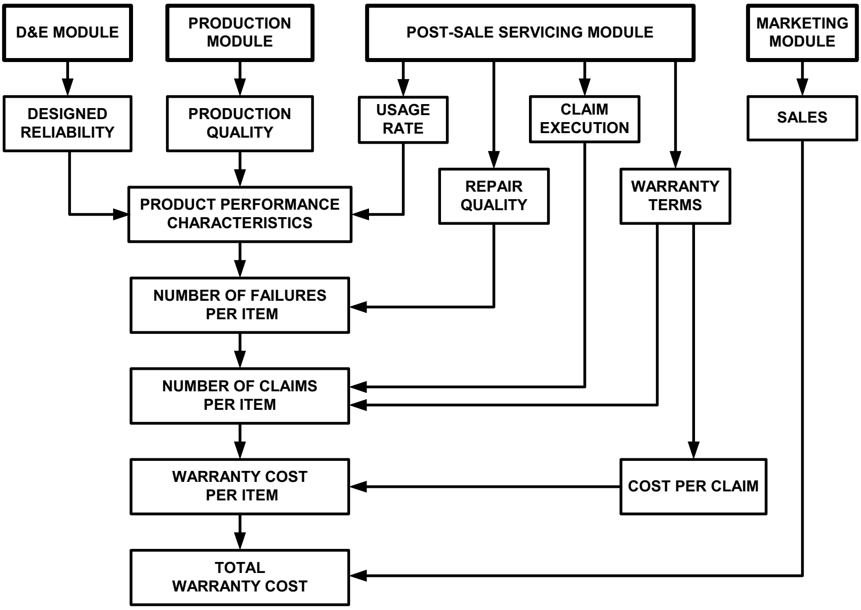


Figure 5.7. Detailed system characterization of warranty cost analysis

The failure of a product occurs in an uncertain manner and is influenced by several factors. These include the usage mode (continuous or intermittent), usage intensity (high, medium or low), operating environment (normal or abnormal) operator skills (for certain types of products), and, in most cases, maintenance actions taken by the user. Typically, a product is complex and comprised of many components. The failure of a product is due to the failure of one or more of its components. For a non-repairable product, the item is discarded after only one failure. In contrast, for a repairable product there can be several failures over its useful life. These failures are influenced by repair and maintenance (preventive and corrective) actions.

As a result, the modeling of failures raises several challenging issues. Modeling can be done either at the system (product) level or at the component level or anywhere in between. In addition, the modeling activity is influenced by the information available. This may relate to the degradation processes at the component level, the interconnections between the different components at the system level, the usage environment, and so forth. This information can vary from very minimal (or none) to complete or anywhere in between.

Modeling of failures also depends on the goal (or purpose) that the model builder has in mind. For example, if the goal is to determine the type and amount of spare parts needed for non-repairable components, then the modeling of failure must be done at the component level. On the other hand, if one is interested in determining the expected warranty servicing cost, one might model failures at the system 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 data. In this case the modeling is empirical or data driven. These are the two extreme situations and are referred to as the "white-box" and "black-box" approaches to modeling. In between, we have different degrees of understanding or information. For example, an engineer, through analysis, might identify several modes of failure so that the modeling needs to take this into account. In this case, we have a "gray-box" approach to modeling.

A similar situation arises at the system level. In the white-box approach, the different components of the systems and their inter-relationships are known whereas in the black-box approach this information is either not known or ignored.

5.6.1 The Black-box Approach

Here the item (component, system, or something in between) is characterized as being in one of two states – working or failed.

5.6.1.1 First Failure

The time to first failure is modeled by a continuous probability distribution.[5] The form of the probability distributions (for new and repaired items) and the appropriate parameter values are decided based on the data or other information available.[6]

Associated with the probability distribution is the hazard function. It characterizes the probability of component failure as a function of the age of the component.[7] The hazard function for many components has a bathtub shape that is characterized by three regions. The hazard function is decreasing over the initial region (Region I), roughly constant over the middle region (Region II) and increasing over the final region (Region III) as indicated in Figure 5.8.[8]

---

[5] Let X denote the time to failure (or time between failures). The uncertainty in the values that X can assume can be described through a probability distribution $F(x;\theta)$ that is defined as $F(x;\theta) = P\{X \le x\}$. θ denotes the set of parameters of the probability distribution. A related function (when it exists) is the *density function* $f(x;\theta)$, given by $f(x;\theta) = dF(x;\theta)/d\theta$.

[6] The probability distribution is characterized by the form of function $F(x;\theta)$. Many different forms have been used in modeling failure times. Blischke and Murthy [7] list several of these and give references where many more can be found.

One particular distribution that has been used extensively in modeling failure times is the *Weibull distribution* given by

$$F(x;\theta) = 1 - exp\{-(x/\alpha)^{\beta}\}.$$

Here θ is the set $\{\alpha,\beta\}$. α is called the scale parameter and β the shape parameter. Another distribution that is used extensively is the *exponential distribution*, which is a special case of the Weibull distribution with $\beta = 1$.

[7] The hazard function $r(x)$ is given by $r(x;\theta) = f(x;\theta)/[1 - F(x;\theta)]$. The probability that a component that is of age x and is working will fail in a small interval δx is given by $r(x)\delta x$. For the Weibull distribution, the hazard function is increasing with x when the shape parameter $\beta > 1$ and is constant when $\beta = 1$. The Weibull distribution with $\beta > 1$ has been used to model failures of mechanical components and the exponential distribution to model failures of electrical and electronic components.

[8] Some components exhibit a roller-coaster shape. This is discussed further in Chapter 9.

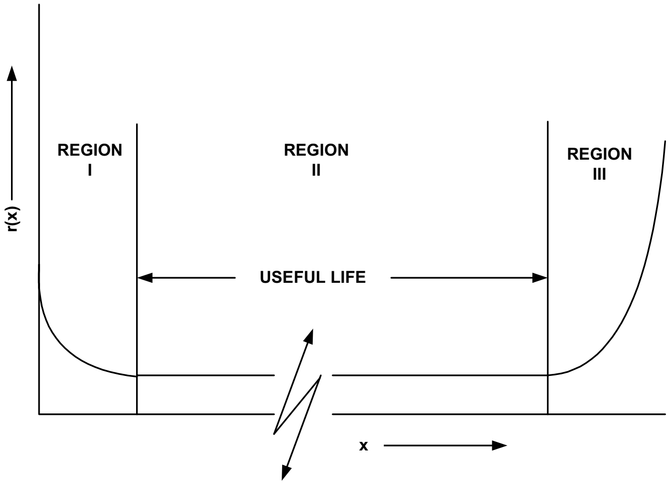


Figure 5.8. Bathtub hazard function

The mean time to failure (MTTF) is the expected value (or average) of the time to first failure. For a given probability distribution, the MTTF depends on the form of the distribution and the parameters.[9]

5.6.1.2 Subsequent Failures

The times between subsequent failures depend on whether the item is repairable or not and, if it is, the type of repair that is done. In this context, the repair or replacement time also needs to be modeled. However, if these times are relatively small in relation to the mean time between failures (MTBF), they can be ignored and the repairs or replacements can be viewed as being instantaneous.

In the case of a non-repairable item, the failure times are all statistically similar (in the sense that they all can be modeled by the same distribution) and hence have the same MTBF.

In the case of a repairable component, the times between subsequent failures depend on the type of repair. One kind of repair is "minimal repair". In this case, the failed component is made operational with the reliability of the component (given by 1 minus the probability of failure) unaffected. An example of this is fixing the leak (in a tire or pipe) with a small patch. In the case of minimal repair, the hazard function after repair is nearly the same as that just before failure.[10]

5.6.1.3 Count of Failures over an Interval

The number of failures a product experiences changes over time in an uncertain manner. Since this number can only be a nonnegative integer, it is modeled by a

[9] For the Weibull distribution, the MTTF = $\alpha\Gamma(1+1/\beta)$, where $\Gamma(x)$ is a mathematical function called the *Gamma function*. For some examples, see Section 11.1 of Kapur and Lamberson [8].

[10] There are several other kinds of repairs. See Blischke and Murthy [7] for details.

mathematical construct called a *continuous time, discrete valued stochastic process*.

The distribution for the number of failures depends on whether the component is repairable or not. In the case of a non-repairable component, it is easily obtained in terms of the component failure distribution. For the case of minimal repair, it is easily obtained in terms of the hazard function.[11]

Another approach to modeling failures over time is through a function called the "rate of occurrence of failures" or ROCOF[12] for short. This is similar to the concept of hazard function, except that it gives the probability of a failure occurring in a small interval.[13] One can decide on the form for the ROCOF based on failure data over time. Since a product degrades with time (and/or usage) ROCOF is an increasing function of time. The rate at which it increases depends on the environment in which the product is used. The harsher the environment, the higher the rate of increase as indicated in Figure 5.9.

5.6.2 The White-box Approach

In the white-box approach, failures are modeled at the component level, based on the underlying degradation mechanism. There are many different mechanisms of failure but they can be broadly grouped into two categories – over-stress and wear failures.[14,15]

5.6.2.1 Over-stress Failures[16]

Here the strength of the item and/or the stress to which it is subjected changes with time. The strength of an item degrades with time, so that it is non-increasing. Stress can change with time in an uncertain manner. An example of this are the legs of an offshore platform where the strength decreases due to aging effect and the stress depends on the amplitude of the waves hitting the legs and these vary in an uncertain manner over time. The time to failure is the first time instant the strength falls below the stress.

---

[11] Blischke and Murthy [7] give expressions for the distribution of $N(t)$ for both the non-repairable case as well as the repairable case with minimal repair.

[12] See Rigdon and Basu [9] for more on ROCOF and the modeling of count data.

[13] Under minimal repair, the ROCOF is the same as the hazard function so that the probability of a failure occurring in a small interval between t and $(t + \delta t)$ is given by $r(t)\delta t$.

[14] Material science deals with the study of failures at the micro-structural level. One can broadly group materials into three categories – metals, polymers and ceramics.

[15] See Dasgupta and Pecht [10]. This is the first in a series of several tutorial papers in *IEEE Transactions on Reliability*. Each deals with a different mechanism of failure. References to these papers can be found in Blischke and Murthy [7].

[16] Over-stress failures include the following: brittle fracture, ductile fracture, yield, buckling, large and elastic deformation.

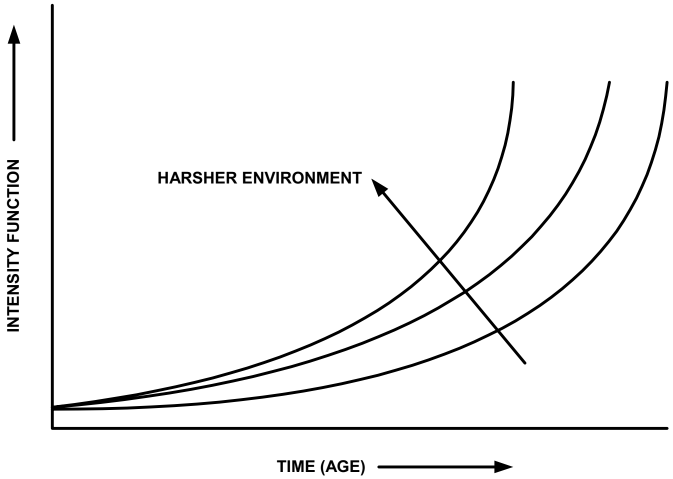


Figure 5.9. Typical plots of ROCOF

5.6.2.2 Wear-out Failures[17]

Wear is a phenomenon whereby the effect of damage accumulates with time, ultimately leading to item failure. Typical examples are crack growth in a mechanical part, a tear in a conveyor belt, or bearings wearing out. These can be modeled by a variable that increases with time in an uncertain manner and failure occurs when the value of it reaches some threshold level.

5.6.3 Modeling Component and System Failures

At the system level, system failures can be modeled in terms of the failures of the components of the system. The linking of component failures to system failures is 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.

5.6.3.1 FMEA[18]

FMEA involves decomposing 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

---

[17] Wear-out failures include the following: wear, corrosion, dendritic growth, interdiffusion, fatigue crack propagation, diffusion, radiation, and creep.

[18] FMEA is qualitative. Section 7.5 of Blischke and Murthy [7] discusses FMEA at an introductory level, and additional references are given.

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?

For each component at the part level, the failure modes and their effects are usually documented on worksheets. The documentation involves the following:

- Description of the different parts
- Characterization of failure
- Effect of failure on the system.

If, in addition to FMEA, a criticality analysis is carried out, the process is called a *failure mode, effects and criticality analysis* (FMECA). In this case, in addition to the above documentation one needs to document the following:

- Severity ranking which characterizes the degree of the consequence of each failure.

5.6.3.2 FTA[19]

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 more components of the system, environmental conditions, human errors and other factors. In this section we focus on qualitative fault tree analysis.

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 logical gates, where the output from a gate is determined by the inputs to it.

Example 5.1 [Automobile]

An automobile is in non-failed state if it is capable of performing its operations in a satisfactory manner and of meeting any requirements with regard to fuel efficiency, environmental regulations, and so forth. When one or more of these conditions is not met, the automobile is deemed to have failed. Thus there are many different failures that may occur. An illustrative sample is as follows:

- Failure to start

---

[19] FTA is both qualitative and quantitative. One can compute the probability of the top event occurring in terms of the reliability of the elements of the fault tree. FTA is discussed in Section 7.6 of Blischke and Murthy [7].

- Failure to stop
- Failure to deliver the stated power output
- Failure to meet emission standards
- Failure to meet the stated fuel efficiency.

The consequence of some of these failures can be catastrophic. For example, brake failure can result in serious damage to property and loss of lives. On the other hand, some failures, while not catastrophic, result in a limitation on the use of the automobile. For example, a failed headlight results in the automobile usage being restricted to only daylight. In addition, a large number of failures are mainly inconveniences. Examples are failure of a window crank, improper operation of a CD player, odometer failure. Finally, many failures are merely cosmetic. These include poor paint jobs, minor dents in a new car, missing trim.

The failure of an automobile is due to the failure of one or more components. In the FTA, one relates the automobile failure to component failure. For example, in the case of failure to start, some of the components are battery, starter motor and fuel delivery line. A complete fault tree would list all such components and the various ways in which each could fail.

There can be several causes for each component failure and these define the failure modes. Some of the failure modes for the above three mentioned components are as follows:

1. Battery: leak of acid, short circuit of plates, flat battery
2. Starter motor: burnt rotor, loose electrical connection
3. Fuel delivery line: blocked line, leak in the line.

The consequence of failure to start can vary from minor inconvenience to something significant – missing an important meeting or failure to catch a flight and so on.

The consequence of failures has an impact on the manufacturer. If the failure occurs within the warranty period, the manufacturer needs to rectify it and the cost incurred depends on the type of warranty policy. In some cases, the Federal Transport Authority can increase the warranty coverage for certain components and these are referred to as "hidden warranties."[20] In this case, the manufacturer needs to rectify any failures of these components for the extended duration.

In few cases, the manufacturer is either forced (or volunteers) to recall the items sold in order to replace one or more of its components to minimize the consequences of their failure. There are several examples of these over the last two decades.[21]

---

[20] Hidden warranties arise in response to manufacturing defects at the factory that can be costly to repair. The warranty covers some or all costs of automobile repairs, even if the vehicle is out of warranty. The Lemon-aid website (www.lemonaidcars.com) lists various defects of this type for selected models.

[21] Table 2 in Gibson [11] gives the number of vehicles recalled over the period 1966–1990. The numbers run into several millions each year. More recent figures can be found at htpp://Science.howstuffworks.com/link64.htm

Proper FMEA deals with a thorough study of the various failure modes and its consequences so that they are effectively dealt with during the design stage.[22]

■

Example 5.2 [Photocopier]
A photocopier is in a failed state if (i) there is no output or (ii) the quality of output is unacceptable. Failure of the copier is due to the failure of one or more components. There are a numerous modes of failure, which manifest themselves in a diversity of ways.

In the case of no output, the failure could be due to a paper jam, failure of the feed mechanism, no toner, or bulb failure resulting in blank pages, etc. Poor quality of output includes the following: smudged or smeared copies, paper damage during copying, over/under exposure, etc.).

From the user point of view, the failure of photocopiers to operate correctly causes significant inconvenience through the production of documents of poor appearance and quality, as well as delays in production and increased costs because of waste and loss of time. The costs not only involve down time and waste of copies but service costs and replacement parts.

From the manufacturer's point of view, in the long to medium term, profitability and market share can be adversely affected by poor reliability and customer dissatisfaction. In the short term the manufacturer normally will be expected to cover parts and service under a warranty agreement. Typically a service plan or contract outside warranty is offered with the sale of a photocopier. The nature of such plans is necessarily based on an understanding of the reliability of the machine, and consequently the analysis of failure data and the modeling for reliability.

■

References

[1] Murthy, D. N. P., Page, N. W., and Rodin, E. Y. (1990), *Mathematical Modeling*, Pergamon Press, New York.

[2] Moore, D. S., and McCabe, G. P. (2002), *Introduction to the Practice of Statistics*, 2nd Edition, W. H. Freeman & Co., New York.

[3] Meyer, M. H. and Utterback, J (1997), *Product development cycle time and commercial success*, from http://web.cba.neu.edu/~mmeyer/research/5/article/article.html.

[4] Blischke, W. R., and Murthy, D. N. P. (1994), *Warranty Cost Analysis,* Marcel Dekker, New York.

[5] Murthy, D. N. P., Lyons, K. F., and Blischke, W. R. (2003), “Designing a warranty management system,” submitted for publication.

---

[22] FMEA is used extensively in the automobile industry, see for example, Dale and Shaw [12].

[6] Meeker, W. Q., and Escobar, L. A. (1998), *Statistical Methods for Reliability Data*, John Wiley & Sons, Inc., New York.

[7] Blischke, W. R., and Murthy, D. N. P. (2000), *Reliability, Modeling, Prediction, and Optimization*, John Wiley & Sons, Inc., New York.

[8] Kapur, K. C., and Lamberson, L. R. (1977), *Reliability in Engineering Design*, John Wiley and Sons, Inc., New York.

[9] Rigdon, S.E. and Basu, A.P. (2000), *Statistical Methods for the Reliability of Repairable Systems*, John Wiley and Sons, Inc., New York.

[10] Dasgupta, A. and Pecht, M. (1991) "Material failure mechanisms and damage models," *IEEE Transactions on Reliability* **40**: 531–536.

[11] Gibson, D. C. (1995) "Public relations consideration of consumer product recall," *Public Relations Review*, **21**, 225–240.

[12] Dale, D. G. and Shaw, P. (1990). "FMEA in the UK motor industry" *Quality and Reliability Engineering International*, **6**, 179–188.

6

The Role and Use of Data in Warranty Management

6.1 Introduction

The information needs for decision making during the course of the life cycle of a product are very extensive. Adequate, relevant, and accurate information of many types and from many sources is required for effective management at every stage, from front-end to post-sale activities. This has been apparent in our discussion of the decision making process in previous chapters, where many data-based inputs have been indicated. Many more will be identified in the chapters to follow. In this chapter, we discuss some important aspects of acquisition, analysis, and interpretation of data, with emphasis on reliability and warranty applications and on numerical data.

The information available in any given application may be qualitative or quantitative, vague or precise, uncertain or reliable, and may range in quantity from minimal to voluminous. This variability in types, reliability, and amounts of data is a result of a number of factors, including:

- Source of the data – internal or external, single or multiple source, etc.
- Method of collection – haphazard to well-designed tests, sampling, and so forth
- Structure of the data – number of items, types of measurements, factors controlled, and so forth
- Inherent variability – in materials, procedures, people, and nearly anything else that might affect the results
- Costs – of data acquisition, testing, sampling, information systems, and related items
- Planning and foresight – identification of data needs at each stage
- Management – provision for data acquisition and dissemination.

The importance of the last two points cannot be overemphasized. If data needs are identified at an early stage and adequate resources are provided for collection, analysis, and proper dissemination of relevant information, many problems inherent in the earlier items on the list will be minimized.

There are a number of issues that must be addressed in dealing with data. These include methods of data acquisition such as those listed above, proper and adequate data summarization and analysis and interpretation of results, provision for data storage and retrieval and for dissemination of information as appropriate. In this chapter, we touch briefly on a number of these issues.

The outline of the chapter is as follows: Section 6.2 discusses the types of data needed in the five phases of the product life cycle as well as some aspects of the structure of the data that are typically available. Sources of data that may be accessed are listed in Section 6.3. In Section 6.4, we discuss the nature of data, the concept of variability, and the implications of this for decision making. Summarization, analysis and interpretation of data are discussed in Sections 6.5 and 6.6. Section 6.7 is concerned with the use of data in decision-making. Some special problems encountered in dealing with warranty claims data are addressed in Section 6.8. Computerized methods are discussed in Section 6.9.

6.2 Types of Data

Many types of data are needed in all phases of the product life cycle. A few of the many activities that require data input are:

- Front end – for evaluating alternative product options, technology implications (such as technology acquisition, research and development, etc.), commercial implications (such as marketplace, competitors actions, sales, revenue, etc.), the financial cost implications, and assessing risk
- Design and development – evaluating preliminary designs and design improvements, building and evaluating parts, components and prototypes, designing and evaluating production processes
- Production – evaluating outsourced components, determining product quality and reliability, assessing production costs, process improvement
- Marketing – tracking sales, designing promotions and evaluating their effectiveness, assessing customer satisfaction, evaluating the competition
- Post-sale – assessing demand for service, evaluating product performance, tracking warranty claims, determining failure causes and frequencies, estimating warranty costs, providing input for product improvement.

In all of these and the many other activities involved in designing, developing, producing, marketing, and servicing a product, data are used for many purposes: modeling, evaluation, comparative studies, cost estimation, and so forth. Types of data required include technical, commercial, historical, vendor, and handbook data.

In the following sections we list some of the various kinds of data that may be useful or necessary. In practice, the types and amounts of data required are, of course, dependent on the type and complexity of the product, the technology involved, the raw materials used, the production process, and other relevant factors.

For quite simple products based on existing technology, only a few of the items listed below may be required. For very complex products, the list may be quite lengthy (and quite different from that given). The point is that it is important early on to deal with data issues, including what data are essential, what additional data are desirable, what data are available, and what steps must be taken to obtain the necessary data. It is important that data collection be done continuously over the product life cycle and that the data are properly analyzed. This information provides critical input to decisions regarding possible changes to the various strategies.

6.2.1 Data on Earlier Similar Products

Current and historical data on the performance of similar products are particularly useful in the early stages of the product life cycle. Examples are:

- Design and development costs and time frames
- Promotional efforts and costs
- Sales and trends
- Failure analysis information
- Time line of life cycle
- Test data
- Product performance data
- Production costs
- Quality control data
- Repair data
- Reliability data
- Warranty claims data
- Warranty cost information
- Usage data
- Consumer survey results.

6.2.2 Data from External Sources

Information from sources outside the company is necessary for many purposes and is needed in most stages of the product life cycle. Some examples of useful external information are technology-related information, data concerning the marketplace, vendor data, handbook and other published data, scientific and engineering information, and results from independent laboratories.

6.2.3 Product and Process Related Data

Data are necessary for monitoring and, if necessary, improving the product and/or the manufacturing process. Some examples are:

- Bench test data on parts and components
- Reliability test data on components and sub-systems

- Test data from full-scale prototype testing
- Performance data of various types
- Test data on production equipment.

6.3 Sources of Data

There are many sources from which data of the types listed above may be obtained. Here we briefly discuss the major sources of information usually available to companies.

6.3.1 Historical (Archival) Records

Historical records are generated from data obtained from the various business management systems. The importance of this in new product development is that all new products, even those involving major design changes or completely new designs, often have some parts or even major components in common with earlier products.

6.3.2 Business Management Systems

Businesses use many different types of management systems. These, along with examples of the kind of data they provide, include:

- Accounting systems: cost data
- Project management systems: product-related data during development
- Production systems: product-related data (for example, conformance to specification) during production
- Supply management systems: material flow data
- Customer support systems: customer-related data.

6.3.3 Scientific Journals and Conference Papers

These provide scientific and engineering data and information. There are a very large number of such journals, but search engines in the internet make it easy to obtain the information.

6.3.4 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.

6.3.5 Test and Experimental Results

Typically, many tests are carried out during the development and production phases of the product life cycle. Test data allow performance to be quantified and reliability to be estimated. Experiments should ideally be designed and carried out under controlled conditions, in accordance with accepted principles of statistical design of experiments, and the data properly analyzed, 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.

6.3.6 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, formulas for various technical relationships, market indices for commodities, environmental constants, physical properties such as conductivity of materials, and many other such quantities.

6.3.7 Experts

Experts are the source for the intuitive, judgmental data. This type of information is particularly useful in situations where little or no other data are available, e.g., in the early stages of new product development. It is also used in certain types of statistical analysis.[1] The experts can be either in-house or external consultants.

6.3.8 Market Surveys

Market surveys are carried out to obtain commercial and customer related data. This involves sampling, and proper statistical sampling techniques and carefully designed questionnaires must be used in order to obtain valid and reliable data.

6.3.9 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 are collected properly, it should also provide useful customer-related information such as usage mode and intensity, customer satisfaction and needs.

---

[1] In *Bayesian analysis*, prior information regarding a characteristic of interest (for example, mean time to failure) is used along with test data to form conclusions. This prior information is often judgmental or subjective in nature. For a comprehensive treatment of Bayesian methods in reliability analysis, see Martz and Waller [1].

6.3.10 Consumer Reports and Magazines

Consumer groups carry out different kinds of tests on similar products and conduct customer surveys. The findings of their studies are usually reported in magazines or reports and constitute a valuable source for relative comparison between different products.[2]

A NOTE OF CAUTION: Since many important decisions are data based, it is critical that the data used be valid and reliable. In order to assure this, it is necessary to verify sources of data and other information (particularly when outside sources are used). Both the data and, where possible, the methodology employed in obtaining it, should be checked. Common sense is very valuable in this regard. If the results do not appear to be logical and consistent, they are of little value.

6.4 The Nature of Data

6.4.1 Randomness

In the vast majority of cases, data are collected in situations where it is impossible to control every factor that may influence the results. In fact, it is rare that all such factors are even known. This is true in all data collection, whether in scientifically designed tests, experiments, or sampling schemes, and it is especially true when data are collected haphazardly. As a consequence, there is uncertainty in nearly all data. This is manifested in:

- Nonrepeatability of test results – If a test is repeated, it is rare that the outcome will be identical to the original result. (In fact, if it were possible to measure to a sufficient number of decimals, test results would never agree exactly.)
- Nonrepeatability of measurements – If an outcome is measured repeatedly, the outcomes will not be the same.
- Nonpredictability – Because of the inherent variability of experimental material and the impossibility of reproducing test conditions exactly, it is not possible to predict outcomes exactly.

We call this uncertainty/unpredictability *randomness*. There is a random element in nearly all data collected and it is necessary to recognize and account for this in data analysis and interpretation and in data-based decision making. The implications of randomness in this context are very important. It means that:

- Decisions cannot reasonably be based on a single observation. Repeated tests are necessary to assess the level of uncertainty and improve the precision of results.

---

[2] One of the best of these is the well-known *Consumer Reports.*

- Allowance must be made for randomness in analyzing data and interpreting the results.
- Decisions must reflect the level of uncertainty in the data.
- If the data do not provide sufficiently accurate and precise results, provision must be made for collection and analysis of additional relevant data.

6.4.2 Probability and Statistics

Attempting to understand and deal rationally with randomness is the basic underlying goal of both probability and statistics. These two related fields arose, in part, out of two quite different contexts – analysis of games of chance and analysis of experimental data – and the two look at randomness from essentially opposite perspectives.

In probability, the objective, simply stated, is to construct mathematical models of randomness. Given the model, one can then make statements about the nature of the data that may result in realizations of the random phenomenon. In statistics, the objective is to use the observed data to make meaningful statements about the nature of the probability model. Thus probability and statistics are, in a very real sense, inverses of one another. Schematically,

Probability: Model → Data
Statistics: Data → Model

The relevant probability models in this context are usually probability distributions or some related functions. These expressions ordinarily include some (known or unknown) constants called *parameters*. An example is the true mean time to failure (MTTF) of an item. The process of deducing something about a model or its parameters using random data is called, more specifically, *statistical inference*. Inferences are usually based on some numerical quantities, called *statistics*, calculated from the data. An example would be the average time to failure in a sample of items put on test (called the *sample mean*).
NOTE: A *parameter* is a characteristic of a distribution (or *population*). A *statistic* is a characteristic of a *sample* (an observed subset of a population).

6.4.3 Modeling Randomness

In Section 5.6, the notion of modeling uncertainty was discussed in the context of modeling product failures. The uncertainty or *randomness* of failure times was characterized by means of a probability distribution. The most commonly used probability distributions in reliability are the *exponential* and *Weibull* distributions, though many others are used as well.[3] These vary from relatively simple to quite complex, depending on the application, knowledge of the failure mechanisms, and the approach taken to modeling.

---

[3] Many distributions used in reliability modeling and analysis are given in Chapter 4 of Blischke and Murthy [2].

In the examples used later in this chapter and throughout most of the remainder of the book, we will assume that failure times follow a Weibull distribution. (The exponential distribution is a special case of the Weibull.) This assumption is justified in a great many applications, either on theoretical grounds or because it appears to model the data well, or both.

In its usual form, the Weibull distribution has two parameters, a *shape parameter* β and a *scale parameter* α. Together, these determine the distribution, and hence the model of randomness of failures. The shape parameter, in fact, determines the shape of the distribution (skewness, etc.) as well as the failure rate, which may be increasing, decreasing, or constant, corresponding to $\beta > 1$, $\beta < 1$, and $\beta = 1$, respectively. For most items, the failure rate is either constant or increasing with the age of the item, which corresponds to $\beta \geq 1$.

In practice, the actual distribution of time to failure (and, in fact, of many other random quantities) is rarely known exactly. In such cases, the data may be used to select a distribution for modeling purposes.[4]

6.5 Summarization of Data

We have commented in some detail on the need for data throughout the product life cycle and the various sources of data. In this and the next section, we look briefly at some of the basic techniques for analysis of data. The objective is to provide some insight into the methodology that will assist the user of statistics in interpreting the results.

In this section, we deal with *descriptive statistics*, that is, statistics that are used in the summarization and presentation of data. Summary values provide concise measures of the basic information content; graphical presentations give the overall picture. Note that the entire collection of data is called the *sample*. In this context, each individual measurement is called an *observation* and the number of observations in the sample is called the *sample size* and denoted n.

Later we will deal with *inferential statistics*, that is, statistical methods used to make statements about a population based on information obtained from a sample. In analyzing the data for both descriptive and inferential purposes, we will use the MINITAB statistical software.[5]

6.5.1 Data Structures

We begin with some comments on the many forms or structures of data that may be encountered. It is important to be able to recognize these and distinguish between them as the proper analysis of the data depends crucially on its structure.

Data from carefully designed experiments and tests with proper randomization and control are called *experimental data.* Data of this type are essential to the

---

[4] Many graphical procedures and statistical "goodness-of-fit" tests are available for this purpose. See Blischke and Murthy [2], Chapter 11.

[5] Most statistical packages will do the analyses shown in this chapter. For more information on Minitab, go to www.minitab.com

scientific method and form the basis for valid statistical inference. In practice, it is not always possible to conduct experiments or obtain random samples. In fact, we often deal with data that were collected for another purpose, were collected haphazardly, or were obtained under conditions over which we had no control.

Studies in which we simply observe the items we have at hand rather than selecting a random sample are called *observational studies*. In such cases, biased results or results that are invalid in other ways can be obtained and it is important to recognize these limitations in interpreting the statistical results and using them in forming decisions.

Most statistical procedures assume that we have a sample of data that includes a recorded value for each individual in the sample, e.g., the time to failure for each of 50 items put on test. Data of this type are called *complete*. In many applications in reliability, however, this is not the case. For example, if an item is highly reliable, it may take a very long time for all 50 items to fail. In such cases, it is not uncommon to stop the test at some time prior to failure of all of the items (usually either at a preselected time or upon failure of a preselected number of items). The resulting data then include actual failure times for those items that failed, and *service* times of those items that did not. Data of this type are called *censored* or *incomplete data*, and the methods discussed here must be modified for proper statistical analysis of the data.[6]

Finally, we note that in some cases data may be available only in the form of *grouped* data, that is, data aggregated into groups, usually intervals (e.g., 1 to 100, 101 to 200, etc.). This is most commonly true for handbook data and by law is always the case for U.S. Census data. Analysis of grouped data also requires modification of the methods given below.[7]

6.5.2 Graphical Presentation of Data

6.5.2.1 Histograms

The most commonly used graphical presentation of data is the *histogram.* To form a histogram, the observations are grouped into intervals (usually contiguous intervals of equal length) and counts are made of the number of observations falling into each interval. These counts are called *frequencies*, and the set of intervals and associated counts is a *frequency distribution*. A *histogram* is simply a plot of the frequency distribution.[8] A second type of frequency distribution is a table of counts of occurrence of events, e.g., failures of components or modes of failure of a system.

Example 6.1 [Photocopier]

Data were collected on time between failures and type of failure of an office copier. The data were recorded on 98 service calls over a period of about 4½ years. Failures of the copier were due to failure of 17 different components. The original

---

[6] There are many types of incomplete data. For a discussion of these and methods for their analysis, see Blischke and Murthy [2], Section 8.3, and Lawless [3].

[7] See Blischke and Murthy [2], Section 8.2.

[8] For a detailed discussion of frequency distributions and histograms, see Blischke and Murthy [2], Section 3.6.1.

data are given in Table A.1 of the Appendix to this chapter; a list of the components and their frequency of failure is given in Table 6.1 below.

Time between failures was measured in number of copies made (column 1 of Table A.1 and referred to as "count") as well as days of service (column 2 of Table A.1 and referred to as "days"). We look first at the 14 times between failures of the cleaning web.[9] The data are given in Table 6.2. Figure 6.1 is a histogram of the data on days to web failure. Note that for such a relatively small sample, the histogram is not very informative. In fact, small samples in general provide limited information (which may be adequate for some purposes).

As a further illustration, a histogram of all 39 times to failure (service calls) of the copier system is given in Figure 6.2. Here we see a bit more of a pattern. There are some early failures, a high point at about 20 days, nearly as high a frequency at about 40 days, and then progressively fewer instances of longer times to failure. This pattern of a skewed right distribution is typical of the failure patterns of many items. Such patterns are often (though not always) modeled well by a Weibull distribution.

■

Table 6.1. Frequency distribution of copier component failures

Failed component	Frequency
Cleaning web	15
Toner filter	6
Feed rollers	11
Drum blade	2
Toner guide	7
Cleaning blade	7
Dust filter	6
Drum claws	5
Crum	6
Ozone filter	8
Upper fuser roller	5
Upper roller claws	5
TS block front	2
Charging wire	6
Lower roller	2
Optics PS felt	3
Drive gear D	2

[9] The time to first failure is omitted for technical reasons.

Table 6.2. Time in days and number of copies run between failures of the copier cleaning web

Days	Copies
99	71,927
269	232,996
166	61,981
159	74,494
194	96,189
100	78,102
95	40,795
245	183,726
56	33,423
36	4,315
66	56,497
69	51,296
26	22,231
31	9,413

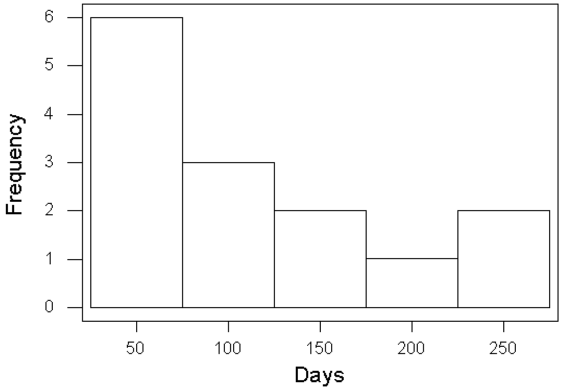


Figure 6.1. Histogram of days to failure of copier cleaning web

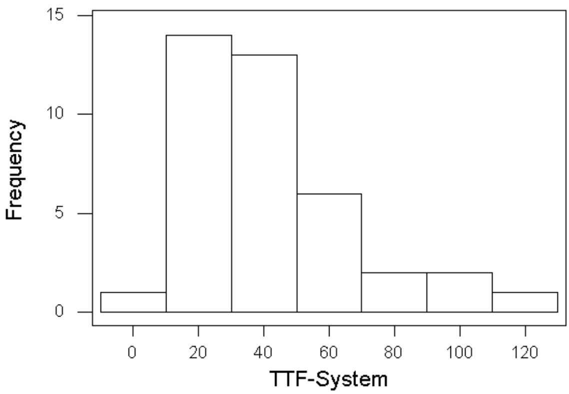


Figure 6.2. Histogram of days to failure of copier

6.5.2.2 Pareto Charts

A *Pareto chart* is a graphical representation of qualitative or categorical data such as those in Table 6.2. The chart is formed simply by ranking categories by frequency of occurrence, from highest to lowest, and then forming a histogram-type graph, with frequencies as heights and category names as identifiers.

The usefulness of a Pareto chart is that it gives an immediate identification of the most important categories. In typical reliability and quality applications, the charts are used to determine defects, failure modes, and so forth, that are most in need of attention, i.e., those whose rectification (for example, through engineering or production changes) would have the greatest impact in increasing overall reliability and quality and hence reducing warranty costs.

Example 6.2 [Photocopier]

Figure 6.3 is a Pareto chart of the failure modes of the copier discussed in Example 6.1, as identified by the failed component. The chart includes a curve indicating the cumulative failure proportion. Note that there is not a predominant failure mode or even a few that account for a majority of the failures. The first five account for a total of only 49% of the failures. The conclusion is that significant improvements of many items are needed to reduce service costs.

■

6.5.2.3 Other Graphical Methods

Many other techniques are used to display both quantitative and qualitative data. These include familiar techniques such as pie charts, pictographs and other pictorial representations, as well as less familiar representations of numerical data such as box-plots and stem-and-leaf diagrams used in descriptive statistics.[10]

6.5.3 Averages

An average indicates the location of the center of a set of numerical data. The two most common types of averages are the *sample mean*, which is simply the numerical average of the data,[11] and the *sample median*, which is calculated as the center value of the set of data when ranked from smallest to largest.

A comparison of the sample mean and median is instructive in that it provides some evidence of skewness. If a frequency distribution is roughly symmetrical, the mean and median will be nearly the same. If the mean is significantly larger than the median, this indicates that the distribution is skewed right (i.e., has a long "tail" on the right-hand side). A mean significantly smaller than the median indicates left skewness.

It is important to note that the *population mean* and *population median* are defined in an analogous way and have the same interpretation as characteristics of an entire population. The same is true with regard to a probability distribution.

---

[10] See Blischke and Murthy [2], Sections 3.6.1 and 3.6.2. For more detailed information regarding graphical methods, see Tufte [4 and 5].

[11] The formula for the sample mean, denoted $\overline{x}$, is $\overline{x} = \sum_{i=1}^{n} x_i$, where $x_1, \ldots, x_n$ are the sample observations.

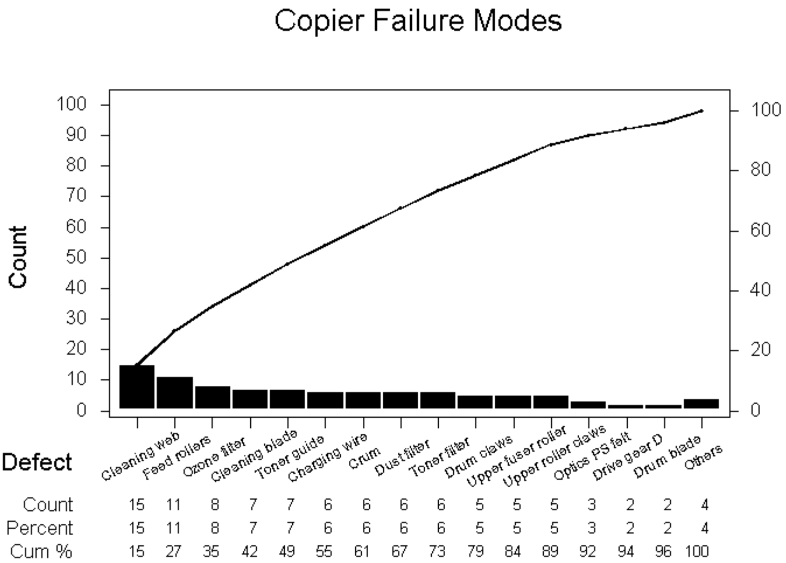


Figure 6.3. Pareto chart of copier component failures

Example 6.3 [Photocopier]

For the 14 times between failure of the copier cleaning web, the sample mean and median of times to web failure, obtained from Minitab, are 115.1 and 97.0 days, respectively. Note that the mean is well in excess of the median, suggesting the right skewness shown in Figure 6.1. From the data of Table A.1, these statistics can also be calculated for number of copies between failures. The resulting mean and median are 72,670 and 59,239 copies, respectively, again indicating right skewness, as one might expect. Finally, the mean and median for time to failure of the system data given in Table 6.1, also calculated by Minitab, are 41.5 and 40.0, respectively. These also show right skewness. Note, incidentally, that the average time to failure for the system is much shorter than that for the web. This is as expected, since the system as a whole can fail in many more ways.

■

6.5.4 Measures of Variability

In addition to notions of center and skewness, a third important characteristic of a set of data is a measure of its variability (also called dispersion or spread of the distribution). The most commonly used measures of variability are the *sample range, variance,* and *standard deviation*. All of these and a number of others[12] can again be found directly or with a simple computation, from standard outputs of descriptive statistics from programs such as Minitab.

[12] Other measures of variability and other descriptive data characteristics are discussed in Blischke and Murthy [2], Section 3.6.

The sample range is simply the difference between the largest and smallest values in the sample. The variance is obtained by a relatively straightforward calculation; the standard deviation is the square root of the variance.[13] The most useful of these is the standard deviation. In distributions that are symmetrical and approximately bell shaped, about 68% of the values will lie within one standard deviation of the mean and about 95% will lie within two standard deviations of the mean.[14]

Example 6.4 [Photocopier]

For days to failure of the cleaner web, the range is 269 – 26 = 243. The sample standard deviation, obtained from Minitab, is 79.2. For the system, these values are 112 and 27.1, respectively. The system mean was 41.5, so we would expect that approximately 95% of the failures would occur between 0 and 41.5 + 2(27.1) = 95.7. In fact, 36 out of 39, or 92.3% of the interfailure times were in this range. (We note that these were the first, third, and fourth observations in the sample, suggesting that perhaps the failure rate is increasing.) This is reasonably close to the expected 95%, given the relatively small sample size and the skewness of the frequency distribution.

■

6.5.5 Measures of Relationship and Trend

When data are collected on more than one variable in a study, a question of interest is whether or not the variables are related, and, if so, in what way are they related and how strong is the relationship. In the copier study, for example, data were collected on both time to failure and number of copies until failure. Clearly one expects these two variables to be related.

The most frequently used measure of strength of relationship is the *correlation coefficient*. More specifically, the correlation coefficient is a measure of strength of the *linear* component of the relationship. It is a type of index number that varies from –1 to 1, with a value of zero indicating no linear relationship and values close to either extreme indicating a strong linear relationship.

The corresponding study of the structure of a data relationship is *regression analysis*. A regression relationship may, in fact, be linear or nonlinear.[15] The simplest linear regression model relates two variables (one called the *predictor* and the other the *response*) by means of an expression in which the predictor variable appears to the first power. The usual approach is to "fit" data to the line by the *method of least squares*, which determines the best fitting line as that for which the

---

[13] The sample variance s^2 is given by $s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$. The sample standard deviation is s.

[14] For other distributions, the results will be similar, but the percentages will vary. The values hold exactly for the well-known *normal distribution*. They will usually not be a very good approximation for distributions that are extremely asymmetrical and/or very different from bell shaped.

[15] Most introductory and intermediate statistics texts include regression and correlation. For a detailed treatment of these, see Draper and Smith [6].

total distance of the data from the line is minimized. This notion is easily extended to more than two variables and to nonlinear models. Correlation and regression analyses are easily done on standard statistical packages such as Minitab.

Data relationships are of interest in many other contexts as well. For example, in business and economics there are many applications in which one of the variables is time. In these applications, the data exhibit certain special features, for example, fairly strong correlations between successive observations. Indeed, this is of interest in the context of the copier example as well, since the observations were taken sequentially in time. Techniques for statistical analysis of such data are covered in *time series analysis*. These are beyond the scope of our treatment, though regression analysis provides the foundation of some of the analyses.[16]

Example 6.5 [Photocopier]

For the copier cleaner web data, the correlation coefficient between number of copies and time to failure of the web is found (from Minitab) to be 0.917. This indicates a very strong relationship between the two. Since failure in this case is simply loading of the web with material from the drum, i.e., wearout, the strong relationship is not surprising.

We next look at a plot of the data on all failures of the copier, plotted against time. The result is given in Figure 6.4. Note that the trend line that is shown on the plot gives a definite indication of a decrease in time between failures, i.e., of an increasing failure rate. The same phenomenon is observed in a plot of the web failures. (Figure 6.4 also includes a formula for the linear trend model that is plotted in the chart.)

■

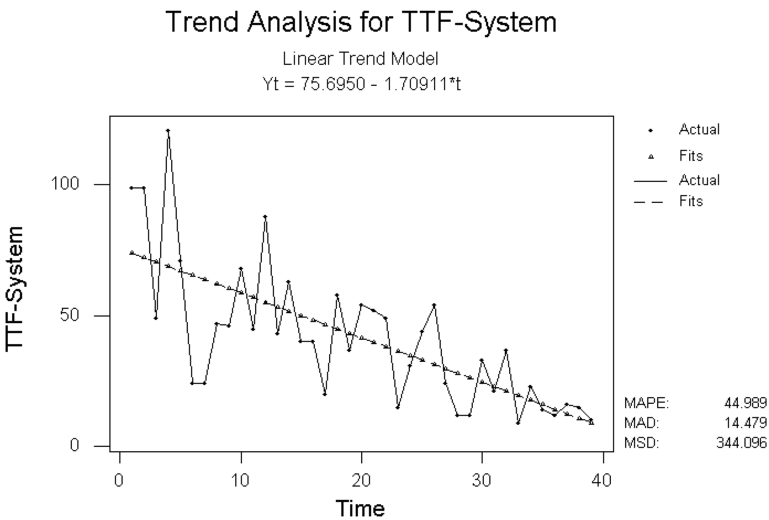


Figure 6.4. Time series plot of copier system time to failure

[16] There are a very large number of books on time series analysis. One that looks at regression in this context is Kedem and Fokianos [7].

6.6 Inferences from Data

6.6.1 The Role and Methods of Statistical Inference[17]

The goal of statistical inference is to use data to provide numerical values for unknown parameters or other characteristics of probability models. It is important to note that the resulting values are not the "true" values of the parameters, but are approximations of the true values. We call these *estimates*. They are characteristics of the sample, and, as such, are statistics.

Another way of looking at this is recognize that the estimates include an element of randomness or uncertainty. This becomes apparent if one repeats a study (i.e., collects a second sample by an identical experimental procedure). The calculated value of the estimate will rarely, if ever, agree exactly with the original result. In a proper data analysis, it is essential to recognize and deal appropriately with the uncertainty in the estimated values. This is especially important in management applications. If it is determined that there is a great deal uncertainty in statistical results that are important inputs to a management decision, this may significantly impact the actions to be taken.

We will look briefly at two key statistical techniques, *estimation* and *hypothesis testing*. Estimation deals with procedures for calculating estimates that are "best" in that, in some sense, they make the best use of the information in the data, and also provide some measure of the uncertainty in the results.

In hypothesis testing, data are used to choose between competing hypothesized models. These may be different probability models, different sets of parameter values for a specified model, different reliability models, warranty cost models, and so forth.

6.6.2 Parameter Estimation

Procedures used for calculation of estimates are called *estimators*. In a sense, an estimator is the formula defining the procedure and an estimate is the numerical value that results on application of the formula to a set of data. Thus the formula for the sample mean given in the previous section (see footnote 11) is an estimator. The calculated value of the average time to failure of the cleaning web – found to be 115.1 days in Example 6.3 – is an estimate.

A key concern of the field of theoretical statistics is the derivation of "best" estimators, i.e., procedures that perform optimally when applied to a large variety of possible data sets. In this context, there are many notions of "optimality;" from a practical point of view, these deal with appropriate, efficient, and cost effective use of all of the information in a sample.[18] Procedures that are optimal for all data and under all assumptions do not exist. In this section, we list a few procedures that are useful in basic data analysis and are optimal under fairly general conditions (not stated here).

---

[17] An excellent treatment of data analysis in this context is given by Meeker and Escobar [8].

[18] A thorough treatment of theoretical statistics may be found in Stuart and Ord [9] and Stuart *et al.* [10].

An approach to accounting for uncertainty in estimators is *confidence interval estimation*. A confidence interval is basically an interval of values calculated by means of a procedure that leads to intervals that, on average, include the true value a specified proportion of the time. (To distinguish between the two procedures, the basic estimate defined above is called a *point estimate*.) The derivation of confidence interval estimators involves probabilistic assumptions concerning the nature of the data. The result is a formula that provides the end points of the confidence interval. To apply the procedure, the user must specify the probability of making correct statements (called the *confidence level*). Typical choices are 0.95 and 0.99; the results are called 95% and 99% confidence intervals, respectively.

To illustrate these inference procedures, we look first at estimation of the population mean and standard deviation. The best point estimators of these in most cases (i.e., for most populations and most data sets) are the sample and sample standard deviation as defined in the previous section. We note, however, that for censored data, often encountered in reliability and warranty applications, much more complex procedures are required.[19]

The calculation of confidence intervals for the mean and standard deviation depends on the assumptions made regarding the population from which the sample was drawn, i.e., on the probability distribution underlying the data. The usual assumption in most applications is that this is a normal distribution. In this case, the confidence interval procedures are based on standard tabulated statistical distributions. The intervals can easily be calculated using these tables or any available statistical program package. Unless otherwise noted, the intervals based on normality will be used in the examples in this book.[20]

The normal distribution is unusual in that the mean and standard deviation (or, equivalently, the variance) are, in fact, the *parameters* of the distribution. They appear explicitly in the formula for the normal distribution. For other distributions, and in particular for the most important functions of this type in reliability applications, this is not the case. In these cases, estimation of the parameters requires special procedures that are specific to the particular distribution and the data structure. The same is true in estimating reliabilities, failure rates, reliability functions, and many other characteristics of interest in reliability and warranty

---

[19] See Nelson [11] for some key methodology.

[20] The formula for a confidence interval for the population mean, based on a complete sample and the assumption of a normal distribution, is

$$\bar{x} \pm t_{tab} s / \sqrt{n}$$

where $\bar{x}$ and s are the sample mean and standard deviation, and t_{tab} is a tabulated value of the Student-t distribution with n–1 degrees of freedom (df). t_{tab} depends on the level of confidence and on the sample size n. For details, see Blischke and Murthy [2], Section 5.3.2, or any standard statistical text, e.g., McClave and Benson [12]. This procedure is also appropriate for large samples from non-normal populations. A confidence interval for the variance is based on the Chi-Square distribution. For details, see Blischke and Murthy [2], Chapter 5, p. 152.

applications.[21] Many of these important procedures are available in standard statistical or special reliability program packages.

Example 6.6 [Photocopier]

To illustrate the confidence interval procedure, we calculate a 95% confidence interval for the mean time to failure of the copier. (Note from Figure 6.2 that the distribution of times to failure is skewed right and does not appear to be normal. We have a modest sample size of 39, however, so the normal approach is considered to be a reasonable approximation.) The sample mean and standard deviation were given in Examples 6.3 and 6.5, respectively, as 41.5 and 27.1. With $n - 1 = 38$ df, the appropriate tabulated t for 95% confidence[22] is 2.025. The 95% confidence interval is $41.5 \pm 2.025(27.1)/\sqrt{39}$, giving the interval (32.7, 50.3). We are 95% confident that the true mean time to failure lies between these two numbers. This is a very wide interval and reflects the uncertainty in the result due to the fact that there is substantial variability in the data. To decrease the size of the interval, we would need to either decrease the variability in time to failure or increase the sample size.[23]

■

6.6.3 Hypothesis Testing

In estimation, we deal with the problem of obtaining numerical values for unknown parameters or other population characteristics, based on sample information. Another type of problem dealt with in statistical inference involves the use of data to determine whether or not some stated assumption or condition is plausibly true. The statistical methodology that addresses problems of this type is *hypothesis testing.*

Examples of applications that may be formulated as hypothesis testing problems are:

- Determining whether or not there is evidence that the average lifetime (as measured by usage) of a newly designed model of tire can reasonably be assumed to be at least 50,000 miles.
- Determining whether or not the average time between failures of a copy machine is 50 hours.
- Determining whether the reliability of an electronic ignition system is at least 0.99.
- Determining whether or not the data support the hypothesis that warranty cost per automobile for a particular model year is less than that of the previous model year.

---

[21] Estimation procedures for the parameters of many distributions are given in Chapter 5 of Blischke and Murthy [2], for complete data, and in Chapter 8 for censored data. Many other aspects of estimation and related topics are covered elsewhere in the book.

[22] Found by interpolation in Table C2 of Blischke and Murthy [2].

[23] In situations such as this, decreasing variability is probably not feasible. Another problem here is that we have data on only one copier. To deal with many of the issues realistically, data would be collected on more machines in a properly designed experiment.

- Determining whether or not the time to failure of a photocopier has a Weibull distribution.

In the classical approach to hypothesis testing, two mutually exclusive hypotheses, the *null* and *alternate hypotheses*, are formulated, and the data are used to determine which of these is "correct". Testing is done by determining whether or not the data support the null hypothesis. If not, the null is rejected and the alternate is accepted. If the null cannot be rejected, it may be accepted or judgment may be withheld (e.g., until additional data are obtained). In this set-up, the burden of proof (often the situation in which action is taken) is put on the alternate hypothesis. In the tire example, for instance, we may wish to verify an engineering judgment that the tire will last at least 50,000 miles, or we may wish to know this in devising a warranty strategy or to compare this model with previous models, and so forth. In all of these cases, we might reasonably state that we wish to "prove" that the tire satisfies this assumption. In this case, the null hypothesis would be that the average lifetime of the tire is less than or equal to 50,000 miles and the alternate would be that it exceeds this value. Note that here by "average lifetime" we mean the average in the population all such tires, not just the average in a sample. In general, hypotheses are statements about population characteristics.

In this formulation of the problem, either the null or the alternate hypothesis must be true. It follows that there are two types of incorrect decisions or errors that can be made. The first is rejecting a null hypothesis that is true; the second is failing to reject one that is false. Hypothesis tests are constructed so as to control the probabilities of these two types of errors, called error rates. The probability of rejecting a null hypothesis that is true, called the *level of significance* of the test, is selected by the user. Commonly used values for this probability are 0.05 and 0.01 (called testing at the 5% level and 1% level, respectively).

Tests are performed by calculating values of appropriate statistics (e.g. a statistic based on the sample mean for testing a null hypothesis about the population mean). The calculated values are then compared with corresponding tabulated values (obtained from standard statistical tables or by an equivalent computerized procedure) to determine whether the sample can be considered to be likely or unlikely, given that the null hypothesis is true. Unlikely values (e.g., those that occur less than 5% of the time) lead to rejection of the null hypothesis and acceptance of the alternate. Statistics used for this purpose are called *test statistics.*

In many problems, an equivalent test procedure can be applied by use of an appropriate confidence interval, if one exists. One may think of a confidence interval as an interval of relatively likely values for the parameter in question. If a hypothesized value of the parameter lies in the interval, this would suggest that the hypothesis should be accepted (or at least not rejected). This is, in fact, how intervals are used for testing. To test at the 5% level, for example, we calculate an appropriate[24] 95% confidence interval. The null hypothesis is rejected if the

[24] Which confidence interval is appropriate depends on the alternate hypothesis, which may state that the true value is greater than, less than, or equal to the null hypothesized value. In the first two cases, one-sided confidence intervals are used; in the last, a two-sided interval

hypothesized value lies outside the interval; otherwise, it is not rejected. Suppose, for example, that a sample of 100 tires put on test yielded a mean usage to failure of 56,645 miles and a 95% confidence interval of 56,645 $\pm$ 1,220, or (55425, 57865) was obtained. If one wished to test the null hypothesis that the true mean of all such tires was 50,000 against the alternative that it was not this value, to test at the 5% level we simply note that the null hypothesized value is not in the interval and conclude that the mean is different from 50,000. Another way of stating this is that the sample evidence leads us to conclude that the null hypothesis should be rejected at the 5% level.

Standard statistical program packages include procedures for testing hypotheses about the mean and standard deviation of a normal distribution, the mean of an exponential distribution, and a number of additional tests of parameters and other characteristics of importance in reliability applications.

There are a number of other inferences that may be formulated as hypothesis testing problems. These include determining whether or not an assumed distribution (e.g., the normal or Weibull) adequately "fits" a set of data, whether or not two or more variables are correlated, whether or not the proportion of failures meets a specified standard, and many more.[25]

Example 6.7 [Photocopier]

Suppose that the copier discussed in the previous examples was designed with the expectation that the average time between failures (MTBF) under normal usage would be 50 days. Do the data on the machine used in this study provide evidence that the true mean time to failure is different from 50? In formulating this as a hypothesis testing problem, we note that 50 is the nominal value and we are interested in detecting differences in either direction – values less than 50 and greater than 50 will require that some action be taken. If the machines break down more frequently than expected (mean less than 50), it may be necessary to increase service staff, parts inventory, and so forth, or to increase fees, cost of service contracts, etc. If the average is greater than 50, staff may be decreased, more competitive warranties and service contracts offered, and so forth.

To test the hypothesis that MTBF is 50 days against the alternative that it is not 50, we select the 5% level of significance.[26] To perform the test, we use the calculated 95% confidence interval for the mean, found in Example 6.6 to be (32.7, 50.3). Since this interval includes the null-hypothesized value of 50.0, we conclude that we cannot reject the null hypothesis. Thus, testing at the 5% level, we cannot reject the hypothesis that the true mean is 50, even though the sample mean is 41.5! The problem, again, is variability, which leads to the substantial uncertainty in the results. This could be overcome by obtaining more data, as previously suggested.

■

(such as those in the examples) is appropriate. For more on hypothesis testing and the relationship of this to confidence interval estimation, see Blischke and Murthy [2].

[25] See Blischke and Murthy [2] and Lawless [3] for these and many other procedures.

[26] For a discussion of choice of level of significance, see Blischke and Murthy [2], Section 5.6.1.

6.7 Data-based Decision Models

In Chapter 5, we discussed modeling as a tool for decision making. Models are used as descriptive tools representing relevant features of the real world in such a way that they are amenable to analysis. Thus they are a critical link between real-world problems and the analytical tools that are used in problem solving, in the decision process, and ultimately in implementation of the solution. Many aspects of the process may be modeled, including the probabilistic structure, relationships between important variables, cost factors, changes of variables and relationships through time, and many others.

The three major steps in the process are model selection, estimation and validation. These are discussed in some detail in Chapter 5. The model-building process may be either empirical or theoretical, as described in Figure 6.5. The empirical approach is used when knowledge and understanding of the process being modeled is not sufficient to provide a foundation for derivation of a theoretical model. In the empirical approach, all three steps in the formulation of a tenable model are data-based. In this case, appropriate and adequate data and other information must be available so that various candidate models can be estimated and compared. Additional data (i.e., data not used in the model building) are needed for validation.

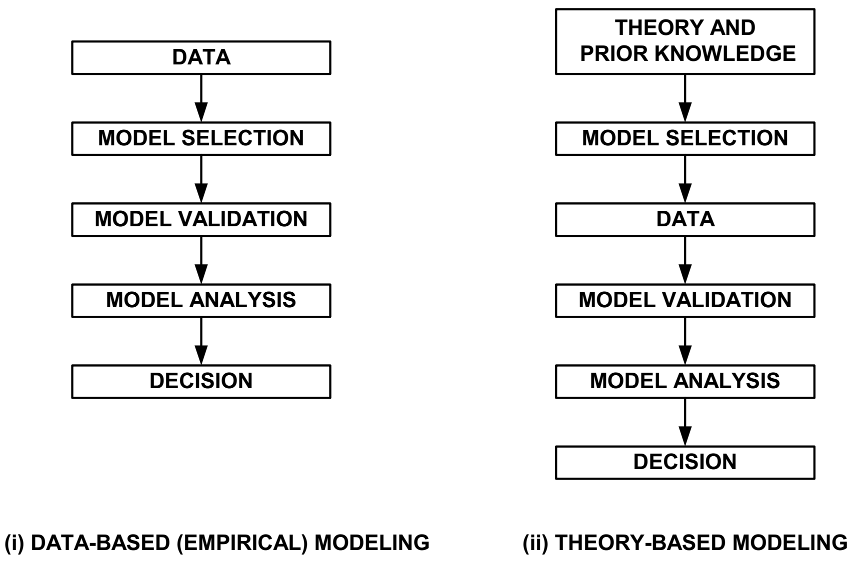


Figure 6.5. Data-based and theory-based modeling

The models used in analyses of this type are generally descriptive models, with parameters that do not necessarily lend themselves to explicit interpretation in the context of the original problem. As an example, the Weibull model is often used to describe the distribution of time to failure in reliability applications. This model can be fitted to data, parameters estimated and validated at least to the extent that it cannot be rejected as an adequate descriptive model. This enables one to make statements about the reliability of the item that was on test and related issues. Only rarely, however, would one be able to relate the estimated parameter values obtained to underlying failure causes, environmental conditions that might lead to failure, and so forth. Thus the purely descriptive model may be quite adequate for many purposes, including predictions of reliability, costs, and so forth, but it is important to keep in mind the distinction between *description* and *understanding*, particularly when the results are to be used as the basis for key management decisions.

The theoretical approach to model building is described in Figure 6.5(ii). Here we assume that sufficient information is available and the phenomenon being studied is sufficiently well understood that it is possible to select a well-defined, adequate mathematical model to describe the phenomenon. One of the key consequences of this understanding is that parameter values will relate to important elements of the process. As a result, important factors will be identified and it may, in fact, be possible to manipulate these so that a decision that optimizes the outcome may be reached.

As shown in Figure 6.5, data also play an important role in situations where a well-developed theory exists. Here data are needed for model estimation and validation, for comparison of models (e.g., for similar products), and so forth. This is particularly important in analysis and evaluation of new products and processes. Some of the essential needs are data on materials, vendors, production, performance of the product, warranty claims, marketing and sales, and many related items, as discussed in Sections 6.2 and 6.3.

In this context, we reiterate the importance of proper data collection and analysis. It is essential that effective and efficient sampling and testing be done. This is accomplished by use of carefully designed surveys in sampling (e.g., of customers) and use of scientific principles of experimental design in formulating test plans, and adequate resources must be provided for this purpose.

Because of the large amount of relevant data that may be collected during the course of the life cycle of a product, and the need to process this data and provide inputs to management decision problems, it is necessary to provide adequate resources for this purpose as well. We comment briefly on data collection and processing systems in Section 6.9. The subject will be discussed in detail in Chapter 14.

Example 6.8 [Photocopier]

To illustrate empirical modeling, we look briefly at modeling failures in the case of the photocopier. The nature of the data allows for the possibility of modeling at both the component and system levels. There are many uses for such models. At the system level, for example, the model may be used to predict future claims under warranty, analyze staffing and related issues, and so forth. Component models enable the user to identify specific causes, allocate resources, determine spares requirements, and address many other issues.

To illustrate modeling at the component level, we use the copier cleaner web. We have previously found that there were 14 failures of this component with an average time to failure of 115.1 days and a standard deviation of 79.2 days. The histogram of the data (Figure 6.1) suggests that the distribution is skewed right. To complete a preliminary analysis, a candidate failure distribution is selected. We use a Weibull distribution for this purpose. A Weibull plot[27] of the data (shown as dots) is given in Figure 6.6. For samples from Weibull distributions, the plot should be approximately linear. Here the result is reasonably acceptable.[28]

For modeling failures of the copier at the system level, we use a ROCOF model (see Section 5.6.1). A plot of the number of failures over time shown as a staircase function is given in Figure 6.7 and can be modeled by a Weibull intensity model [14]. A plot of the expected number of failures over time based on the ROCOF model is shown as a continuous curve in Figure 6.7. As can be seen, the two plots are in reasonably close agreement and we can conclude that the Weibull intensity model is acceptable for decision-making purposes.

■

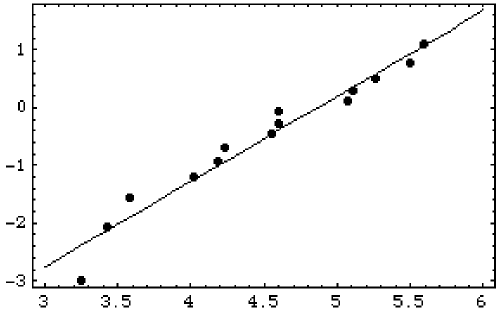


Figure 6.6. Weibull plot of days between cleaning web failures

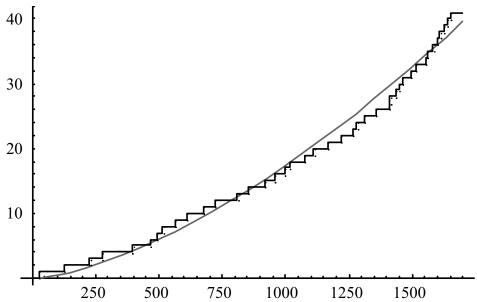


Figure 6.7. Plots of actual and expected numbers of copier system failures from ROCOF model

---

[27] For a detailed discussion of probability plotting, see Meeker and Escobar [8], Chapter 6. Murthy *et al*. [13] discuss many other models derived from the basic Weibull distribution and selection of a best model based on special plots used for this purpose. For the data set considered in Example 6.8, the authors consider ten different models and conclude that a model involving two Weibull distributions is most appropriate.

[28] In practice, many other plots, corresponding to alternative probability models, would be looked at as well. This is done for the cleaning web data in Bulmer and Eccleston[14].

6.8 Analysis of Warranty Claims Data

A key concern in warranty management is estimation and control of the cost elements associated with warranty. A good deal of data is often collected in connection with this effort. These might include marketing information, reliability test results, quality information, responses to consumer surveys, warranty claims data, and relevant data from many other potential sources. The study of these data and their interrelationships can provide important management information. Here we look briefly at some approaches to analysis of warranty data and some of the difficulties typically encountered.

6.8.1 Warranty Data[29]

The specific claims data collected may vary considerably from company to company, but ordinarily the data consist of date of sale of the item and date of claim, and, if relevant, usage (these being necessary to verify the validity of the claim), as well as a number of items of identification, e.g., product, model number, dealer, identification of part(s) that failed, cost of replacement (usually parts and labor separately), service facility, and so forth. More complete data may also include mode of failure, test results and other evidence of failure, repair time, and so forth, and, for complex items, maintenance records and other relevant information.

Key issues in analysis of claims data include classification and tabulation of failures, analysis of failure frequencies, assessment of cost elements, and other issues that may depend on the product and the intended use of the information. In addition, analysis of a number of more fundamental issues may be desired. These include mean time to failure, failure distribution, root causes of failure, and engineering issues such as materials, design, manufacture, quality programs, and so forth. For most of these purposes (and often even for the simpler issues), claims data are notoriously poor. This is due primarily to the fact that the data are provided by consumers, dealers, repair personnel, and others over whom the manufacturer has little or no control.[30] Some of the principal difficulties frequently encountered in claims data are:

- Inaccurate, incomplete data – missing or incorrect entries; transpositions, etc.
- Delays in reporting – periodic or haphazard reports of claims
- Lags in making claims (particularly for minor failures or failures that do not seriously affect operation of the item)
- Invalid claims – claims after expiration of the warranty, failures due to misuse, or claims on items that did not fail
- Valid claims that are not made – ignorance of warranty terms; compensation deemed not worth the effort of collecting, etc.

---

[29] The material in this section is from Iskandar and Blischke [15].

[30] An excellent discussion of data problems and related issues is given by Suzuki *et al.* [16].

As a result of these and other difficulties, warranty data are usually quite messy and a good deal of careful editing may be required.[31] Beyond this, two common and very important characteristics of warranty data that significantly impact the analysis are:

- Very little, if any, information on failures times or usage is obtained on items that fail after the end of the warranty period.
- Data on some important variables are not collected. A common example is total daily sales.

As a consequence of the first item, warranty data are usually very heavily censored (e.g., 95% or more missing observations). Worse, essential censoring information is often not known. (A common example is usage.) In this situation, it may be very difficult to obtain accurate and precise estimates of model parameters. The consequence of missing variables may also be serious, since it may preclude the use of a powerful model.

Because of these shortcomings, many of which are inherent to the process, there is often little done by way of analysis of warranty data other than simple descriptive statistics. In most companies, it is important that management provide the necessary resources for improvement of the collection and analysis of claims data. This requires the cooperation of, and input from, all users of such data, including design, production, reliability and quality, and so forth, as well as the producers of the data, including service providers, dealers, and, to the extent possible, the costumers themselves.

6.8.2 Data Analysis

A number of approaches have been taken to analysis of claims data and to dealing with some of the issues discussed above. Data quality may be a significant problem, and it is essential that the data be cleaned to the maximum extent possible. This involves removal of obviously erroneous data, detecting missing data elements and attempting to obtain the missing information, verifying that only relevant data are included, and any other necessary data editing. Some of the tools discussed in this chapter may be used in description and initial analysis of the data. For example, Pareto charts are very useful in identifying important failure modes and components. Methods of estimation and hypothesis testing, such as those discussed in Section 6.6, are also needed. The procedures given there assume complete (as opposed to censored) data, and are therefore appropriate for some purposes, e.g., estimation of warranty costs, but may not be for others, such as estimating mean time to failure. This is because warranty data are censored in that no information on usage is obtained on items for which no claim has been filed. For reliability analysis, methods for analysis of censored data, available in many standard statistical packages and in reliability program packages, are required.

---

[31] See Iskandar and Blischke [15] for a discussion of just a few of the difficulties encountered in analysis of motorcycle claims data.

In analysis of claims data, one of the most important initial objectives is estimation of claim rates and prediction of future claims. This is a difficult problem, particularly in the case of two-dimensional warranties. Two approaches to this, used primarily in analysis of two-dimensional automobile warranties, are:

1. Modeling based on age-specific claims rates.[32] In most cases, effective application of the model requires supplementary information on usage patterns. This may be obtained, for example, by surveying consumers. The method also can provide estimates of field reliability.[33]
2. A model based on reducing the two-dimensional data (age and mileage in the case of autos) to a one-dimensional formulation.[34] Here a time scale that is a combination of age and usage is devised and the data are analyzed and used to predict claims rates on this scale.

A number of additional efforts have focused on the analysis of automobile warranty claims data. Of particular note are:

- Studies of the use of warranty and other data in assessment of field reliability[35]
- Studies that deal with estimation of life distributions and the mean time to failure using auto warranty data[36]
- Use of prior information in analysis of warranty claims data.[37]

6.9 Computerized Data Analysis

In the preceding sections of the chapter, we have noted that many statistical program packages are available. Most of the statistical calculations of the case studies and examples in this book have been done using Minitab, which is a comprehensive package often used in teaching. Other comprehensive statistical packages include SAS, S-Plus, SPSS, Statistica, and many others. Spreadsheet programs such as Excel also include statistical procedures. These packages typically include programs for basic summary statistics, graphical procedures, regression, analysis of variance, time series analysis, distribution analysis,

[32] For an application, see Iskandar and Blischke [15].
[33] For a review of the method, its uses and related issues, see Lawless [17]. Additional discussion of the analysis of field reliability data and the Kalbfleisch–Lawless method in particular may be found in Suzuki *et al*. [16].
[34] See Gertsbakh and Kordonsky [18]. The method was also applied by Iskandar and Blischke [15] in analysis of the motorcycle data.
[35] See, for example, Kalbfleisch and Lawless [19], and Robinson and McDonald [20].
[36] See Lawless *et al.* [21]. Additional references may be found in Iskandar and Blischke [15].
[37] Statistical procedures specifically formulated for using prior information are called Bayesian methods. A Bayesian approach to prediction of warranty claims is given in Chen *et al.* [22]. See Iskandar and Blischke [15] for additional information.

reliability, quality control, and many other analyses, each with numerous options. Most packages also include algorithms for test design. The programs vary in emphasis, extent of options, quality and amount of graphics, level of detail of output, speed, and special features.

Program packages with emphasis on reliability analysis include Relex, Relia Comp, Item Software, NCSS Statistical Software, and many others, including specialized packages with comprehensive sets of tools for specific analyses, e.g., FMEA, modeling and simulation, test design, and so forth.[38]

Comprehensive reviews and evaluations of program packages are provided periodically in professional journals. A few of the many such sources that review statistical and/or reliability programs are *The American Statistician*,[39] *ORMS Today*,[40] *Computational Statistics and Data Analysis,* and *Statistical Software Newsletter*.[41]

Another aspect of analysis, not mentioned previously, is *data mining*. This is a relatively recent development in dealing with data that is oriented toward very large data sets, e.g., millions or billions of observations. Even with large, powerful computers, problems arise in attempting to manipulate, analyze, and extract useful information from such vast quantities on data, and special techniques are being developed for this purpose.[42] This becomes increasingly important in analysis of warranty claims data as more comprehensive data are collected and more thorough analyses are required, particularly as data are aggregated through time and over models, etc.[43]

Statistical, reliability, and related program packages are intended primarily as aids in data collection, analysis, and interpretation, modeling, and decision analysis. All of the programs listed above (and many others) work well for this purpose. In warranty management, however, vast quantities of relevant data are obtained from many diverse sources, and a more comprehensive approach is needed. The large amounts of information that become (or should become) available during the course of the product life cycle have been listed in several instances in the previous chapters. As data are compiled for various products, product lines, and so forth, the magnitude of information becomes ever greater. Furthermore, a great deal of this information is relevant to many of the numerous activities in product development, production, sales and service. In order to manage this effectively, a comprehensive system linking all phases and activities is needed. The system must not only perform statistical and reliability analyses effectively, it must provide for

---

[38] For a comprehensive list of reliability and related program packages, see Blischke and Murthy [2].

[39] Published by the American Statistical Association. Contact www.amstat.org for information.

[40] Published by INFORMS. See www.informs.org

[41] The last two are published by Elsevier. See www.elseviermathematics.com

[42] For an introduction to the subject, see Berry and Linoff [23].

[43] For comments on data mining in analyzing warranty claims data, see *Warranty Week*, July 21, 2003.

- Obtaining and storing data from many sources
- Summarizing and analyzing data
- Feeding results back to related activities.

Specifications for a data management system that would accomplish this will be discussed in some detail in Chapter 14.

Appendix. Data for Example 1

Table A.1. Photocopier failure data (from Bulmer and Eccleston [14])

Count	Day	Component	Count	Day	Component
60152	29	Cleaning Web	769384	1165	Feed Rollers
60152	29	Toner Filter	769384	1165	Upper Fuser Roller
60152	29	Feed Rollers	769384	1165	Optics PS Felt
132079	128	Cleaning Web	787106	1217	Cleaning Blade
132079	128	Drum Cleaning Blade	787106	1217	Drum Claws
132079	128	Toner Guide	787106	1217	Toner Guide
220832	227	Toner Filter	840494	1266	Feed Rollers
220832	227	Cleaning Blade	840494	1266	Ozone Filter
220832	227	Dust Filter	851657	1281	Cleaning Blade
220832	227	Drum Claws	851657	1281	Toner Guide
252491	276	Drum Cleaning Blade	872523	1312	Drum Claws
252491	276	Cleaning Blade	872523	1312	Drum
252491	276	Drum	900362	1356	Cleaning Web
252491	276	Toner Guide	900362	1356	Upper Fuser Roller
365075	397	Cleaning Web	900362	1356	Upper Roller Claws
365075	397	Toner Filter	933637	1410	Feed Rollers
365075	397	Drum Claws	933637	1410	Dust Filter
365075	397	Ozone Filter	933637	1410	Ozone Filter
370070	468	Feed Rollers	933785	1412	Cleaning Web
378223	492	Drum	936597	1436	Drive Gear D
390459	516	Upper Fuser Roller	938100	1448	Cleaning Web
427056	563	Cleaning Web	944235	1460	Dust Filter
427056	563	Upper Fuser Roller	944235	1460	Ozone Filter
449928	609	Toner Filter	984244	1493	Feed Rollers
449928	609	Feed Rollers	984244	1493	Charging Wire
449928	609	Upper Roller Claws	994597	1514	Cleaning Web
472320	677	Feed Rollers	994597	1514	Ozone Filter
472320	677	Cleaning Blade	994597	1514	Optics PS Felt
472320	677	Upper Roller Claws	1005842	1551	Upper Fuser Roller
501550	722	Cleaning Web	1005842	1551	Upper Roller Claws
501550	722	Dust Filter	1005842	1551	Lower Roller
501550	722	Drum	1014550	1560	Feed Rollers

Count	Day	Component	Count	Day	Component
501550	722	Toner Guide	1014550	1560	Drive Gear D
533634	810	TS Block Front	1045893	1583	Cleaning Web
533634	810	Charging Wire	1045893	1583	Toner Guide
583981	853	Cleaning Blade	1057844	1597	Cleaning Blade
597739	916	Cleaning Web	1057844	1597	Drum
597739	916	Drum Claws	1057844	1597	Charging Wire
597739	916	Drum	1068124	1609	Cleaning Web
597739	916	Toner Guide	1068124	1609	Toner Filter
624578	956	Charging Wire	1068124	1609	Ozone Filter
660958	996	Lower Roller	1072760	1625	Feed Rollers
675841	1016	Cleaning Web	1072760	1625	Dust Filter
675841	1016	Feed Rollers	1072760	1625	Ozone Filter
684186	1074	Toner Filter	1077537	1640	Cleaning Web
684186	1074	Ozone Filter	1077537	1640	Optics PS Felt
716636	1111	Cleaning Web	1077537	1640	Charging Wire
716636	1111	Dust Filter	1099369	1650	TS Block Front
716636	1111	Upper Roller Claws	1099369	1650	Charging Wire

References

[1] Martz, H. F., and Waller, R. A. (1982), *Bayesian Reliability Analysis*, John Wiley and Sons, Inc., New York.

[2] Blischke, W. R., and Murthy, D. N. P. (2000), *Reliability, Modeling, Prediction and Optimization*, John Wiley and Sons, New York.

[3] Lawless, J. F. (1982), *Statistical Models and Methods for Lifetime Data*, John Wiley and Sons, New York.

[4] Tufte, E. R. (1983), The Visual Display of Quantitative Information, Graphics Press, Cheshire, CT.

[5] Tufte, E. R. (1997), Visual Explanations, Graphics Press, Cheshire, CT.

[6] Draper, N. R., and Smith, H. (1998), *Applied Regression Analysis, Third Edition*, John Wiley and Sons, Inc., New York.

[7] Kedem, B., and Fokianos, K. (2002), *Regression Methods for Time Series Analysis*, John Wiley and Sons, Inc., New York.

[8] Meeker, W. Q., and Escobar, L. A. (1998), *Statistical Methods for Reliability Data*, John Wiley and Sons, Inc., New York.

[9] Stuart, A., and Ord, J. K., *Kendall's Advanced Theory of Statistics, Vol. I, Sixth Edition*, Oxford University Press, New York (1998).

[10] Stuart, A., Ord, J. K., Arnold, A., and Kendall, M. (1999), *Kendall's Advanced Theory of Statistics: Classical Inference and the Linear Model*, Oxford University Press, New York.

[11] Nelson, W. (1982), *Applied Life Data Analysis*, John Wiley and Sons, New York.

[12] McClave, J. T., and Benson, P. G. (1994), *Statistics for Business and Economics*, *Sixth Edition*, Macmillan, New York.

[13] Murthy, D. N. P., Xie, M., and Jiang, R. (2003), *Weibull Models*, John Wiley and Sons, New York.

[14] Bulmer, M., and Eccleston, J. (2003), “Photocopier Reliability Modeling Using Evolutionary Algorithms,” Chapter 18 in Blischke, W. R., and Murthy, D. N. P., *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[15] Iskandar, B., and Blischke, W. R., “Reliability and Warranty Analysis of a Motorcycle Based on Claims Data,” Chapter 27 in Blischke, W. R., and Murthy, D. N. P., Editors, (2003), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[16] Suzuki, K., Karim, Md. R., and Wang, L. (2001), “Statistical Analysis of Reliability Warranty Data,” Chapter 21 in *Handbook of Statistics* (N. Balakrishnan, and C. R. Rao, Editors), Elsevier Science, Amsterdam.

[17] Lawless, J. F. (1998). “Statistical analysis of product warranty data,” *International Statistical Review* **66**:40–60.

[18] Gertsbakh, I. B., and Kordonsky, K. B. (1998), “Parallel time scales and two-dimensional manufacturer and individual customer warranties,” *IIE Transactions* **30**:1181–1189.

[19] Kalbfleisch, J. D., and Lawless, J. F. (1988), “Estimation of reliability in field-performance studies,” *Technometrics* **30**:365–388.

[20] Robinson, J. A., and McDonald, G. C. (1991), “Issues Related to Field Reliability and Warranty Data,” Chapter 7 in *Data Quality Control: Theory and Pragmatics* (G. E. Liepens and V. R. R. Uppuluri, Editors), Marcel Dekker, New York.

[21] Lawless, J., Hu, J., and Cao, J. (1995), “Methods for estimation of failure distributions and rates from automobile warranty data,” *Lifetime Data Analysis* **1**: 227–240.

[22] Chen, J., Lynn, N. J., and Singpurwalla, N. D. (1996), “Forecasting Warranty Claims,” Chapter 31 in Blischke, W. R., and Murthy, D. N. P., Editors, *Product Warranty Handbook*, Marcel Dekker, New York.

[23] Berry, M., and Linoff, G. (1997), *Data Mining Techniques*, John Wiley and Sons, New York.

7

Warranty Cost Analysis

7.1 Introduction

When a product is sold with warranty the manufacturer (and sometimes the consumer) incurs additional costs in the servicing of the warranty. This cost is referred to as the warranty cost and it depends on several factors, with product reliability being one of the very important ones. There are several different notions of warranty costs; we discuss three of these in Section 7.2. We then look at system characterization for warranty cost analysis in Section 7.3, where we discuss two different characterizations. The three different notions of warranty costs are discussed in Section 7.4 for some simple warranty policies. We present some numerical results and discuss their managerial implications. In Section 7.5 we briefly discuss some extensions that incorporate additional features that make the models more realistic and reflect the real-world situation.

7.2 Basis for Warranty Cost Analysis

Whenever an item is returned under warranty, the manufacturer incurs various costs (handling, material, labor, facilities, etc.). These costs are random (unpredictable) quantities. The following three costs are of importance to both consumers and manufacturers:

1. Warranty cost per unit sale
2. Life cycle cost per unit sale
3. Life cycle cost over repeat purchases.

In this section we define these three costs and discuss their relevance. Models for determining cost per unit will be given for a few basic warranties. Some of the more complex models involved in life cycle costing will be briefly discussed.

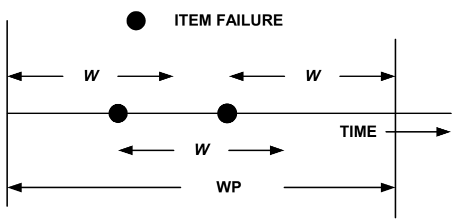
7.2.1 Warranty Cost per Unit Sale

The basic cost of warranty is the sum of the costs associated with the servicing of an item that fails under warranty. The type of warranty determines the warranty period (WP) for which the item is covered. In the case of a one-dimensional non-renewing warranty, this is simply *W*, the length of the warranty. In the case of one-dimensional non-renewing warranty, the warranty period is uncertain as the warranty ceases only when an item does not fail for a period *W,* as indicated in Figure 7.1(i). For a two-dimensional non-renewing warranty with rectangular warranty region, determining the warranty period is a more complex problem. The warranty can cease before *W* should the usage exceed *U* before the item reaches an age *W* or else at *W,* as indicated in Figure 7.1(ii). The warranty period for the renewing case is still more complex.

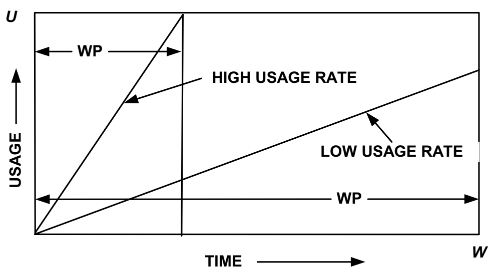
The warranty cost (i.e., the cost of servicing all warranty claims for an item over the total warranty period) is a sum of a random number of such individual costs, since the number of claims over the warranty period is also random.

The cost to the manufacturer per unit sold, which is a function of the length of the warranty period, is the sum of the cost of the initial item sold and the cost of servicing any claims over the warranty period associated with the sold unit. In the analysis and examples presented, we give the expected (or average) value of this cost. This cost is important in the context of pricing the product. The sale price must exceed this cost in order to ensure that, in the long run, the manufacturer will not incur a loss.

Similarly, the cost to the consumer is the sum of the initial purchase price and other costs resulting from warranty claims over the warranty period.



(i) ONE-DIMENSIONAL RENEWING WARRANTY POLICY



(ii) TWO-DIMENSIONAL NON-RENEWING WARRANTY POLICY

Figure 7.1. Total warranty period

7.2.2 Life Cycle Cost per Unit Sale

Many products are used for long periods (for example, aircraft and locomotives are often used for 30–50 years, automobiles for 10–15 years). Let L denote the life of the product. Over the life of the product, one or more components (for example, engines in the case of an aircraft or batteries in the case of an automobile) need to be replaced more than once. Many component replacements occur after the original warranty has expired, and the replacements are covered by a separate warranty. As a result, we have repeat purchases of a component over the period L. A typical history of repeat purchases for a component sold with a non-renewing warranty policy with warranty period W is shown in Figure 7.2. The duration between repeat purchases of a component is uncertain. It depends on the time of first failure outside the original warranty period in the case of non-repairable products, and on consumer replacement decisions in the case of a repairable product.

Warranty costs over the life cycle for the consumer are different from those for the manufacturer. For both, however, the costs are uncertain and depend on L, W and other factors such as product reliability, consumer's replacement decisions, etc. The cost to the manufacturer includes the production costs associated with units sold at full price and the cost of servicing claims under warranty over the period L. Similarly, the cost to the consumer includes the purchase price and any costs associated with warranty claims.

This cost is of relevance in determining the total cost over the life of the product which is often referred to as the life cycle cost.

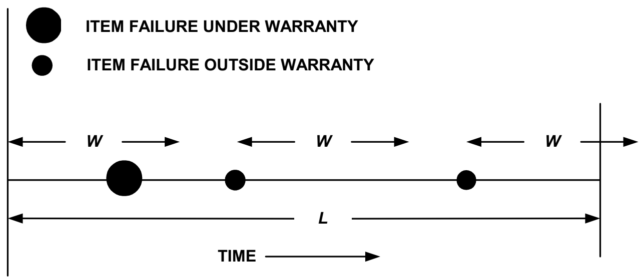


Figure 7.2. Typical history of repeat purchases over period L

7.2.3 Life Cycle Cost over Repeat Purchases

From a marketing perspective, the product life cycle is the period (which is usually denoted L) from the instant a new product is launched on to the market to the instant it is withdrawn from the market due to obsolescence and replacement by another product. Over the product life cycle, product sales (first and repeat purchases) occur over time in a dynamic manner. The manufacturer must service the warranty claims with each such sale.

Warranty claims occur over a period that is greater than L and depend on the type of warranty. In the case of products sold with one-dimensional non-renewing warranty, this period is simply $L + W$. If the warranty is renewing, the period would be longer than this.

The expected number of warranty claims per unit time changes dynamically and is a function of the sales over time, product reliability and other factors such as usage intensity, the usage environment, etc. It is needed for planning of spares, repair facilities, and other service elements. This topic is discussed further in Chapter 8. The expected warranty cost per unit time also changes dynamically over time and is needed for determining the warranty reserves required to service warranty.

In summary, the three methods of costing warranties discussed above are cost per unit sold, cost over the lifetime of an item, and cost over the life cycle of a product. We will be concerned primarily with the first of these.[1]

7.3 Methodology for Warranty Cost Analysis

An overview of the approach to warranty cost analysis is shown in Figure 7.3. In order to estimate and predict warranty costs, a cost model is needed. Analysis of the model will provide the estimates. Proper formulation of the model requires an understanding of the warranty process. This begins with an appropriate system characterization. We briefly discuss each aspect of the methodology.

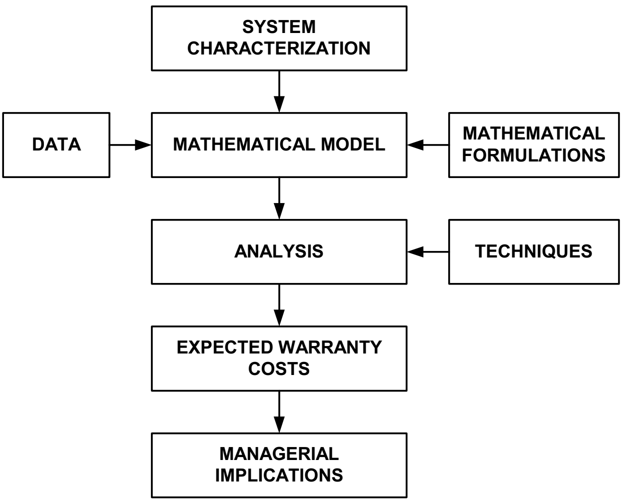


Figure 7.3. Warranty cost estimation methodology

7.3.1 System Characterization

In order to calculate costs associated with warranty, it is necessary to model the random elements underlying the warranty process. To do this adequately, an appropriate characterization of the warranty process (or system) is required. Two

[1] Other cost bases that might be considered are cost per unit of time, other life cycle concepts, and so forth. For discussion of many of these, see Blischke and Murthy [1 and 2].

such system characterizations – simple and detailed – were discussed in Chapter 5. The simple characterization, shown in Figure 5.6, is adequate for building models to obtain warranty costs per unit sale from both manufacturer and consumer perspectives. The detailed characterization, shown in Figure 5.7, is needed for building models to obtain life cycle costs. Here we look at this only from the manufacturer's perspective.

In practice, characterization of each element in Figures 5.6 and 5.7 is needed in order to formulate a working cost model. The modeling efforts may be synthesized as follows. In essence, the direct cost of warranty is primarily a result of two key determinants: (i) the structure of the warranty policy and (ii) the failure pattern of the product. The latter depends on the life distribution of the product. Although it is recognized that each of these is a function of many factors, the cost models that will be discussed in this chapter require precisely these two inputs.

The first of these is directly controlled by the manufacturer through choice of the policy to be offered, although this choice may be influenced by market and other factors. We will look at cost models for a few of the common consumer warranties discussed in Chapter 2. The objectives here are (i) to provide some insight into the cost modeling process, (ii) to evaluate warranty costs as a function of warranty length in realistic applications, (iii) to compare costs of different warranty policies, and (iv) to assess, to a limited extent, the sensitivity of the results to some of the assumptions made.

The second important input to the analysis, the failure pattern of the item, is only partly controlled by the manufacturer and, in any case, is far more difficult to determine precisely. The failure pattern is influenced not only by the design of the product and the manufacturing process, but also by the raw materials used, the failure patterns of components received from suppliers, the type and intensity of usage by the purchaser, and many additional uncontrolled (and usually uncontrollable) factors. As a result, careful attention must be paid to two important inter-related ingredients of this aspect of the modeling effort, (i) selection of an appropriate, realistic probabilistic model, and (ii) acquisition and analysis of as much relevant data as possible.

7.3.2 Modeling

We consider cost models from the manufacturer's point of view. As noted, cost models for warranty analysis depend on the type of warranty offered and the failure distribution of the items sold under warranty. The type of warranty affects the cost in that it specifies the terms of rectification, that is, the type of action to be taken in case of failure under warranty, the amount and timing of payment (e.g., whole or partial refund, discount on purchase of replacement), the duration of liability, and, in the case of renewing warranties, the risk of future warranty liabilities.

A number of probability distributions are used to model the failure distribution of items. These range from quite simple to highly complex. Which distribution is appropriate in real-life applications depends on the complexity of the item, its modes of failure, operational environment, usage patterns, and age. Failure patterns of simple items or parts may often be modeled quite well by standard distributions. These lead to relatively straightforward (though not necessarily easy!) calculations in the cost models. For complex items with many parts connected in complex patterns, the failure distributions are functions of this structure and become very complex. In many situations, these are not amenable to mathematical analysis and distributions and warranty costs are studied through computer simulation.

7.3.2.1 One-dimensional Warranties

In one-dimensional warranties, failures are modeled by a one-dimensional life distribution (called a "univariate" distribution). The selection of an appropriate distribution depends on whether or not failure data are available; either test and/or field data may be used in the analysis. If data are not available, model selection is based on analogy with similar products in the past or on designer's intuition. If data are available, model selection follows along the lines discussed in Chapter 6.

One distribution that has been used extensively in reliability applications is the two-parameter *Weibull* distribution, which is named after a Swedish physicist, Wallodi Weibull, who first promoted its use in many different disciplines.[2] The two parameters of the Weibull distribution are (i) a non-dimensional "shape" parameter α, whose value determines the shape of the distribution and of the failure rate function, and (ii) a dimensional "scale" parameter β, defined by the units of time (or usage) used. Values of α less than 1 indicate that the failure rate is decreasing in time, $\alpha = 1$ indicates that the failure rate is constant, and values greater than 1 indicate that the failure rate is increasing. For most products, we can expect that the failure rate will increase with time, i.e., usually we expect to find that α is greater than one, because of wear degradation that increases the likelihood of failure as the product ages or usage increases. For the special case $\alpha = 1$, the distribution is also called the *exponential distribution.*[3]

7.3.2.2 Two-dimensional Warranties

In this case, item failures are random points on a two-dimensional plane, with one axis representing age and the other representing usage, as indicated in Figure 7.4. There are two approaches to modeling failures.

Approach 1 [Two-dimensional Approach]: The time and usage between successive failures are random variables that are viewed as a pair and modeled by a bivariate failure distribution with one variable representing age and the other usage.[4]

Approach 2 [One-dimensional Approach]: Usage over time is modeled through a variable called "usage rate". The usage rate varies across the customer population. For a given customer, the usage rate is a constant and, as a result, the usage is a linear function of age. Conditional on the usage rate, failures over the warranty period can be viewed as points along the time axis and the conditional expected number of failures under warranty is obtained based on one-dimensional

---

[2] For more on the Weibull distribution and other distributions derived from it, see Murthy *et al.* [3].

[3] Ibid., pp. 103–104.

[4] A variety of bivariate distributions can be found in Johnson and Kotz [4] and Hutchinson and Lai [5]. For more on the warranty cost analysis based on this approach, see Blischke and Murthy [1], Chapter 8 and Blischke and Murthy [2], Chapter 14.

warranty analysis. The expected number of failures under warranty (for the two-dimensional case) is obtained by averaging over the usage rate.[5]

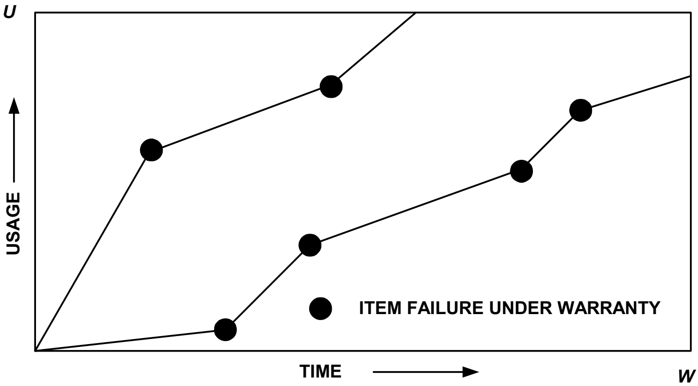


Figure 7.4. Two time histories of age and usage

7.3.3 Some Comments on Analysis

Once the warranty process and the failure pattern of the item are modeled properly, the cost analysis is carried out (at least conceptually) using appropriate mathematical and statistical techniques. A number of approaches may be used, depending on the complexity of the model and analysis and the information that is available to the analyst.

In the simplest cases, the models lend themselves to straightforward mathematical analysis and numerical results are easily obtained. More complex models (which occur even for the simplest warranties) may lead to considerable computational complexities, but are very doable on modern computer facilities. Complex mathematical problems may also be encountered. Intractable mathematical models are often dealt with through simulation studies. These require modeling of the warranty process, simulating part and system failures, repair activities, and elements that affect costs, and repeating the simulation under various choices of input parameters to obtain a detailed profile of predicted warranty costs under different scenarios. A well-designed warranty simulation will enable the user to assess the effect of changing warranty policies, lengths, and other terms.[6]

Another aspect of the analysis concerns the type and amount of information available. In the analysis as described, it is assumed that the models are correct. Implementation of the models requires, in addition, knowledge of the model parameters, including those of the failure distribution. In some cases, all of this information may be obtained from engineering analysis or from a long history of dealing with like products. In other cases, particularly for new products, many of the required model inputs may not be known. Lack of the required information

[5] For more on the one-dimensional approach, see Blischke and Murthy [1], Chapter 8 and Blischke and Murthy [2], Chapter 13.
[6] For an example of such a program, see Hill *et al.* [6].

introduces uncertainty into the results. In order to deal with this problem, data (experimental, historical, and others) are required. This introduces additional uncertainty, and statistical methods are employed in the decision making process. These are discussed in Chapter 6, and include confidence intervals to express uncertainty in statistical estimates, test of assumptions and models, and so forth.

In data-based warranty cost analysis, it is important to investigate the uncertainty of the results. One way of doing this is to use confidence intervals in the cost calculations. This may be done by calculating costs using the nominal estimated parameter values and then repeating the calculations using both the upper and lower confidence limits as inputs. (With multiple parameters, the process may be somewhat more complicated.) One can then reasonably conclude that the true cost will lie somewhere in the range of values obtained. This is a type of *sensitivity study*, and much more detailed studies of this type, varying, for example, the probability model, cost elements, warranty periods and other important drivers of cost, may be done as well. This is particularly important for new products and any other situations involving substantial uncertainty, and proper management requires that resources for such studies be provided.

7.4 Warranty Cost Analysis – Cost Per Unit Sold

We look at cost models for the following common consumer warranties:

- The non-renewing free replacement warranty (FRW), often used for small appliances, electronics, and many other consumer goods
- The non-renewing pro-rata warranty, which is basically a rebate policy and is occasionally used instead of the FRW for non-repairable products
- A two-dimensional FRW such as that commonly used in automobile warranties.

The cost models for all but the simplest of these warranties are mathematically complex. We omit details and provide some numerical results. In discussing the warranty cost models in this and the sections that follow, the following symbols are used:

C_s: cost to the manufacturer of supplying a new item
C_p: purchase (sale) price per unit [cost per unit to consumer]
C_r: average cost of each repair
W: warranty period.

Note that C_s is taken as the total cost to the manufacturer, including materials, labor, testing, inventory, administration, and any other costs in servicing the warranty.

7.4.1 Cost Analysis of the Non-renewing FRW Policy

Under this policy, any item that fails during the warranty period is repaired or replaced free of charge. We first consider the case where the item is non-repairable, so that any failures during warranty require the replacement of the failed item by a new item.

7.4.1.1 Non-repairable Product
Expected Cost to Manufacturer
Under the non-renewing free replacement warranty, if an item fails during the warranty period, it is replaced and the replacement item is warrantied for the time remaining in the warranty period. Thus if an item fails at time X, say, with $X < W$, the replacement item is warrantied for a time $W - X$. If this item fails in that time period, it too is replaced free of charge and warrantied for the net remaining time, and so forth. As a result, the number of failures over the warranty period (a random quantity) is an essential determinant of cost to the manufacturer. In particular, the warranty cost to the manufacturer is the sum of the production cost of unit sold and the required replacements over the warranty period.

The mathematical analysis for determining this cost is rather complex and depends on the failure patterns of the item and on the assumptions made (though slight departures from the assumed conditions will ordinarily not materially affect the numerical results). The expression for expected cost to the manufacturer of the non-renewing FRW is given in Blischke and Murthy [1].[7]
Expected Cost to Consumer
The cost to the consumer is simply the purchase price C_p, as the consumer does not contribute anything toward the cost of replacements over the warranty period. (Realistically, the consumer does incur some costs, e.g., the cost of obtaining the replacement item, the cost associated with loss of use of the item until replacement, and so forth. These are indirect costs that are also random and depend on many factors. Here we deal only with direct costs paid by the consumer to the seller.)
Example 7.1
An electronic module in an automobile is sold with an FRW policy with warranty period W. When a module fails, it must be replaced with a new unit, since it is not practical to repair one that has failed. We will look at the cost of warranties of various lengths under various assumptions regarding the distribution of time to failure of the module.

Suppose that the mean time to failure of the module is 12 years and that we wish to calculate the cost of warranties of 1, 2, 3, 5, and 7 years. To complete the calculation, we must choose an appropriate Weibull distribution. With the mean specified to be 12, this distribution will be determined by the choice of α. Since it is unlikely that the picture will have a *decreasing* failure rate, we restrict consideration to values of $\alpha \geq 1$. For purposes of comparison, we select $\alpha = 1, 2, 3$, and 4. These correspond to a constant failure, a somewhat increasing failure rate,

[7] See [1], Page 135. The expected warranty cost is $C_s[1 + M(W)]$, where $M(W)$ is the average number of replacements during the warranty period of length W.

and two somewhat more rapidly increasing failure rates.[8] Finally, suppose that it costs the manufacturer a total of C_s = \$30 to produce a module.

Results

The total expected costs to the manufacturer under these assumptions are given in Table 7.1 for W = 1, 2, 3, 5, and 7 years. These costs are the average total cost associated with supplying the initial item and all necessary replacements for items that fail under warranty.

In the table, Expected number of failures is the expected number of failed items per unit sale, i.e., the number of free replacements that the manufacturer would have to provide per unit sold, on average, during the warranty period. Expected cost to manufacturer includes the cost of supplying the original item. Thus expected warranty costs alone are calculated as tabulated Expected cost to manufacturer minus \$30.00.

Discussion

Results of the type given in Table 7.1 are useful in managerial decisions regarding the choice of the length of an FRW warranty, particularly for new products. We see from the table that, as expected, costs increase as the length of the warranty period increases. Note, however, that, except for $\alpha = 1$, this increase is not linear. For $\alpha > 1$, warranty costs increase at an increasing rate. This is important in any managerial decision involving a possible change in warranty coverage.

It is instructive to look at warranty costs as a function of the Weibull shape parameter α. We note first that these costs depend quite critically on the value of this parameter. The worst case is when $\alpha = 1$, which corresponds to failures occurring at a constant rate. In this case, warranty costs increase at a constant rate as well, and quickly become unacceptably large. For $W = 1$ (a one-year warranty on an item with an average time to failure of 12 years), the warranty cost, \$2.50, is 8.33% of the cost, C_s, of supplying an item (but significant less than that percentage of the selling price). This may be acceptable, but the corresponding values for longer warranties quickly become excessive. For the standard auto warranty of 3 years, the warranty cost is 25% of the cost of supplying the product.

Table 7.1. Expected warranty costs for example 7.1

	Expected number of failures				**Expected cost to manufacturer**			
W (years)	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$
1	.0833	.0054	.00041	.00003	\$32.50	\$30.16	\$30.12	\$30.00
2	.1667	.0217	.00329	.00052	35.00	30.65	30.20	30.02
3	.2500	.0483	.01107	.00263	37.50	31.45	30.33	30.08
5	.4167	.1304	.05035	.02014	42.50	33.91	31.51	30.60
7	.5833	.2454	.13280	.07525	47.50	37.36	33.98	32.26

The situation is quite different for the other choices of α considered. If $\alpha = 2$, a three-year FRW would lead to a total expected cost of \$31.45, with warranty cost

[8] The constant failure rate ($\alpha = 1$) is appropriate if failure is not affected by age. This is very likely not the case here, but it serves as a useful bound on the results.

being 4.8% of C_s, still very high. For $\alpha = 3$, this value is just above 1% for a three-year warranty and for $\alpha = 4$, it is about a quarter of a percent.

There are several important lessons to be learned from this example:

1. Care must be taken in selecting a warranty period.
2. Assumptions, particularly regarding the failure distribution, may critically affect the results. Here the exponential (α = 1) and Weibull distributions with $\alpha \neq 1$ (and, it should be emphasized, the same mean of 12 years) give very different estimated warranty costs. Other distributions may give still other outcomes.[9]
3. The choices of values for α and the mean time to failure of 12 years were arbitrary selections made for the purposes of this example. In practice, these values (and often others as well) must be known, at least approximately, for the results to be meaningful. If they are not, then they must be estimated from experience, historical data on similar items, test data, and so forth. As noted earlier, proper statistical tools are essential in assimilating such data, and uncertainty in the results must be taken into account in interpreting them. This was discussed in Chapter 6.
4. Here we looked at sensitivity of the results to choices of warranty period and α. In practice, a more thorough sensitivity study would be desirable, covering not only these two characteristics of the model, but also any others that might substantively affect the results. For example, we have not looked at how changes in the mean time to failure would affect the outcomes. If this is not known with certainty, it also must be estimated and should be varied in the analysis as well.

■

7.4.1.2 Repairable Product

Expected Cost to Manufacturer

For repairable items, the manufacturer will usually bear the cost of repairing rather than replacing an item that fails under warranty. (We assume, of course, that repair is less costly than replacement.) In this case, the cost to the manufacturer depends on the nature of the repair. We confine our attention to the case where all failures over the warranty period are minimally repaired. This means that the item is restored basically to its condition immediately prior to the failure. This is essentially the situation, for example, when a product consists of many components, with only one or a few failing, and repair is made by replacing only the failed components. After repair, the item is basically as it was prior to the failure, because all non-replaced items have the same usage and age as before. Other types of repair can be modeled in the cost analysis as well. Other issues in this context are the cost of repair versus that of replacement, changing type of repair, sometimes repairing and otherwise replacing, and optimal policies in this regard. These will be discussed in Chapter 11.

---

[9] A number of additional failure distributions are discussed in Blischke and Murthy [7], Chapter 4. See also, Meeker and Escobar [8], Chapters 4 and 5.

In modeling in the case of repairable items, it is usually assumed that the repair times are small in relation to the mean time to failure of the item, so that they can be ignored. The important determinant of cost in this case is the number of repairs over the warranty period. The warranty cost to the manufacturer is the sum of the production cost of the unit sold and the cost of repairs over the warranty period. Note that this is again a random quantity. The mathematical analysis is again complicated, but an expression for the expected warranty cost has been obtained.[10]

Expected Cost to Consumer

The cost to the consumer is simply the purchase price C_p, as the consumer does not contribute to the cost of replacements over the warranty period.

Example 7.2

We consider the photocopier discussed in Example 6.1 and succeeding examples in Chapter 6. The analysis will be of the system as a whole, and will assume that failures during the warranty period are rectified by minimal repair. Machines of this type are often covered under limited warranty for periods of about three to five years.

The data on which the analysis is based are given in Table 6.1. The mean time to failure was given in Example 6.3 as 41.5 days; from Example 6.4, the sample standard deviation is 79.2. Note that these statistics are relevant to the period of observation, which for this machine was about 4 years.

Figure 7.5 is a plot of cumulative number of failures versus time. The plot is a "step function," increasing one unit at each time of failure. Also shown in the figure is a plot of a fitted failure rate curve (ROCOF) corresponding to a Weibull distribution of time to failure.[11] The Weibull parameters corresponding to the fitted curve are $\alpha = 1.55$ and $\beta = 157.5$ days. The α value corresponds to an increasing failure rate with age, as expected.

The ROCOF curve may be used to predict system failures. The results for the first ten years of operation are given in Table 7.2. The increasing rate of failures with age is apparent in this table. The warranty cost to the manufacturer is calculated as the product of estimated number of failures and average repair cost per failure. This is important in evaluating warranty policy and is also very useful in determining repair strategies, e.g., repair versus replacement, stocking of spares, and so forth.

Table 7.2. Estimated number of service calls per year for photocopier

Year	1	2	3	4	5	6	7	8	9	10
Service calls	3.7	7.1	9.4	11.3	13.0	14.6	16.0	17.3	18.5	19.7

[10] Blischke and Murthy [7], p. 601. Formulas for good-as-new repair and other situations are given in Section 4.2.4 of Blischke and Murthy [1].

[11] The curve of this step function can be modelled using a power function of the form $\Lambda(t) = (t/\beta)^{\alpha}$. For details of this and other fitted models, see Bulmer and Eccleston [9].

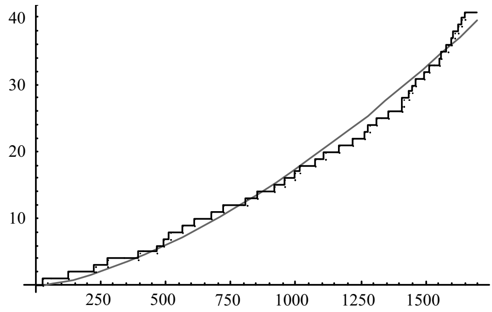


Figure 7.5. Step function and ROCOF plot of days to system failure, with power function fit

■

7.4.2 Cost Analysis of the Non-renewing PRW Policy

Under this policy, a rebate is given to the consumer in case of item failure, rather than a repair or replacement. We confine our attention to the case where the rebate is a linear function of time to failure of the item. This is expressed mathematically as rebate = $(1 - X/W)/C_p$. Thus, if $X/W = 0.75$, i.e., an item fails three-quarters of the way through the warranty period, then under this warranty the customer in refunded one-quarter of the purchase price, i.e., $0.25C_p$. This warranty is sometimes used instead of the FRW when it is felt that this will reduce warranty costs. Note that for a rebate warranty, whether or not the item is repairable is irrelevant.

Expected Cost to Manufacturer

The cost per unit to the manufacturer is sum of the production cost of the unit sold and the average refund given on failed units. The expected total cost to the manufacturer per unit sold is a function of both the manufacturer's cost C_s and the selling price of the item, C_p (for this purpose, usually taken to be the manufacturer's suggested retail price). Formulas for calculating this expected cost have been developed.[12] As before, the cost of warranty is calculated as the difference between total cost and C_s.

Expected Cost to Consumer

The cost per unit to the consumer is the sale price minus any refund resulting from a warranty claim. An expression for the expected net cost to the consumer has also been derived.[13]

---

[12] The expected cost to manufacturer is given by Blischke and Murthy [1], p. 172. The result is

$$Average\ cost\ per\ unit = C_p + C_b[F(W) - \mu_W/W]$$

where $\mu_W = \int_0^W xf(x)dx$ is the partial expectation of X.

[13] The result is

Example 7.3
An automobile battery is sold with a four year pro-rata warranty. We consider the warranty cost associated with the initial sale. Thus whether or not the warranty is renewing is irrelevant and we may consider this to be a rebate warranty. The relevant cost elements are the cost of providing the item and the expected amount of the rebate (which, for a renewing warranty, would actually be a discount on the purchase price of a replacement). The battery is not repairable.

Cost models have been developed for the PRW rebate warranty.[14] The models involve the costs and the distribution of time to failure. For the latter, we will assume an exponential distribution. This is appropriate when failures occur randomly throughout the warranty period, i.e., at a constant rate. This appears to be the case for some batteries. To investigate the effect of changing the warranty period, we consider warranties of length $W = 1.5, 2, 2.5, 3, 4$, and 5 years.

For the rate parameter in the exponential distribution, we use values corresponding to median times to failure of 4, 5, 6, and 7. (One-half of the batteries will fail prior to the median and one-half after this value. The equivalent MTTF in each case is 1.443 times the median.) Note that many failures may be expected to occur during the warranty period for the longer warranties and/or shorter MTTFs. On the other hand, the cost of many of these will not be large, since they will occur near the end of the warranty period. In practice, the long warranties would not be offered on a short-lived item.

The expected cost to the manufacturer of a warranty of length W is of the form $C_s + K_W C_p$. It is a function of the buyer's cost C_p since the rebate is based on this value. K_W may be thought of as the long-run average proportion of rebate given for items that fail under warranty. Values of K_W for all combinations of the selected median times to failure and warranty periods are given in Table 7.3. From the table, we see that for a battery with a median life of 4 years and a two-year warranty, $K_W = 0.1549$, i.e., the cost of the warranty is $0.1549C_p$. Thus if the total cost of the battery to the manufacturer is \$45 and it sells for \$75, the cost to the manufacturer, including warranty, is \$45 + (0.1549) × 75 = \$56.62. For a four-year warranty on the same battery, this total cost would be \$65.90.

In each of these numerical examples, the manufacturer would realize an overall profit on the transaction. One can easily see that other combinations of cost structure, warranty terms, and product reliability (as expressed in median time to failure), would lead to losses because of the relatively high cost of the warranty. In fact, profitability can be expressed in terms of K_W. The result is that in order to realize a profit, we must have the ratio C_s/C_p less than $(1 - K_W)$. Thus a four-year battery with a two-year warranty will be profitable as long as C_s/C_p is less than 1 –

$$\textit{Expected cost to consumer} = C_b\left[\frac{\mu_W}{W} + 1 - F(W)\right]$$

[14] See Blischke and Murthy [1], Section 5.2.1. The relevant cost model for the exponential distribution, namely the first formula on the top of page 175 of the book, is missing a term. The correct result is

$$E[C(W)] = C_s + C_p[1 - (1 - e^{-\lambda W})]/\lambda W$$

0.1549 = 0.8451, i.e., as long as the manufacturer's cost is less that 84.1% of the selling price.

We note the following regarding the battery example:

- For a renewing warranty of this type, this rebate would only be provided as a discount on the purchase price of a replacement, which would then be covered under warranty, thus retaining the buyer as a customer. This has been used as a marketing strategy.
- Actual battery warranties are usually renewing and have traditionally been PRW policies. At present, most manufacturers are offering a combination warranty, with free replacements provided for an initial period of six to eighteen months, and replacement at pro rata cost for the remainder of the warranty period. The cost to the manufacturer of this warranty would be somewhat higher because of the free replacement feature.
- In this example, we have used the exponential distribution to model failures. This is appropriate in situations where age has no effect on the failure rate, which is a reasonable assumption for batteries, at least in the earlier part of their useful life. (If batteries tended to fail more frequently near the end of the warranty period, a failure distribution that can model an increasing failure rate, such as the Weibull, would be more appropriate.) Computations in this case are somewhat more complex.[15] For the Weibull, the general pattern of the results would be essentially the same, but the cost factors K_W would be somewhat smaller, reflecting the fact that smaller costs are incurred for longer-lived items. In practice, it is important to select the failure distribution carefully and to study the effect of alternative choices.

Table 7.3. Factors K_W for calculating manufacturer's cost of PRW policy

Median time to failure (years)	***W* (years)**					
	1.5	**2**	**2.5**	**3**	**4**	**5**
3	0.1548	0.1992	0.2403	0.2787	0.3473	0.4070
4	0.1194	0.1549	0.1884	0.2202	0.2787	0.3311
5	0.0971	0.1266	0.1548	0.1818	0.2324	0.2787
6	0.0818	0.1071	0.1314	0.1549	0.1992	0.2403

■

7.4.3 Cost Analysis of the Non-renewing Two-dimensional FRW

A very common automobile warranty at present is a 3-year/36,000 mile "bumper to bumper" FRW. Under this warranty, all failed items (except for normal wear and tear) are repaired or replaced at no cost to the buyer as long as the failure occurs within three years of purchase of the automobile *and* the odometer shows less than 36,000 miles. The warranty expires when either the age or usage limit is reached.

[15] See Blischke and Murthy [1], Example 5.2, p. 176.

This type of warranty is used in virtually all new car sales, on many other motorized vehicles (e.g., trucks, motorcycles), and on other items on which both age and usage can be recorded and tracked. Other examples of two- and higher-dimensional warranties involve age and/or usage plus characteristics such as fuel efficiency, noise (e.g., of aircraft), and so forth. For the general warranty of this type, we use *W* to denote the age limit and *U* the usage limit of the warranty.

As noted in Section 7.3.2, there are two approaches to modeling two-dimensional warranties, based on one-dimensional and two-dimensional representations of the failure distributions. In the example below, we will use the one-dimensional approach, which assumes that usage is linearly related to age of the vehicle, with the ratio of usage and age varying randomly in the population. The expected cost of warranty depends on the distribution of this ratio and on the structure of the warranty, in this case assumed to be an FRW policy. Cost models have been developed for this and a number of other two-dimensional warranties under various distributional assumptions.[16]

Example 7.4

In studying the cost of warranty, an automobile manufacturer wishes to predict costs as a function of warranty terms. In the analysis, *W* is measured in years and *U* in units of 10,000 miles. We take $W = U$ and consider values of $W = U = 2, 3, 4$, and 5. These correspond to warranties of 2 years/20,000 miles, 3 years/30,000 miles, and so forth.

We consider the following three cases.

<u>Case 1 [Light usage]</u>: The usage rate is randomly distributed uniformly over the interval zero to one. This implies that the average usage rate is 0.5 or an average usage of 5,000 miles per year. Here all the customers are light users with usage varying from 0 to 10,000 miles per year.

<u>Case 2 [Light and medium usage]</u>: The usage rate is randomly distributed uniformly over the interval zero to two. This corresponds to half of the customers being light users, with average usage 5,000 miles per year, and the other half being medium users with usage varying from 10,000 to 20,000 miles, and an overall average usage rate of 15,000 miles per year.

<u>Case 3 [Light, medium and heavy usage]</u>: The usage rate is randomly distributed uniformly over the interval zero to three. This corresponds to 1/3 of the customers being light users with average usage of 5,000 miles per year and 1/3 of customers are medium users with an average usage of 15,000 miles. The remaining 1/3 are heavy users, with usage varying from 20,000 to 30,000 miles and an average usage of 25,000 miles per year.

We use the one-dimensional approach to modeling failures over time. The rate of occurrence of failures (ROCOF) conditional on usage rate, is a linear function of age, usage and usage rate.[17]

---

[16] See Blischke and Murthy [1], Chapter 8, and Blischke and Murthy [2], Chapters 13 and 14.

[17] Conditional on the usage rate being *r*, the ROCOF is given by $\lambda(t.r) = \theta_0 + \theta_1 r + \theta_2 t + \theta_3 rt$, where the θ 's are the model parameters. The usage rate is assumed to be distributed uniformly over the interval $[a,b]$. The expected warranty cost is given by

Table 7.4 gives the expected number of warranty claims under warranty for the three cases for $W = U = 2, 3, 4$, and 5. This can be used to predict warranty costs. Suppose, for example, that a car is sold at \$18,000 with a 3 year/30,000 mile warranty, and that on average the repair cost \$200 per claim. Then from Table 7.4, the total expected cost of warranty is calculated to be \$200(0.825) = \$165 or 0.92% of the sale price of the car for Case 1 and this changes to \$200(2.549) = \$509.8, or 2.83% of the sale price of the car for Case 3. If the warranty is increased to 5 years/50,000 miles, the average warranty cost for Case 3 increases to \$200(5.781) = 1156.2 or 6.42 of the sale price.

■

Table 7.4. Expected number of warranty claims
Two-dimensional free replacement warranty

Case	$W = U$			
	2	**3**	**4**	**5**
1	0.450	0.825	1.350	2.025
2	1.027	1.831	2.982	4.363
3	1.423	2.549	3.952	5.781

7.5 Life Cycle Cost Analysis

In looking at the long term, we are interested in the cost over a life cycle of length L. As noted in Section 7.3, a life cycle may be defined in a number of ways. In the case of a manufacturer, for instance, a common interpretation of this concept is that it is the total period from inception of a product until its withdrawal from the marketplace. In this case, life cycle cost would include all upfront costs in planning, design, testing, and so forth, all production and distribution costs, warranty costs, and many others. For a consumer, the life cycle cost may be the total cost of ownership of an item, including acquisition costs, purchase price, costs of operation and maintenance, and so forth. Alternatively, it may be the total cost associated with repeat purchases over a specified longer period of time. Here we look briefly at the latter case and consider only the warranty component of the cost over a life cycle.

In modeling the life cycle cost of warranty, we will use $C_b(L, W)$ and $C_m(L, W)$ to denote the life cycle cost to the buyer and to the manufacturer, respectively. These costs are functions of W, the length of the warranty period, and of L, which we take to be greater than W. They are also functions of the other terms of the warranty (FRW, PRW, etc.), the distribution of time to failure of the item, and the way in which the life cycle is defined. In connection with the last, we will look at the two definitions given in Section 7.3.

$$E[N(W,U)] = [\theta_0 + \theta_2 W^2/2](\gamma - a) + [\theta_1 + \theta_3 W^2/2][(\gamma^2 - a^2)/2]$$
$$+ [\theta_0 U + \theta_3 U^2/2]\log(b/\gamma) + \theta_1 U(b - \gamma) + 0.5\theta_2 U^2(b - \gamma)/b\gamma$$

For the numerical example, we assume $\theta_0 = \theta_1 = \theta_2 = \theta_3 = 0.1$.

7.5.1 Life Cycle Cost, Non-renewing FRW Policy

We consider a non-repairable product, so that failed items must be replaced by new ones. Under the non-renewing FRW, the first failure after expiration of the warranty results in a new purchase by the buyer and this comes with a new identical warranty. The time intervals, say *Y*, between successive repeat purchases, with the first purchase occurring at $t = 0$, are the key units in the analysis. The *Y*'s are of the form $Y = W + Z$, where *Z* is the remaining life of the item in use at the expiration of the warranty. Thus, after the initial sale, the manufacturer incurs the cost of all replacements until time $W + Z$, receives income from a new sale at this time, and the cycle begins anew, ending when the total length of time reaches *L*. The buyer, on the other hand, during the initial warranty period has only the initial cost of purchasing the item, C_p, with the next cost, also in the amount C_p, occurring at time $W + Z$, and so on.

As a result, the cost analysis from the buyer's point of view is based on renewals associated with the variable $W + Z$, and cost models involve the distribution of this variable. For the manufacturer, the cost involves the distribution of time to failure of the item, with incomes equivalent to the cost to the buyer. Expressions for the buyer's and seller's expected life cycle costs for the FRW have been derived.[18]

Example 7.5

A high-intensity lighting system is installed in a parking facility. Each unit contains a bulb with a purchase price of $C_p = \$100$. The bulb is warrantied for $W = 1$ year and the buyer is interested in a life cycle for the system of 15 years. Suppose that the total cost to the manufacturer of supplying a bulb to the buyer is $60 per unit.

We will assume that the distribution of time to failure of the bulb is exponential with a mean time to failure of MTTF = 2.0 years. From the cost model analysis, it is found that the buyer can expect to make an average of 5.722 purchases over the 15-year life cycle, at a total expected cost of $572.20. During this period, the manufacturer will be required to supply a total of 8.58 items, on average, including free replacements under warranty. The total expected cost to the manufacturer is $514.98, giving an expected profit per initial unit sold of $57.22 over the life cycle of the product.

Suppose now that the reliability of the bulb is increased and that this results in an increase of the MTTF 2.5 years. In this case, the total cost to the buyer becomes $504.10 and the total cost to the manufacturer is reduced to $423.44, resulting in a profit of $80.65. We conclude that, in this example, the increase in reliability results in an increase in expected profit per unit. A few comments on this:

- Here we are looking at a 25% improvement in MTTF. Many changes, e.g., reengineering, improvements in production, raw materials, and so forth, may be required to achieve the corresponding increase in reliability. The cost could be significant and must be less than the calculated increase in profit.

---

[18] See Blischke and Murthy [1], Section 4.5.1 for buyer's life cycle cost and Section 4.5.2 for seller's profit. Seller's cost is the difference between the two.

- If a significant improvement in reliability is achieved, the manufacturer may be able to sell the bulb at a higher price and still remain competitive.
- Changes made in production and other areas may affect cost in other ways as well. A systems analysis to investigate the impact of these is appropriate.

■

7.5.2 Life Cycle Cost, Non-renewing PRW Policy

For this policy, warranty costs involve refunds to the consumer for claims occurring within the warranty period. Expressions for the expected life costs for the manufacturer and consumer have been derived.[19] Many of the results are quite complex, and we forego a detailed discussion. As with per unit costs, however, life cycle expected costs to the manufacturer for the PRW are much less than those of the FRW. Correspondingly, they are much higher for the buyer.

7.5.3 Life Cycle Cost – Dynamic Sales Model

Another approach to life cycle costing is to consider manufacturer's warranty costs with sales occurring over time. In order to compute the cost, it is necessary to model dynamically the product sales over the life cycle of the product. This includes both first and repeat purchases for the total consuming population. It is assumed that the life cycle L exceeds W, the warranty period, and that items are put into use immediately after they are purchased. Since the manufacturer must provide a refund or replacements for items that fail before reaching age W, and since the last sale occurs at or before time L, the manufacturer has an obligation to service warranty claims over the interval $[0, L+W)$.

Models of this type for life cycle costs for non-renewing versions of both the FRW and PRW have been developed.[20] The usefulness of these results is that models characterize more features of the sales and warranty processes and thereby may provide realistic results, particularly from the manufacturer's point of view.

References

[1] Blischke, W. R., and Murthy, C. N. P. (1994). *Warranty Cost Analysis,* Marcel Dekker, New York.

[2] Blischke, W. R., and Murthy, D. N. P. (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

---

[19] See Blischke and Murthy [1], Section 5.4.
[20] See Blischke and Murthy [1], Chapter 9.

[3] Murthy, D. N. P., Xie, M, and Jiang, R. (2003), *Weibull Model*, John Wiley and Sons, New York.

[4] Johnson, N. L. and Kotz, S. (1972), *Distributions in Statistics: Continuous Multivariate Distributions*, John Wiley and Sons, New York.

[5] Hutchinson T. P. and Lai, C. D. (1990), *Continuous Bivariate Distributions, Emphasizing Applications*, Rumsby Scientific Publishing, Adelaide, Australia.

[6] Hill, V. L., Beall, C. W., and Blischke. W. R. (1991), "A simulation model for warranty analysis," *International Journal of Production Economics* **22**, 131–140.

[7] Blischke, W. R. and Murthy, D. N. P. (2000), *Reliability: Modeling, Prediction, and Optimization*, John Wiley and Sons, New York.

[8] Meeker, W. Q. and Escobar, L. A. (1998), *Statistical Methods for Reliability Data*, John Wiley and Sons, New York.

[9] Bulmer, M., and Eccleston, J., "Photocopier Reliability Modeling Using Evolutionary Algorithms," Chapter 18 in Blischke, W. R., and Murthy, D. N. P. (2003), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

8

Warranty Considerations in Product Design and Development

8.1 Introduction

In Section 4.3 we indicated that the product life cycle involves two stages (pre-launch and post-launch) and that the pre-launch stage involves three phases as shown in Figure 4.3. In Section 5.4 we discussed the front-end [Phase 1]. As indicated in Figure 5.5, the outcome of Phase 1 is defined target values for product features, warranty terms, customer satisfaction, etc., that are needed for achieving desired business objectives. Determining the target values requires building models that capture the interactions between the different variables of importance.

Product features can be divided into two categories – reliability and non-reliability related features that need to be defined in the front-end. The non-reliability features are product specific. For example, in the case of an automobile these can be engine efficiency, environmental impact, ride characteristics etc. In this and the next chapter we focus our attention on reliability related features.

Product failures over the warranty period and over the remaining useful life depend on the reliability of the product. The warranty cost, in turn, is dependent on the number and severity of failures over the warranty period. In Chapter 7 we discussed models linking warranty cost and product reliability. Also, customer satisfaction depends on failures over the warranty and post-warranty periods and this is discussed in Chapter 10. This implies that product reliability is very important in the context of product warranty.

Product reliability depends on the decisions made during the Design and Development [Phase 2] and the Production [Phase 3] of the product. As the reliability improvement effort is increased, the reliability increases. This results in a decrease in the warranty cost, but this is achieved at the expense of increased development cost, as shown in Figure 8.1. This implies that in the front-end one needs to take into account the link between warranty cost and development cost in crafting strategies that define the targets for product warranty and product development.

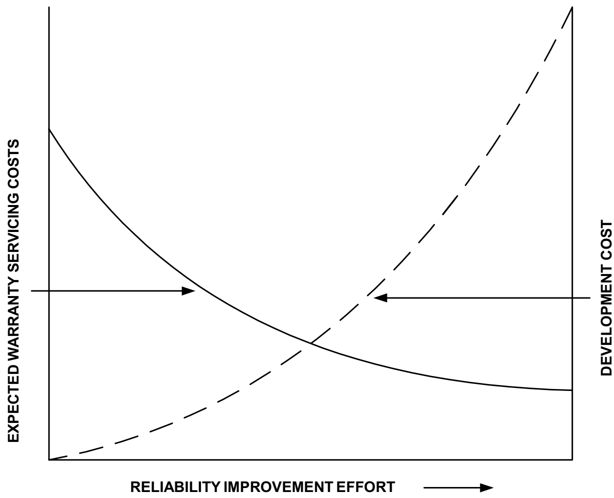


Figure 8.1. Reliability improvement effort

In this chapter we look at making reliability related decisions during the design and development phase of the product life cycle based on the warranty decisions made in the front-end phase. We start with an overview of the design and development process in Section 8.2. The process begins with conceptual design and then proceeds to detail design. The various issues that impact on reliability related decision-making for these two stages of product design are discussed in Sections 8.3 and 8.4 respectively. Reliability issues in the context of development are discussed in Section 8.5. Section 8.6 gives some illustrative examples.

8.2 The Design–Development Process

The design and development process is shown in Figure 8.2. The starting point for the Design and Development phase of product life cycle is the output of the front-end phase that defines the products features. Note that there are no explicit statements about product reliability. However, statements such as warranty costs, development cost and customer satisfaction are related to product reliability.

The design process evolves with increasing levels of detail, starting at the product level and ending at the component level. These can be broadly grouped into two sub-stages: (i) conceptual design and (ii) detailed design as indicated in the top half of Figure 8.2. The starting point of the design process is definition of the reliability specification. This must be done in a manner so that the stated performance target requirements (such as warranty costs below a specified value) are met. Following this, different design options are examined as part of the conceptual design activity and a decision is made regarding which option is to be pursued further. Once this is done, the detail design commences and reliability targets at the lowest component level are derived from the reliability at the product level.

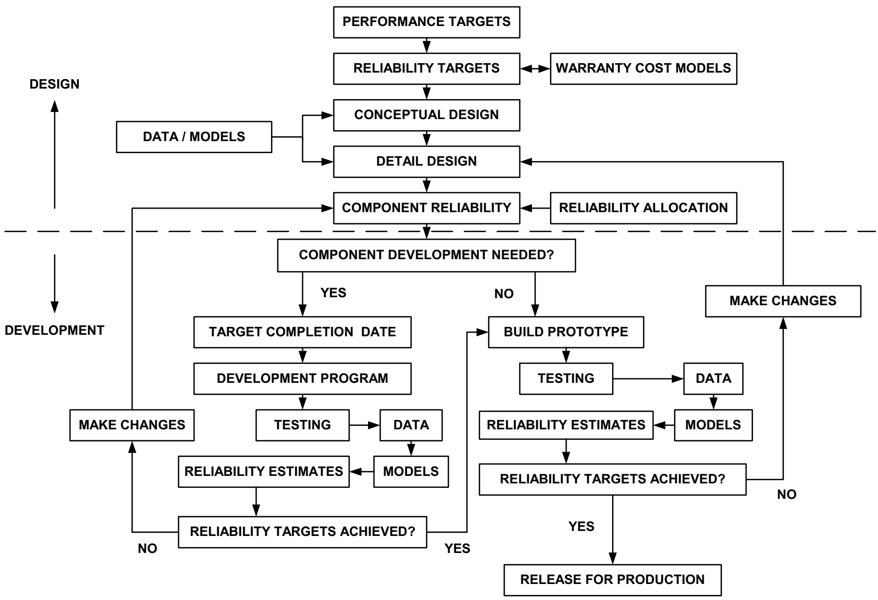


Figure 8.2. Design and development process

The development process is shown in the bottom half of Figure 8.2. If the component reliability target exceeds that possible with current technologies, then a development program to achieve the targets through improvements to the component is needed. Development is an iterative process involving making changes based on test data. Once the component reliability targets are achieved, or no component development is needed, then a prototype is built. Here again, changes as indicated in Figure 8.2 may be necessary in order to achieve the desired reliability at the product level.

8.2.1 Product Performance / Specification

Product performance and product specification are central to any design process and in this sub-section we discuss them briefly.

8.2.1.1 Product Performance

Many different definitions of product performance can be found in the technical literature as illustrated by the following sample:

- "Product performance is the measure of function and behavior – how well the device does what it is designed to do." [1]
- "Product performance is described as the response of a product to external actions in its working environment. The performance of a product is realized through the performance of its constituent components." [2]

When one considers product performance, one must also consider properties such as form, durability, price, and so forth. 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 (dimensions, surface, tolerance, etc.), internal properties (corrosion properties, durability, strength, etc.) and/or external properties (function, economic properties, ergonomics, conformance, etc.).[1]

8.2.1.2 Product Specification

Similarly, many different definitions of specification can be found in the literature as illustrated by the following sample:

- "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."[2]
- "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" [4].

8.2.1.3 Relationship between Performance and Specification

Performance and specifications are strongly interlinked, and play a central role in the new product development (NPD) process. There are two kinds [forward and backward] of relationships between performance and specification as indicated below [5].

- *Forward Relationship [Performance to Specification]:* The desired performance (DP) outlines *what* is to be achieved in the NPD process. The specification (SP) 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

---

[1] For further discussion on design, internal and external properties, see Hubka and Eder [3].

[2] British Standards: BS 5760-4 (1986). Figure 1 lists reliability content of the following specifications in the overall life cycle context of context of new products: Target Specification, Function Specification, Product Specification, Materials Specification, Process Specification, Inspection Specification, Test Specification, Acceptance Specification, Handling, Storage and Transport Specification, Installation Specification, Use Specification (Manual), Maintenance Specification (Manual), and Disposal Specification (Manual)

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 (AP) 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 specifications leads to a unique actual performance of the product.

In general, the design process involves several sub-phases. For sub-phase i, the desired performance DP_i (for the object under consideration) serves as the input for deriving the specification SP_i that 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, 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 8.3. This process repeats at an increasing level of detail as one proceeds through the design process.

8.3 Conceptual Design

Conceptual design deals with two activities that are to some extent inter-linked. These are (i) the reliability specification at the product level (or product reliability) and (ii) alternate design options that will achieve the desired product reliability. It is important to note that at this stage, one is looking at product performance rather than just reliability. However, as mentioned earlier, our focus is on reliability.

8.3.1 Product Reliability Specification

The process of deriving product reliability specification has as its input the output from the front-end phase and is shown in Figure 8.4. Some consequences of the link between the reliability related performance and reliability specification are:

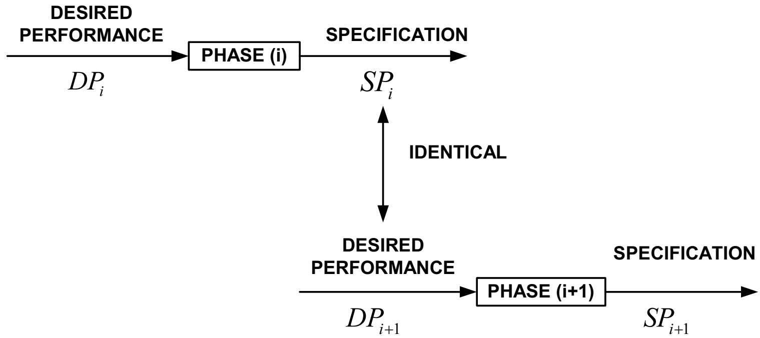


Figure 8.3. Specification–performance link

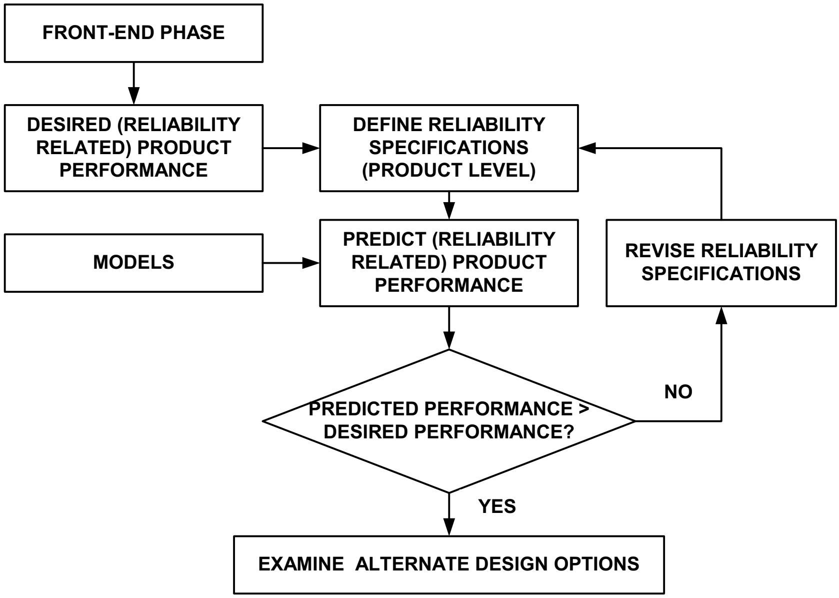


Figure 8.4. Reliability specifications [product level]

- One notion of customer dissatisfaction is product failure very soon after purchase, for example, failure with a period t_1 subsequent to the purchase. The reliability of the product is the probability that the product will not fail within a specified period. If the outcome of the front-end is a statement that the fraction of dissatisfied customers needs to be less than an upper limit p, then this translates into the requirement that the reliability of the product for period t_1 be greater than $(1 - p)$.
- Customer dissatisfaction is high should the product fail within a short period after the warranty expires. To ensure high customer satisfaction, one might specify an upper limit p_1 on the probability of such a failure. This translates into a reliability specification that the conditional reliability given that the item is of age W (the warranty period) is greater than $(1 - p_1)$.
- Warranty costs depend on the number of failures (a random variable) over the warranty period. The average warranty cost per unit needs to be less than some specified value δ. This translates into a reliability specification requirement that the expected number of failures over the warranty period be less than δ/C_r where C_r is the average cost of each repair. (Note that the expected number of failures over the warranty period depends on product reliability as well as on the type of repair strategy used.)
- Complex product failures are repaired through minimal repair. A requirement that the expected number of failures per unit time over the useful life be less than ν, translates into a reliability specification requirement that the ROCOF be less than ν over the useful life.

- The mean time between failures (MTBF) must be greater than some specified value to ensure a desired level of availability.[3]

Once the specifications have been stated, one can use models to determine the predicted reliability performance. Models for warranty cost analysis are discussed in Chapter 7. If the predicted performance is lower than the desired performance, then one needs to revise the specifications as indicated in Figure 8.4.

8.3.2 Alternate Design Options

During conceptual design, the capabilities of different design approaches and technologies are evaluated. The aim is to ensure that a product that embodies these design features is capable of meeting all the performance targets and the cost limits on unit manufacturing cost defined in the feasibility stage, while taking into account the manufacturability issues. During this stage, the objective is to decide on the best design approach in fairly general terms – the structure for the product, the materials and technologies to be used, and so on. This involves a study of the following issues:

- Technology implications
- Research and development (R&D) implications
- Trade-off studies
- Project costs and feasibility
- Manufacturing implications
- Technical risks.

Design trade-off studies examine alternative designs with the goal of choosing the best, taking into account costs and risks, with the latter being especially important when the design involves new and untested technologies.

The outcomes of conceptual design are not only the reliability specification at the product level but also an indication of the possible reliability development implications, the constraints (time and cost) and the technologies needed. Decision-making at this point not only requires models but many different kinds of data as well, as indicated in Figure 8.5.[4]

---

[3] A popular approach to setting the desired reliability performance based solely on a single number, such as MTBF, is inappropriate and has been criticized in the literature (see, e.g., Wang [6] and Moss [7].

[4] The reliability of automobiles has improved continuously over time. For the year 2003, consumers cited 133 problems per 100 new autos, compared with 176 per 100 in 1998 [8]. This has led to a reduction in the warranty servicing income for dealers, viz. [9]:

- Auto dealerships across the country have seen an estimated 20% decline in their warranty business in 2002 and up to a 50% drop since 1998.
- For GM, the overall new-vehicle quality – based on the number of customer complaints – improved 10% in 2002 and 24% since 1998.
- For Ford, the warranty cost fell 25% in 2002.
- For Chrysler Group, the warranty cost fell by 21% in 2002 and by 50% since 1997.

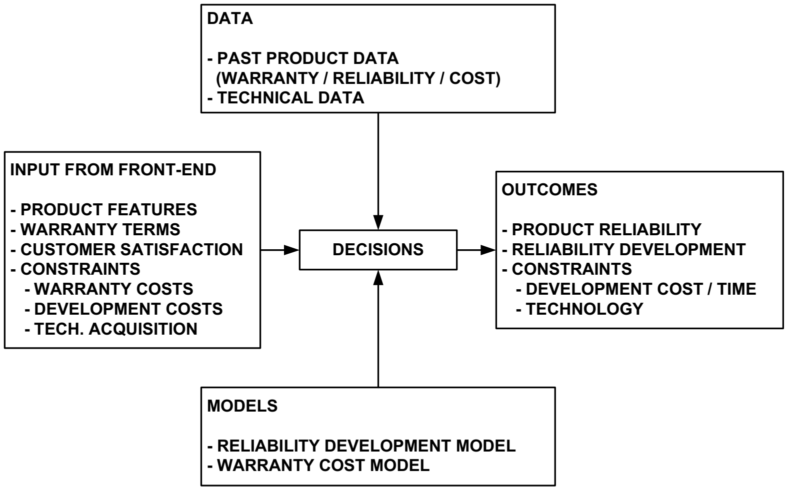


Figure 8.5. Concept design outcomes

8.4 Detail Design

The detail design begins with an initial design concept (obtained from the output of conceptual design) that is further elaborated down to the component level. This requires linking performance at each sub-phase to specifications as indicated in Figure 8.3. Note that the specification at a sub-phase defines the performance required at the subsequent sub-phase. This process is carried down to the lowest component and/or material level.

The process of deriving the reliability specification is shown in Figure 8.6. It is an iterative process where one needs to iterate back to alter the specifications at earlier phases if the desired performances are not achieved. Once the detail design process is completed, then the designer can evaluate the overall product reliability by building models before a prototype is built.

8.4.1 Reliability Allocation

The reliability specification process involves deriving the specifications at each sub-phase in terms of the reliability at the earlier sub-phase. This process is repeated down to the component level and yields the desired reliabilities for the various components. The product reliability is a function of these assigned component reliabilities. Reliability allocation is a term used to indicate this assignment of reliabilities to the various components. How this is executed depends on the design of the product, but must be done in a manner that ensures design feasibility and is consistent with current technology. Also, it must be done in such a way that constraints (cost, time, etc.) are not violated. There are a number of reasons for the use of reliability allocation in designing the reliability of a system. The two most important of these are: (i) it forces the designer to understand and develop the relationship between component, sub-system, and system reliabilities and (ii) the designer can consider reliability in a framework that incorporates other issues, such as cost, physical dimensions, weight, etc., in the design process.[5]

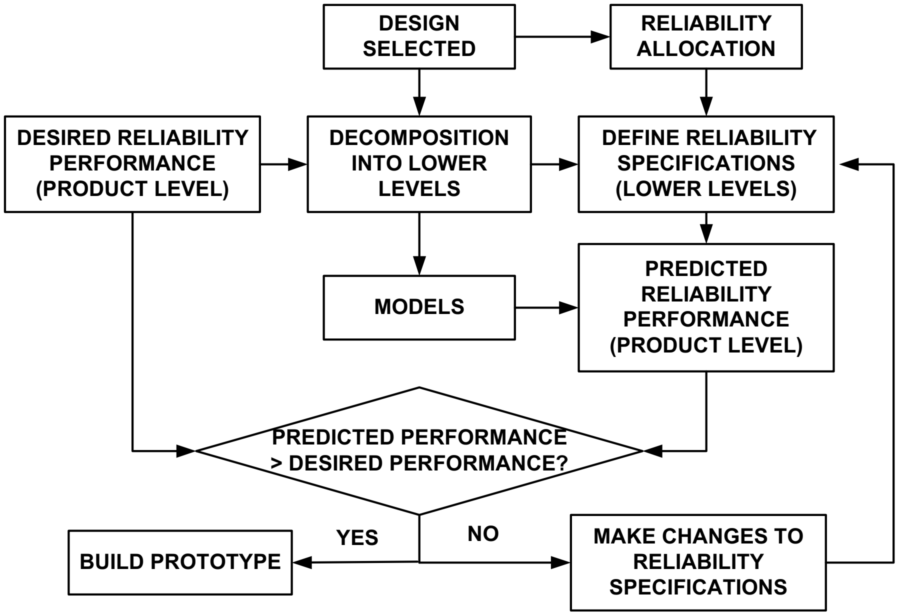


Figure 8.6. Reliability specifications [component level]

8.4.2 Achieving Desired Component Reliability

The assigned component reliability can be achieved through one or more of the following approaches:

1. Redundancy
2. Preventive Maintenance
3. Research and Development.

We briefly discuss the first two approaches. The last will be discussed in the next section.

8.4.2.1 Redundancy

Redundancy is a design technique under which one or more components are replicated to improve the reliability of the product. For a component that is replicated we have a module of *k* (where *k* is 2 or more) identical (or functionally similar) components instead of a single component. The three different types of redundancy that have been used are (i) hot standby, (ii) cold standby and (iii) warm

[5] For more details, see Kapur and Lamberson [10].

standby. In hot standby, all *k* replicates are connected in parallel and are in use. The module fails when the last working component fails. In cold standby, only one component is in use at any given time and the rest are used as spares. When a working component fails, it is replaced by a spare (if available) through a switching mechanism. The module fails when there are no spares left. Warm standby is similar to cold standby except that the spares are partially energized in contrast to not being energized. This is used for items that take some time to reach operational state from rest.

Redundancy involves replication and might not be appropriate if it leads to violation of one or more design constraints (such as weight, volume or functional). Another complicating factor in the case of both cold and warm standby redundancy is the unreliability of the switching mechanism. If the switch reliability is low, then this type of redundancy might not be a good strategy to improve product reliability.

8.4.2.2 Preventive Maintenance

Component reliability decreases with age and as a result, it can fall below the desired value. In Figure 8.7 the curve labeled "current" denotes this for the component under consideration. The dotted line defines the lower limit for the desired reliability. As can be seen, the desired reliability is not achieved.

Preventive maintenance (PM) actions are used to control component degradation and reduce the likelihood of failure. Actions such as replacement or reconditioning increase the reliability. PM actions can be used effectively to ensure desired reliability as shown in Figure 8.7. Addressing the maintenance issues in the design stage is called *maintainability*.[6]

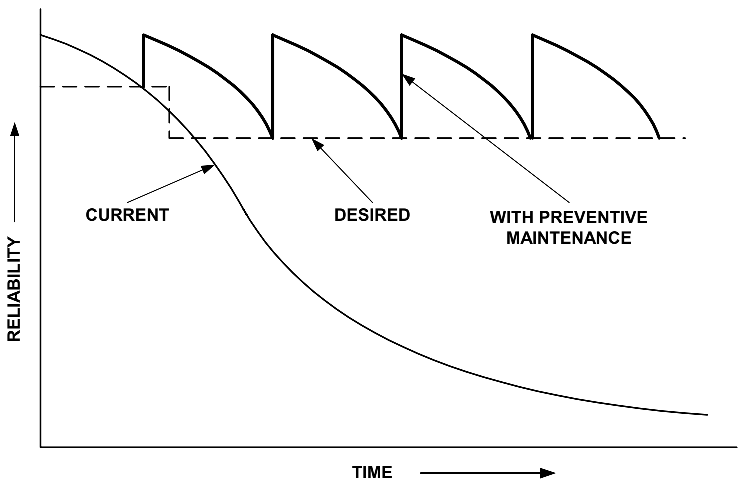


Figure 8.7. Maintenance and reliability

[6] For more on maintainability, see Blanchard *et al.* [11].

Achieving desired reliability through PM actions does not suffer from the functional constraints that might negate the use of redundancy. However, it suffers from other shortcomings. One is that it requires periodic interruptions to the operation of the product and increases the operating costs (and reduces availability) to the customer. Through proper design, the downtime resulting from an interruption can be kept within reasonable limits.

8.4.3 Additional Topics

Some other topics that need to be addressed at the end of the design stage are the following:

Final design review: The final design review is a review of the final product design usually carried out by an independent group. The group acts as an auditor to critically evaluate all aspects including reliability. Final design review seeks answers to questions of the form:

- 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 during production (such as reversed wiring for an electronic product or mis-assembly for a mechanical product)?[7]

Risk analysis: A major part of designing for reliability is to predict the potential effects of failures. The failure of the product is related to failures at the component level. Two design techniques for understanding the link between component failures and product failures and their consequences are (i) Fault Tree Analysis (FTA) and (ii) Failure Mode Effects and Criticality Analysis (FMECA).[8] These are discussed briefly in Section 5.6.3.

FMECA is usually carried out during the design phase. The objective is to reveal weaknesses and potential failures. This enables the design engineer to make appropriate modifications that may reduce the likelihood of failures and/or the seriousness of their consequences. This is important as the cost of fixing a design error increases by a factor of 10 if it is detected during production phase and by a factor of 100 or more if detected during post-sale phase.

Planning product development: This is needed to ensure that the research and development projects that are needed to achieve the desired reliability can be carried out in an effective manner and within the time and cost constraints. These require models to predict reliability growth as a function of time and development effort for proper planning.

Figure 8.8 outlines the outcomes of the detail design process. An important

---

[7] IEC 61160 (1992) provides guidance for carrying out formal design reviews.

[8] FMEA has received a lot of attention in the automotive industry. See Dale and Shaw [12] and Johnson and Khan [13].

issue to note is the kind of data needed for model building to assist in the decision-making process.

8.5 Development Process

As seen in Figure 8.2 the development process involves component-level development followed by the building of a prototype. As the process moves forward, new data are obtained through testing. This allows one to estimate (or predict) the actual reliability (from component level upwards to product level) and check it against the desired reliability. If the actual reliability does not meet the desired reliability, then one needs to iterate back as indicated in the figure. In this section we look at a variety of topics relevant to the development process.

8.5.1 Component-level Development

The improvement in component reliability is achieved through a Test-Analyze-And-Fix (TAAF) program in an iterative manner, where during each iteration, the different steps are executed sequentially, as shown in Figure 8.9.

The process begins with the testing of a manufactured component, usually under increasing levels of stress. Should failures occur, the failure data, including modes of failure, Total Time to Failure (TTF), and any other relevant information, are collected and analyzed by engineers to discover the causes of failure. Corrective actions are then taken to reduce the frequency of future failures. This process is repeated until the test results are satisfactory. It is very important that, in such programs, all failures are analyzed fully, and action is taken in design or production to ensure that they do not recur.

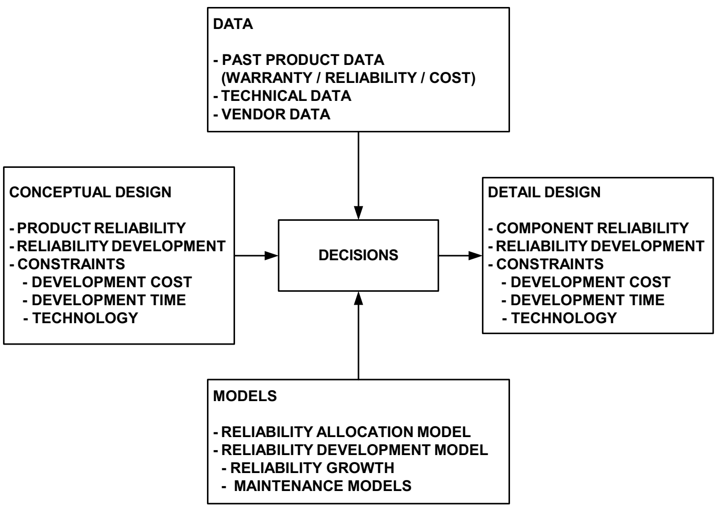


Figure 8.8. Detail design outcomes

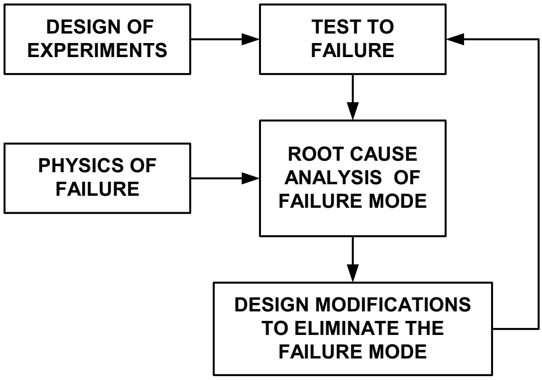


Figure 8.9. TAAF cycle

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.

8.5.2 Product-level Development

Here the focus is on building a prototype and comparing the actual with the desired reliability performance. This involves testing at several intermediate levels during the construction of the prototype and is very similar to that at the component level.

8.5.3 Development 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 with design requirements. Properly designed tests are critical to obtaining the maximum information about 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 then analyzed and fixed during the development process.

Environmental and design limit yesting: 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. These tests are to assure that the product performs at the extreme conditions of its operating envelope.

Accelerated life testing: When a product is very reliable, it is necessary to use accelerated life tests to reduce the time required for testing. This involves putting items on test under environmental conditions that are far more severe than those normally encountered. In order to conduct and analyze an accelerated life test, an understanding of the relationship between environmental conditions and their impact on product failure is necessary.[9]

8.5.4 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. 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.

8.5.5 Reliability Assessment

Assessment of the reliability of a part, component, or prototype requires the development of adequate and appropriate test plans, completion of the tests, and proper analysis of the resulting data. If properly done, the output of this process will be a statistical estimate of the reliability of the product under specified conditions of operation. This was discussed in Chapter 6.

Modeling plays a very important role in reliability assessment and prediction. Here the models needed are

- Physical models of failure, if possible
- Probabilistic models of time to failure, usually at the part, component and other levels up to the system model
- System models relating system performance to that at the subsystem and lower levels.

Finally, since the final result is data based, uncertainly in this result must be recognized. Statistical methods such as confidence intervals and other techniques given in Chapter 6 are used for this purpose.

8.5.6 Decision Problems

Figure 8.10 shows the outcome of the product development sub-phase. Inputs to the decision process are the detailed design, including reliability goals and constraints, initial data and test data, and models as discussed above. After analysis of all relevant data, decisions are made regarding product performance expectations, prototype construction and testing and production specifications.

In this process, it is important to keep in mind the limitations of the models used, reliability of the data collected, validity of the assumptions made, and any

[9] For an overview of accelerated testing models, see Caruso and Dasgupta [14].

other aspects of the process that may lead to uncertainty in the results and the decisions made.

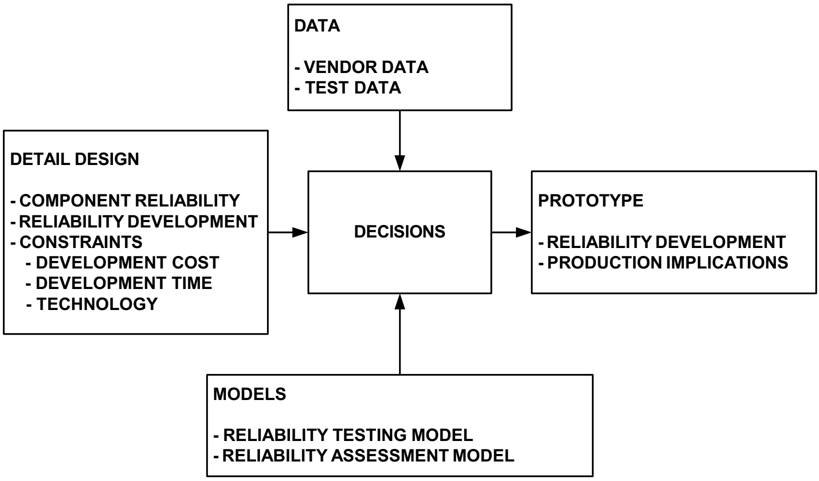


Figure 8.10. Product development outcomes

8.6 Some Illustrative Examples

Example 8.1 [Photocopier][10]

The paper feeder is an important element of a photocopier. The feeder uses a vacuum belt to hold and feed papers. The normal operation requires feeding one sheet at a time at set specific times. Maintaining appropriate timing, speed, vacuum pressure and gap between the paper and the platform is essential to avoid failure of the paper feeder. The following are some of the failure modes for the paper feeder:

- No paper being fed
- More than one sheet of paper fed at the same time
- Paper jam resulting in paper flow blockage
- Paper fed skewed so that the image is mis-aligned
- Paper curling so that the quality is affected.

The root causes for the failure due to paper jam are as follows:

- Paper condition
- Paper path
- Measurement control
- Environment
- Operator.

[10] For details, see Chen and Chang [15].

An on-line control system is used to reduce the occurrence of this failure mode. The control system consists of three modules – sensor, controller and actuator. The sensors (such as photo, pressure, motor current sensors) feed the data to the controller. These are processed and the output is used to adjust the settings of various factors (such as pressure, gap, timing, etc.) to improve the reliability of the feeder.

■

Example 8.2 [Automobile][11]
1995 saw the largest recall in auto history, involving nearly 9 million automobiles from model years 1986–1991 manufactured by several manufacturers (which included Honda, Nissan, Mazda, Ford, GM and Chrysler, among others), and sold in the USA. The recall was due to problems with the safety seat belts. This incident was not the result of a mandatory recall by the U.S. Highway National Traffic Safety Administration but rather a voluntary recall agreed to by Takata Corporation, the manufacturers of the seat belts, and the affected automobile manufacturers. Under the recall, owners of affected vehicles were requested to take their cars to their dealers for inspection and subsequent action of either replacement or modification of the seat belt. The potential cost of this was 1 billion dollars.

The operation of the seat belt is relatively straightforward. There are four key parts – clasp, slider, latch and locking slider. The steel clasp is inserted into the locking mechanism where it encounters a polymeric slider. The clasp forces the slider to compress a spring. The lock slider rotates counter-clockwise into locked position when the clasp becomes aligned with the male portion of the latch. When the latch is locked into the position it is prevented from rotating back. To release the belt, the release button is pushed against the locking slider so that it slides back and the latch can rotate back until the male portion of the slider no longer engages the opening in the clasp. Then the compressed spring behind the slider extends itself and ejects the clasp.

There are several modes of failure for the safety seat belt.

- Mode 1: The clasp is inserted into the receptacle, but it refuses to lock in position.
- Mode 2: A small piece of the plastic from the release button gets wedged behind the locking slider.
- Mode 3: A small piece of plastic from the release button becomes lodged in such a way that the locking slider cannot quickly slide to its fully locked position.

Once the failure modes were identified attention shifted to the degradation and eventual fracture of the release button. The button was injection molded from ABS (acrylonitrite butadiene styrene) copolymer. The failure process was identified and environmental degradation of the button was a significant factor leading to the button fragmenting. The solution to improve the reliability was to use environmentally resistant polymers (for example, acetal copolymers).

[11] Discussed in detail in Henshaw, Wood, and Hall [16].

This illustrates the point that a proper FEMA should have identified this problem. Either this was not done or the manufacturers tried to save a few pennies by not using environmentally resistant copolymers. This may have saved them a few cents per car in production costs, but in the end it cost them a very great deal more.

■

Example 8.3 [Automobile][12]

The automotive wheel bearing assembly is a collection of lubricated steel balls that roll in the outer bearing house and allow the wheel to rotate. The hub flange attaches the wheel bearing to the wheel. The bearing cap covers the portion of the anti-lock brake system (ABS) internal to the wheel bearing. A friction seal prevents contamination ingress between the cap and the outer bearing housing. The wheel bearing contains an ABS sensor to detect and transmit wheel rotation to the control unit.

There are several failure modes. One of them is the excessive noise that caused consumer inconvenience and resulted in replacements of wheel bearings under warranty for Ford. The design improvement to reduce the warranty cost involved the following steps:

- Step 1: Building a team of suitable members and obtain management commitment
- Step 2: Analysis of Ford and competitors' products to determine the "*best-in-class*" (BIC) product; Identification of failure modes
- Step 3: Failure mechanisms understood; Cost of failures quantified; BIC product evaluated for potential solutions
- Step 4: Comparison of current design with design standards; Plans to achieve design compliance
- Step 5: Bench test to reproduce failure modes; Bench test of current design
- Step 6: Strategies for design changes
- Step 7: New product design; FMEA.

The performances of the current design and target values that Ford defined for the new design were:

Performance variable	*Current*	*BIC*	*New design target*
Returns/1000 over 21 months	31.6	0.62	7
Average warranty cost per unit	\$7.40	\$0.62	\$1.40
B5 life*	38 MIS	152 MIS	120 MIS

* B5 life is such that 95% of the units will have life greater than this value. The life of the unit is measured in months in service (MIS).

The analysis of replaced units indicated a significant rusting due to contaminants (especially water) and this was confirmed by the discoloration of the

[12] For details, see Majeske, Riches, and Annadi [17].

grease. The potential root cause was ingress in two locations – entry through the ABS cap to bearing mating surface and/or the ABS sensor cap to interface. The team came up with 11 possible short-run design changes. The top ranking idea was to add a groove and an O-ring in the cap to bearing interface area. For the long run solution, the idea was to use a design similar to the BIC wheel bearing of a competitor.

■

Example 8.4 [Automobile]
Mechanical losses resulting from friction in piston assemblies, bearings and valve train account for nearly 15% of the total energy loss in an internal combustion engine [18]. The resulting wear affects the reliability and endurance life of the components involved. Lubrication is a method for controlling friction and wear by introducing a lubricating material (for example, oil) between the interacting moving surfaces.

One way of ensuring high reliability is through monitoring and operational control. Condition monitoring has received a good deal of attention [19]. In the case of an engine, severe wear can lead to its failure and the symptoms for this are smoking, consumption of oil in excess of normal consumption of around 1 qt./1000 miles), loss of power or the actual failure of a cam, piston or bearing.

The reliability aspects of tribology in this context have been studied in detail [20]. An example is an oil change to ensure reliability. This can be viewed as preventive maintenance to control degradation and possible failure of the engine.

The oil change mileage (OCM) was as short as 15 miles prior to 1910. Since then, it has increased steadily and current recommendations vary from 6000 to 7500 miles for normal service and around 3000 miles for severe service. At the same time the engine speed has increased from around 500 to 8000 rpm and the engine life has increased from 20,000 miles to around 300,000 miles [21]. The effect of OCM on engine reliability has received considerable study and it has been found that the optimum OCM is often at or near the manufacturer's recommendation.

■

References

[1] Ullman, D. G. (1997), *The Mechanical Design Process*, McGraw-Hill, New York.

[2] Zeng, Y. and Gu, P. (1999), "A science based approach to product design," *Computer Integrated Manufacturing*, **15**, 331–352.

[3] Hubka, V. and Eder, W. E. (1998), *Theory of Technical Systems*, Springer-Verlag, Berlin.

[4] Blanchard, B. S. and Fabrycky, W. J. (1998), *Systems Engineering and Analysis (3rd edn)*, Prentice Hall, Englewood Cliffs, New Jersey.

[5] Osteras. T., Murthy, D. N. P. and Rausand, M. (2003), Reliability Performance and Specifications in New Product Development, Draft Report, Norwegian University of Science and Technology, Trondheim, Norway.

[6] Wang, C. J. (1990), “Concept of durability index in product assurance planning,” *Proceedings of the Annual Reliability and Maintainability Symposium*, 221–227.

[7] Moss, R. Y. (1996), “Design for Reliability,” *Handbook of Reliability Engineering and Management*, Ireson, W. G., Coombs, C. F. and Moss, R. Y. (eds.), McGraw-Hill, New York.

[8] Evanoff, T. “Today’s cars are built to last”, http://usatoday.com/money/autos/2002-12-12-newcars_x.htm.

[9] McCracken, J. “Work declining at auto repair shops”, *Detroit Free Press*, February 14, 2003.

[10] Kapur, K. C. and Lamberson, L. R. (1977), *Reliability in Engineering Design*, John Wiley and Sons, New York.

[11] Blanchard, B. S., Verma, D. and Peterson, E. L. (1995), *Maintainability*, John Wiley and Sons, New York

[12] Dale, B. G. and Shaw, P. (1999), “FMEA in the UK motor industry: a state of the art study,” *Quality Reliability Engineering International*, **6**, 179–188.

[13] Johnson, K. G. and Khan, M. K. (2003), “A study into the use of the process failure mode and effect analysis (PFMEA) in the automotive industry in the UK,” *Journal of Materials Processing Technology*, **139**, 348–356.

[14] Caruso, H. and Dasgupta, A. (1998), “Fundamental overview of accelerated testing analytical models,” *Journal of IEST*, **41**, 16–20.

[15] Chen, Y. and Chang C. H. (1998), “Reliability improvement of paper feeder by the integrated robust design and control approach,” *Computers and Industrial Engineering*, **35**, 197–200.

[16] Henshaw, J. M., Wood, V. and Hall, A. C. (1999), “Failure of automobile seat belts caused by polymer degradation,” *Engineering Failure Analysis*, **6**, 13–25.

[17] Majeske, K. D., Riches, M. D., and Annadi, H. P. (2003), “Ford's reliability improvement process – A case study on automotive wheel bearing,” Chapter 24 in *Case Studies in Reliability and Maintenance*, W. R. Blischke and D. N. P. Murthy (eds), John Wiley and Sons, New York.

[18] Taylor, C. M. (1998), “Automobile engine tribology – design considerations for efficiency and durability,” *Wear*, **221**, 1–8.

[19] Rao, B. K. N. (1996), *Handbook of Condition Monitoring*, Elsevier, Oxford, UK.

[20] Holmberg, K. (2001), “Reliability aspects of tribology,” *Tribology International*, **34**, 801–808.

[21] Young, R. D. (2000), “Automobile reliability, maintainability and oil maintenance,” *Proceedings of the Annual Reliability and Maintainability Symposium*, 94–99.

9

Implications of Warranty on Production Decisions

9.1 Introduction

As mentioned in Section 2.3, there are several notions of quality. Two of these are performance and conformance. Product performance is, in general, multi-dimensional, with some elements being related to product reliability and others not. As discussed in Chapter 8, this forms the starting point for product design. Good design ensures that the product has the desired performance. In this chapter we focus our attention on conformance quality.

Once the product design is finalized, the next step in the product life cycle is production. This is a process involving several stages, where activities such as machining, assembly, testing, and so on, are carried out to transform inputs (raw material, components bought from external suppliers) into the final product. Due to variations in the inputs and/or process, the performance of some items produced does not meet the desired performance and that of the remaining items does. The former are called "nonconforming" and the latter "conforming". In the context of reliability, a nonconforming item is less reliable than a conforming item. This implies that such items are more prone to failure. This impacts the manufacturer in a significant manner as increased early failures lead to higher warranty servicing costs and greater customer dissatisfaction. From the customer's point of view, the cost of operating a nonconforming item over its useful life is significantly greater than that for a conforming item. This not only causes economic loss but also a high level of dissatisfaction.

The occurrence of nonconforming items during production depends on several factors. These include the quality of inputs, process state, operator skills, etc. The process state, in turn, is affected by operational decisions (for example, cutting speed in the case of a machine tool), maintenance practices and so on. The occurrence of nonconforming items can be reduced through quality control schemes. These involve additional costs and are worthwhile only if the benefits derived exceed the costs. In this chapter we discuss these issues in the context of product reliability and warranty.

The outline of the chapter is as follows. We start with a discussion of product nonconformance and its implication for warranty in Section 9.2. In Section 9.3 we briefly discuss two different approaches to production, the degradation of the production process, and the notion of process quality. Section 9.4 deals with quality control in general and involves three types of control. These are discussed in Sections 9.5 through 9.7. Optimal decisions for quality control are discussed in Section 9.8. Section 9.9 provides some illustrative examples.

9.2 Product Nonconformance

Conformance quality can be described through either "attribute" or "variable" characterization. Attribute characterization defines an item as either conforming or not. As such, it involves a binary-valued description. In contrast, the variable characterization involves a continuous-valued description and provides information regarding the "degree" of nonconformance.

As an example, the hardness of material is important in determining the strength of a mechanical component. The design requires that the strength be greater than some specified value. In the attribute characterization, an item either has the desired strength (conforming) or not (nonconforming). In the variable characterization, the item is described in terms of its actual strength (which can take any value over an interval). The difference between the actual strength and the desired strength is an indicator of the degree of nonconformance.

In the context of product reliability, one needs to differentiate two types (Types I and II) of nonconforming items. A Type I nonconforming item is in a non-operational state when put into use. This type of nonconformance is usually due to defects in assembly (e.g., a dry solder joint). In contrast, a Type II nonconforming item is operational but its characteristics are inferior to those of a conforming item that meets the design performance. A Type II nonconforming item is in working state when put into use but its reliability (measured through measures such as, for example, the mean time to failure) is considerably less than that of a conforming item. Note that Type I nonconformance can be viewed as a special case of Type II nonconformance with time to failure being zero. As such, we focus our attention on the characterization of Type II nonconformance. This type of conformance involves variable description.

9.2.1 Types of Nonconformance

The rate of occurrence of failures over time (ROCOF) can be described in terms of an intensity function as discussed in Section 5.6. An ideal conforming item has a ROCOF that is roughly constant over the useful life L and then increasing with time as shown in Figure 9.1. The ROCOF for Type II nonconformance can be one of the following:

- **Nonconformance (a)**: The ROCOF for a nonconforming item during the initial life of the item (over period T1) is much higher than that for a conforming item as shown in the top picture of Figure 9.1. This can be due to errors in assembly, using wrong components, machining tolerances being not met, etc. This is also referred to as "infant mortality" and the resulting failures termed "teething" problems. These failures are rectified through replacement of the defective component or fixing the error in assembly or machining.

- **Nonconformance (b)**: The ROCOF for a nonconforming item over the useful life is much higher than that for a conforming item as shown in the middle picture of Figure 9.1. This implies that the nonconforming item will experience more failures (in a probabilistic sense) over its useful life.
- **Nonconformance (c)**: The useful life of a nonconforming item (L1) is much smaller than that of a conforming item (L) as shown in the bottom picture of Figure 9.1. This implies that the consumer needs to replace such an item earlier as operating beyond the useful life results in higher operating costs.
- **Nonconformance (d)**: Combinations of the above (a)–(c). Figure 9.2 shows one such and this is typical in real life.

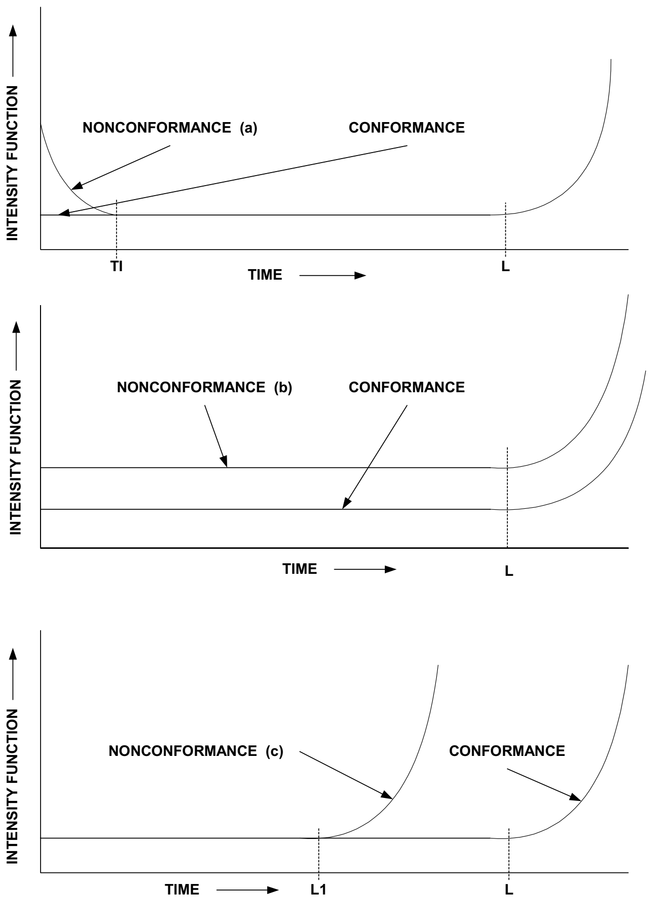


Figure 9.1. Types of nonconformance

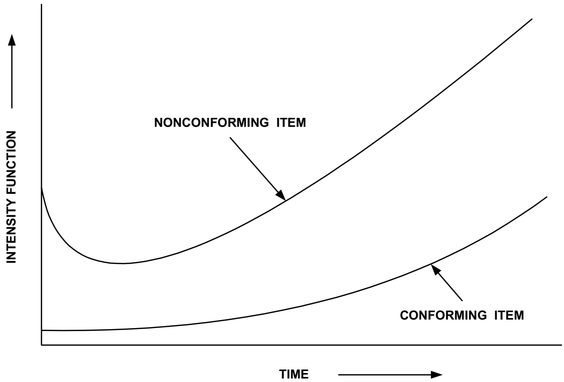


Figure 9.2. ROCOF for conforming and nonconforming items

9.2.2 Implication of Nonconformance

Nonconforming items impact both manufacturer and customer. Not only can the useful life be shortened considerably, the number of failures over the warranty period and the useful life can increase significantly. As a result, the expected warranty servicing cost can increase significantly, as can customer dissatisfaction.

Example 9.1

In Example 7.1, we analyzed an electronic module that cost C_s = \$30 to produce and had a MTTF of 12 years. Warranty costs were calculated for the FRW with warranty periods of W = 1, 2, 3, 5, and 7 years. A Weibull distribution was assumed for time to failure and to assess the effect of the Weibull shape parameter α on warranty costs, values of α = 1, 2, 3, and 4 were used in the calculations. These correspond to constant and increasing failure rates. Warranty costs increase, of course, as W increases, and it was found that they decreased as α increased. This is because for constant MTTF (12 years in this case), increasing failure rates imply relatively fewer early failures, with increasing more frequent later failures expected, i.e., aging increases the chances of a failure. Since many of these later failures take place after expiration of the warranty, expected warranty costs decrease.

Here we look at the effect on cost of changing the MTTF, in particular, the effect of decreasing the useful life of the component. As noted, this may occur because of nonconformance of some or all of the items. For purposes of illustration, α is taken to be 2, which corresponds to a relatively slowly increasing failure rate, and look at MTTFs of 7, 8, 9, 10, 11, and 12 years. These correspond to the nominal level of 12 years, and a number of levels of degraded performance.

<u>*Results*</u>

As in Example 7.1, we calculate the expected number of failures in the warranty period and the expected cost to the manufacturer for the warranty periods considered. The results are given in Table 9.1. In addition, we calculate the probability that no failures occur under warranty for the same combinations of W

and MTTF.[1] This can be taken as a measure of customer satisfaction. The results are given in Table 9.2.

<u>Comments</u>

As expected, warranty costs increase substantially as the warranty period increases and also as the MTTF decreases. In fact, for the nominal warranty period of 5 years, the warranty costs are very high relative to productions costs for any of the warranty periods considered. (Some may be acceptable, however, if the selling price is sufficient to cover these.) For a warranty of 3 years rather than 5, the costs appear to be acceptable; the cost of a seven-year warranty would not be. For relatively short warranty periods and the longer MTTFs, the proportion of sales leading to no warranty claims is quite high. It is apparent from Table 9.2, however, that as the MTTF decreases and the warranty period increases, many more warranty claims will be result.

Table 9.1. Expected number of warranty claims and expected warranty cost, Example 9.1

Expected number of warranty claims

MTTF	$W = 1$	$W = 2$	$W = 3$	$W = 5$	$W = 7$
7	0.0159	0.0628	0.1376	0.3536	0.6240
8	0.0122	0.0483	0.1066	0.2785	0.5017
9	0.0097	0.0383	0.0848	0.2243	0.4104
10	0.0078	0.0311	0.0691	0.1843	0.3412
11	0.0065	0.0257	0.0573	0.1540	0.2877
12	0.0054	0.0217	0.0483	0.1304	0.2454

Expected warranty cost

MTTF	$W = 1$	$W = 2$	$W = 3$	$W = 5$	$W = 7$
7	30.48	31.88	34.13	40.61	48.72
8	30.37	31.45	33.20	38.36	45.05
9	30.29	31.15	32.54	36.73	42.31
10	30.23	30.93	32.07	35.53	40.24
11	30.20	30.77	31.72	34.62	38.63
12	30.16	30.65	31.45	33.91	37.36

Table 9.2. Probability of no warranty claim, Example 9.1

MTTF	$W = 1$	$W = 2$	$W = 3$	$W = 5$	$W = 7$
7	0.9841	0.9379	0.8657	0.6698	0.4559
8	0.9878	0.9521	0.8954	0.7358	0.5481
9	0.9904	0.9620	0.9164	0.7847	0.6218
10	0.9922	0.9691	0.9318	0.8217	0.6806
11	0.9935	0.9744	0.9433	0.8502	0.7276
12	0.9946	0.9784	0.9521	0.8725	0.7655

■

[1] This is equivalent to the probability that the failure time of an item exceeds W, which in this case is given by

$$P(X > W) = 1 - F(W) = \exp\{-(\lambda W)^{\alpha}\}.$$

Example 9.2
To illustrate the impact of changing the useful life of an item on the warranty cost to the manufacturer of the pro-rata rebate warranty, we look again at the automobile battery discussed in Example 7.3. In that example, we considered warranty periods of $W = 1.5, 2.0, 2.5, 3, 4$ and 5 years and batteries with median lifetimes of 4, 5, 6, and 7 years. (The equivalent MTTFs are 5.8, 7.2, 8.7, and 10.1 years, respectively.) An exponential distribution of time to failure was assumed, which is often a reasonable assumption for items of this type. Cost factors for all combinations of median life and warranty period are given in Table 9.3.

Results

Suppose, as before, that the battery costs $45 to manufacture, and that it sells for $75. The total cost to the manufacturer, including cost of the warranty (i.e., average rebate) is given in Table 9.3 for the selected values of median time to failure and warranty period *W*.

Comments

In this example, warranty costs (calculated as tabulated value minus $45) are a substantial portion of the selling price – over 8% in the best case, and increasing to the point of nonprofitability in the worst case. (The worst case is a battery with a median life of 3 years and a warranty of 5 years, and results in a loss.) The point is, however, that nonconformance in the sense of degrading median lifetimes can dramatically affect warranty costs.

Table 9.3. Expected cost ($) to manufacturer of pro-rata warranty, Example 9.2

Median time	**Warranty period, *W***					
to failure	**1.5**	**2.0**	**2.5**	**3.0**	**4.0**	**5.0**
3	56.61	59.94	63.02	65.90	71.05	75.53
4	53.96	56.62	59.13	61.52	65.90	69.83
5	52.28	54.50	56.61	58.64	62.43	65.90
6	51.14	53.03	54.85	56.62	59.94	63.02

■

9.3 Effect of Production Process on Nonconformance

The occurrence of nonconforming items depends on (i) quality of input and (ii) the transformation process that converts the inputs into final products. In this section we discuss the transformation process and its impact on quality of conformance.

9.3.1 Production Process

Items can be produced either continuously or in batches.[2] The choice between the two is dictated by economic considerations. If the demand for the product is high, then it is economical to use continuous production, where a dedicated line is set up

[2] Yet another approach is called flexible manufacturing. Here each item produced is different and as such can be viewed as batch production with batch size one.

for this purpose. However, if the demand is low to medium, then it is more economical to use a batch production process, where items are produced in lots (or batches). In this case, the production line is used for producing more than one product, and needs to be set up every time a batch is produced.

In general, the process involves several stages, with one or more activities carried out at each stage. The output quality (conformance) of a stage depends on the input quality to the stage and the state of the process associated with the stage. We shall confine our discussion to a single stage; the extension to the multi-stage case is relatively straightforward.

9.3.2 Process State

The production process requires ensuring that it is in-control when the production commences. This implies that the variables affecting the process (such as temperature for soldering, cutting edge of a machine tool, etc.) are within the acceptable intervals. In this case, the process is said to be "in-control". As production proceeds with time, the process degrades (for example, machine tool becoming worn out or a drift in the setting) and the variables assume values that are deemed as being unacceptable for production. This is termed as the change in state from in-control to "out-of-control". The change can be gradual or sudden, as shown in Figure 9.3.

The occurrence of nonconforming items is related to the state of the process. When the process is in-control, all the assignable causes are under control, and, although nonconformance cannot be avoided entirely, the probability that an item produced is nonconforming is very small so that it is close to zero. When the state changes to out-of-control, this probability increases significantly.

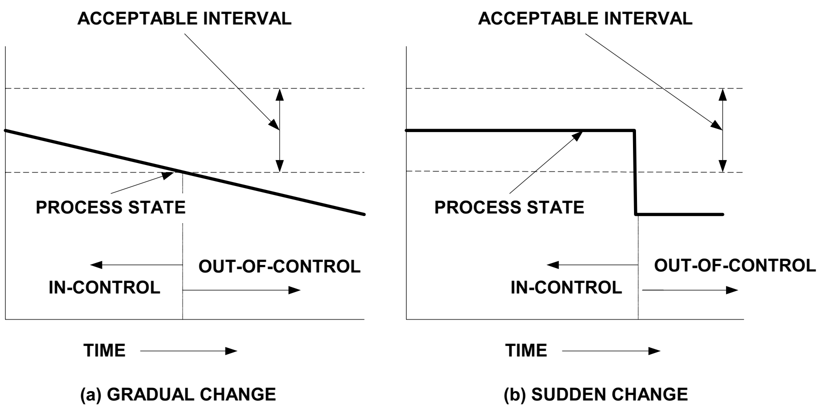


Figure 9.3. Change in process state over time

The process starts in-control and changes to out-of-control after producing a certain number of items. The change occurs in an uncertain manner. Once the change occurs, it stays out of control until some action is initiated to bring it back to in-control. In the case of continuous production, the process needs to be monitored periodically to detect this change. Once a change is detected, the production is stopped and actions initiated to restore the state from out-of-control to in-control. This is referred to as process control. As a result, in the case of continuous production, the average rate of occurrence of nonconforming items over time depends on the quality control scheme used as will be discussed in a later section. In the case of batch production, the state is checked before the start of each batch production to ensure that it is in control and the state is not usually monitored till the end of the batch production. This implies that the number of nonconforming items in a batch (a random variable) depends on the batch size. The bigger the batch, the greater is this number (in the statistical sense).

9.3.3 Process Design

The production process is affected by several factors, some of which are controllable (for example, cutting speed, angle of cut) and others of which are not (for example, humidity or temperature of an open room with no environmental controls). Controllable factors need to be selected carefully so as to ensure that the probability of an item produced is nonconforming is the smallest when the process is in control. This is achieved through proper experimentation. This process is called off-line quality control in contrast to the on-line methods that are discussed later in the chapter.

9.4 Quality Control

The main aim of quality control is to reduce the number of nonconforming items reaching the customer. This can be achieved in several ways, as indicated in Figure 9.4. The approaches are:

1. Weeding out nonconforming items by inspection and testing of the items before they are released for sale. This is called "output" control.

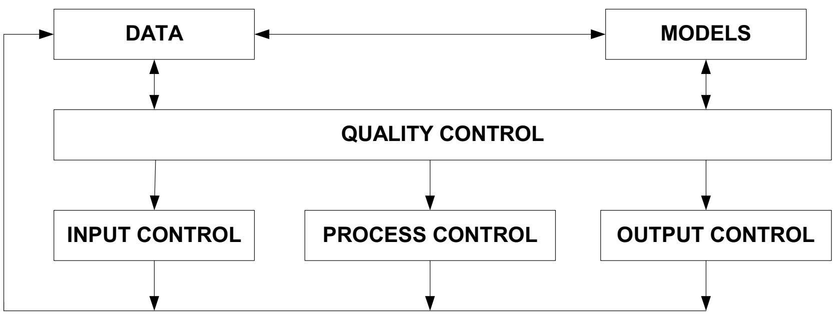


Figure 9.4. Key elements of quality control

2. Preventing the production of nonconforming items. This is done through "input" control that detects and weeds out nonconforming inputs and

"process" control whose main aim is to detect the change in process state from in-control to out-of-control as soon as the change occurs.

Designing effective quality control strategies requires models and appropriate data. In the next three sections, we discuss these and highlight some of the underlying issues.

9.5 Input Control

The quality of input material and components has a significant impact on the final product quality. The inputs are purchased in lots (or batches). For components, quality can be described through attribute or variable characterization and for material it is done through variable characterization.

Suppose we consider a lot of size *N*. Ideally, the manufacturer would prefer that every lot is free of nonconforming components. However, this is not possible due to natural variability and for cost reasons. Usually, the manufacturer specifies that to be acceptable, a batch must contain fewer than *K* nonconforming items. This number would depend on *N* and on the purchase price for the lot. (This price ordinarily increases with quality, so that lots with fewer nonconforming items tend to be more costly.) The contract between the manufacturer and the component supplier specifies *N* and *K*. The manufacturer must ensure that the supplier delivers the stated quality consistently. One way of ensuring this is through inspection and testing of components.

Testing can be either destructive or non-destructive. With destructive testing, only a few items are tested to assess the input quality. In the case of non-destructive testing, economic considerations rule out the option of testing each and every item in a lot. This implies that sampling schemes must be used to assess input quality.

In the context of reliability, testing can involve life testing (to assess the mean time to failure or some specified reliability measure) or testing some properties (such as hardness or strength) and then relating these to some reliability measure. In the former case, testing can stop before all the items on test fail. As a result, the test data consist of failure times and censored data (Types I and II depending on the criterion for stopping the testing). The analysis of test data to draw inferences is discussed in Chapter 5.

A variety of sampling schemes have been developed for this purpose. These include:

1. Single-stage sampling: Here a sample of size n is selected randomly from each lot and tested. Let $\tilde{n}$ denote the number of nonconforming items detected. If $\tilde{n} < k$ (a specified number), the lot is accepted. If not, the lot is either scrapped or subjected to 100% testing.
2. Two-stage sampling: Here a sample of size n_1 is tested. Let $\tilde{n}_1$ denote the number of nonconforming items detected. If $\tilde{n}_1 < k_1$ (a specified number), the lot is accepted and if $\tilde{n}_1 > k_2$ (a specified number $> k_1$), the lot is

rejected. On the other hand, if $k_1 < \tilde{n}_1 < k_2$, then a new sample, of size n_2, is tested. Let $\tilde{n}_2$ denote the number of nonconforming items detected in the second batch. If $\tilde{n}_1 + \tilde{n}_2 < k_3$ (a specified number), the lot is accepted. If not it is rejected and the rejected lot is either scrapped or subjected to 100% testing.

3. Multi-stage sampling: This is similar to two-stage sampling but involves more than two stages, proceeding in a similar fashion.
4. Sequential sampling: Here one item is tested at a time and, based on the outcome of all the items tested to that point, one of the following three decisions is made: accept the lot, reject the lot, or continue testing.

One issue associated with any sampling scheme is the risks to component supplier and to manufacturer. The risk to manufacturer is that the sample might indicate acceptance when the quality of the batch is low. The risk to the component supplier is that the sample might indicate that the batch is unacceptable when the batch quality is high. The parameters of the sampling scheme determine the two risks. Increasing the size of the sample reduces the risks but this is achieved at increased cost of testing.

Figure 9.5 shows the decision processes involved in input quality control. It involves deciding on the sampling scheme and also on the selection of supplier. The optimal sampling scheme is discussed in Section 9.8.

9.6 Process Control

As mentioned earlier, when the process state changes from in-control to out-of-control, the occurrence of nonconforming items increases significantly. As the name implies, process control is to detect the change as soon as it occurs so that the state can be restored back to in-control.

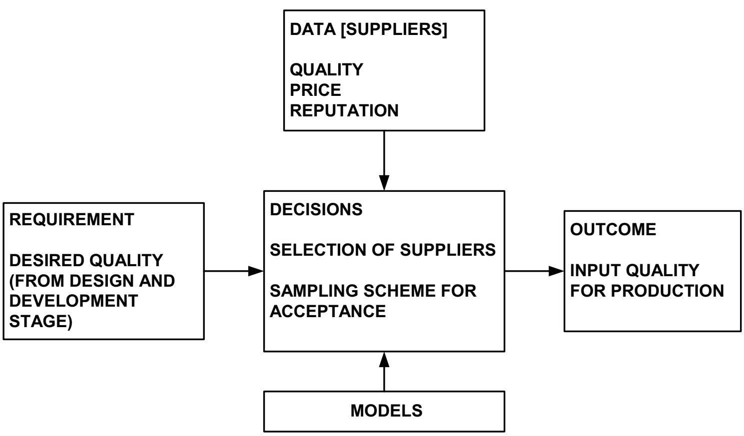


Figure 9.5. Input quality control

For continuous production, this is done through use of control charts. The basis for the chart is fairly simple and is shown in Figure 9.6. A batch of items is taken from the production line on a periodic basis and tested. The sample statistic from the test can be based on attribute characterization (number or fraction of nonconforming items in the batch) or variable characterization (the sample mean, sample range – the difference between the smallest and the largest value in the sample tested – or some other measure). If the process is in control, then the sample statistic is more likely to fall within some specified limits (referred to as *control limits*). When the sample statistic falls outside the specified limits, it is more likely that the process has changed from in-control to out-of-control.

A control chart is a plot of the sample statistic obtained from successive batches and checking them against the limits specified. As long as the plots are within the limits, no corrective action is taken. In the simplest rule (Rule 1), the first time a sample statistic falls outside the limit, the process is stopped and checked to find the possible cause for the change in the process state. If a cause is detected, it is fixed so that process is brought back to in-control. If no cause is detected, then it is a false alarm and no corrective action is needed. More complex rules can involve more than two limits (for example, control limits and warning limits) and the decision to stop the process can involve statistics from several samples. An example of one such decision rule (Rule 2) is where the decision to stop the process is based on two consecutive sample statistics falling outside the warning limits followed by a sample statistic falling outside the control limit. Figure 9.7 shows the actions resulting from Rule 1 and 2, respectively.

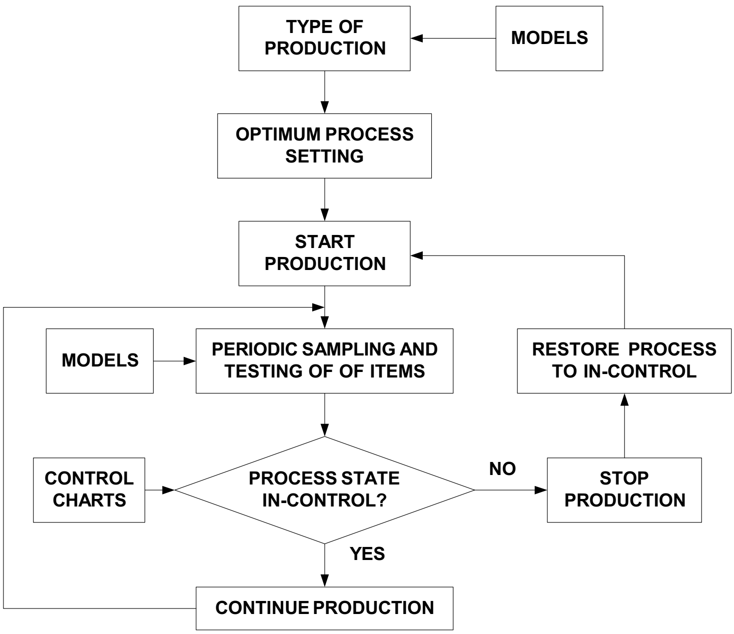


Figure 9.6. Process quality control

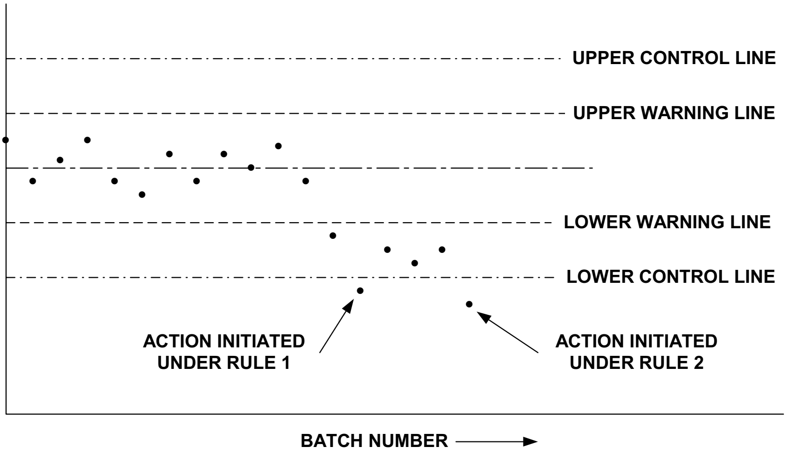


Figure 9.7. Typical control chart

A problem with all charts and any kind of rule is the following. One can commit two types of errors. A Type I error occurs when the sample statistic falls outside the interval defined by the control lines but the process is still in control. This results in the production plant being interrupted when no action is really needed. A Type II error occurs when the process state has changed from in-control to out-of-control but the statistic falls between the control lines. It is not possible to make both these errors small for a given sample size. Reducing the frequency of occurrence of one kind of error increases the frequency of occurrence of the other. In practice, charts should be selected to balance the two types of errors in a way that is acceptable to the user. This is a function of their relative importance, i.e., the consequences of making a Type I versus a Type II error.

A variable of interest in this context is the average run length (ARL). This is the expected time needed (from the time instant a change occurred from in-control to out-of-control) before the change is detected. This occurs when the sample statistic fails to indicate the change when it has occurred (Type II error). The ARL is a function of the degree of change in the process state and the parameters of the chart (sample size and limits). The ARL decreases as the sample size increases, but this also increases the cost of testing. A goal of the design of charts is to ensure that this value is as small as possible.

Some of the charts used extensively in industry are the following:

- $\overline{X}$ Chart: The sample statistic is the sample mean.
- *R* Chart: The sample statistic is the difference between the largest and smallest values in the sample.
- *p* Chart: The sample statistic is the fraction of nonconforming items in the sample.
- *np* Chart: The sample statistic is the number of nonconforming items in the sample.

In the case of batch production, no such testing is carried out during the production of a batch. The process is checked to ensure that it is in-control when the production commences and the production ceases only after a batch has been produced. The process can change from in-control to out-of-control during the production of an item, and it stays in this changed state for the remainder of the production of the batch. If the process is reliable, then the probability of such a change occurring is small. In this case, the number of nonconforming items in a batch is uncertain and depends on the reliability of the process and the lot size. This can be reduced through use of a smaller lot size, but this increases the production cost due to the need for more frequent set ups.[3]

9.7 Output Control

The aim of output control is to detect any nonconforming items and weed them out so that they do not reach the customer. One can either test all the items or only a sample. Usually, one switches between different testing schemes as indicated in Figure 9.8. An illustrative example of switching is the following. Items are tested periodically so that every k^{th} item is tested. If the test reveals a nonconforming item, then every item is tested. This continues till m consecutive items are conforming at which instant the testing reverts back to the original periodic testing. Here there are two schemes – one involving periodic testing and the other involving 100% testing. One can devise many other such schemes. The aim is to reduce the fraction of nonconforming items being released for sale. The reduction depends on the parameters (k and m in the illustrative example) of the different schemes involved. Nonconforming items are either reworked so as to make them conforming or scrapped.

9.7.1 Burn-in

Under nonconformance (a) (see Figure 9.1), the items have a very high ROCOF early in their life. These lead to high early failures and can impact on customer satisfaction and the reputation of the product as well as the manufacturer. One way of avoiding such failures is through "burn-in".

Burn-in involves testing items for a period τ called the burn-in period. Those that fail during testing are either scrapped (in the case of non-repairable items) or repaired (in the case of repairable items) and the testing continues. τ is usually less than the period when the failure rate is decreasing with time. As a result, the ROCOF of an item released for sale has a much smaller value in the initial phase of

---

[3] Let q denote the probability that the state will switch from in-control to out-of-control during the production of an item. Let p_i [p_0] denote the probability that an item produced is conforming when the state is in-control [out-of-control]. If the lot size is L, then the expected fraction of conforming items in the lot is given by

$$\phi(Q) = \frac{q(p_i - p_0)(1-q^Q)}{(1-q)Q} + p_0 .$$

Note that this decreases as Q increases.

its operation, thus reducing the likelihood of its early failure.[4] Burn-in involves additional costs and is worthwhile only if the benefits derived exceed this cost.

9.7.2 Releasing with No Testing

When the manufacturer is unable to carry out testing of the output, all nonconforming items are released and this can affect consumer satisfaction. One way of overcoming this is through an "incentive warranty" policy.[5] Under this policy, should the first failure occur within a period W_1 ($W_1 < W$), the customer is offered the following two options. Option 1 is a total refund (money back guarantee), and Option 2 is a new replacement item with a new warranty identical to the original warranty and a lump sum payment as compensation for the inconvenience caused due to the early failure. All failures beyond W_1 and within warranty are repaired minimally at no cost to the consumer. The choice of Option 1 implies the loss of a customer, which is a penalty cost to the manufacturer resulting from the loss of future sales and of goodwill.

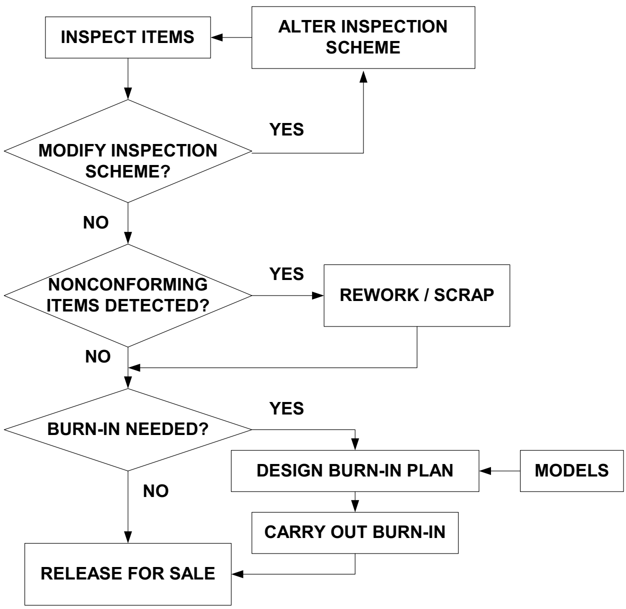


Figure 9.8. Output quality control

[4] Let $F_0(t)$ and $\lambda_0(t)$ denote the failure distribution and ROCOF of the item before burn-in. After a burn-in for period τ, the failure distribution and the ROCOF are given by $F_1(t) = [F_0(t+\tau) - F_0(\tau)]/[1 - F_0(\tau)]$ and $\lambda_1(t) = \lambda_0(t+\tau)$, respectively.

[5] This concept is discussed in Murthy, Djamaludin, and Wilson [1].

9.8 Optimal Quality Control

As the quality control (input, process and output) effort is increased, the fraction of released items which are nonconforming decreases. This results in a reduction in the expected warranty cost. However, this is achieved at the expense of increased quality control cost as shown in Figure 9.9. This implies that one needs to determine the optimal quality control that achieves a balance between the costs and the benefits associated with quality control. Optimal quality control in the context of warranty has received some attention in the technical literature and many models have been developed to determine the optimal quality control effort.[6]

9.9 Illustrative Examples

Example 9.3 [Automobile][7]
The transaxle is an important component of the drive train of an automobile. The transaxle oil seal prevents oil leaking out from the drive shaft. This has serious implications for the drive train for such failures result in high repair cost. Toyota was concerned at the quality of the seals it obtained from its component supplier and initiated a Quality Improvement program to reduce the occurrence of such failures.

The seal consists of a rubber lip molded onto a round metal casing. The rubber lip grips the surface of the shaft around the entire casing, creating a physical barrier to prevent oil leakage. As the shaft rotates, a minute amount of sealed oil forms a thin lubricating film and this prevents excessive wear of the rubber lip and at the same time reduces frictional loss. An excessive film becomes a source of leakage.

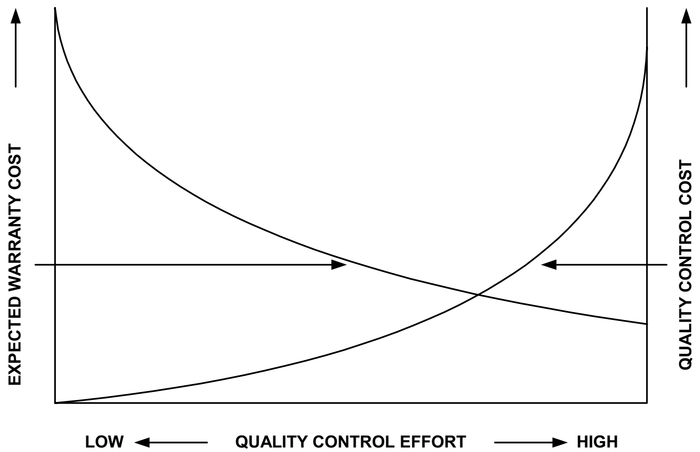


Figure 9.9. Warranty cost versus quality control cost

[6] A review of the literature can be found in Murthy and Djamaludin [2].
[7] For details, see Amasaka and Osaki [3].

The design change for reliability improvement began with a study to answer several questions, such as the following:

1. Why did oil leak from the seal?
2. Had anyone actually seen the phenomenon?
3. What was the basis for the current design (for the axle at rest and when rotating)?

A special facility with visualization capability was built to observe and study the underlying phenomenon. The study revealed that fine foreign matter (resulting from gear engagement operations in the transaxle gearbox) and the microscopic irregularities on the lip sliding surface resulted in pressure variations which led to seal degradation and failure.

A properly designed experiment was carried out to study the effect of the different factors (such as lip margin, lip width, hardness of rubber, to name a few) and it indicated the following:

1. Improvement in wear resistance can be achieved by increasing the gear surface hardness through changes to the gear material and heat treatment.
2. Increasing the oil seal hardness and lowering the allowance range improved the reliability.

The net effect of these changes increased the B10 life to over 400,000 km. (B10 life implies that 90% of the seals will last for at least this usage.)

It then focused on quality control procedures to ensure high quality from the supplier.

■

Example 9.4[8]

Daimler Chrysler set up a Quality Engineering Center at a cost of $32 million. It more than paid for itself in its first year of operation by saving the company $54 million in repair cost alone. Through proper quality control of parts from suppliers, it reduced the warranty problems associated with such parts by 30%.

Some of the activities carried out by the control process are as follows:

- Several vehicles evaluated and repaired each day
- 12 “root cause” meetings conducted by the employees and roughly 100 supplier representatives visiting on any given day
- The Parts Return Group analyzed 600–700 parts that arrived daily from 160 dealerships across the country.
- Returned parts (from dealers and service agents) studied to identify the problems and to come up with fixes.

■

[8] From Priddle [4].

References

[1] Murthy, D. N. P., Djamaludin, I. and Wilson, R. J. (1995) "A consumer incentive warranty policy for items with uncertain quality" *Quality and Reliability Engineering* **11**, 155–163.

[2] Murthy, D. N. P. and Djamaludin, I. (2001), Warranty and Quality, in *Integrated Optimal Modeling in PIQM: Production Planning, Inventory, Quality and Maintenance*, M. A. Rahim, and M. Ben-Daya (eds), Kluwer Academic Publishers, New York, pp. 325–360.

[3] Amasaka, K. and Osaki, S. (2003), "Reliability of oil seal for transaxle – A science SQC approach at Toyota," Chapter 25 in *Case Studies in Reliability and Maintenance*, W. R. Blischke and D. N. P. Murthy (eds), John Wiley and Sons, New York.

[4] Priddle, A. (Ward's Auto World, Jan. 1, 2001) "DCC Tackles Quality, Warranty Issues" (http://waw.wardsauto.com/magazinearticle.asp)

10

The Role of Warranty in Marketing

10.1 Introduction

Marketing is a concept that is not easy to define, as there are several different competing views of the role of marketing.[1] It can be viewed as creating and managing markets, with market defined is an outcome of the interaction between manufacturers and consumers, leading to a transfer of goods (products and/or services). Product warranty plays an important role in the creation of market for the product and for managers to manage the market. This is because of consumer uncertainty regarding product performance over its useful life. Warranties serve as persuasive marketing tools: (i) promotional and (ii) protectional. As a promotional tool, warranties serve to promote the reliability and quality of a product with longer and better warranty terms implying a more reliable product. As a protectional tool, warranties provide assurance to consumers against defective products that fail to perform satisfactorily over the warranty period. This assurance reduces the risks associated with purchase of the product.

In this chapter we focus on the link between warranty and marketing. We start with an overview of the main issues in Section 10.2. Consumer purchase is a key element in the understanding of marketing and the purchase process is discussed in Section 10.3. It involves three stages – pre-purchase, purchase and post-purchase. Manufacturers need to understand the behavior of consumers during the pre- and post-purchase stages, the relevant underlying processes and the role of warranty. Sections 10.4 and 10.5 discuss these in the context of pre- and post-purchase behavior respectively. Section 10.6 deals with product sales and the role of warranty from a marketing perspective. The sales are a function of both warranty and price as well as customer satisfaction. The resulting market outcome from a microeconomics perspective is discussed in Section 10.7. Section 10.8 examines warranty strategy formulation.

---

[1] These are discussed in more detail by Webster [1].

10.2 An Overview

Marketing, viewed in a narrow sense, is the selling of products to consumers and has been practiced for a long time. It has been recognized as a separate discipline (or management function) over the last one hundred years and the role of marketing has been evolving over this period. In this chapter our focus is on marketing as creating and managing markets. Figure 10.1 gives a simplified characterization of this complex process.

The interaction between consumers and manufacturers defines the market for a product. For most products (such as consumer durables, industrial and commercial products), a manufacturer will have several competitors who are producing similar products and attempting to sell them to a given set of consumers, so that the market (for the product) is competitive. For some specific products (mainly industrial and commercial products), the manufacturer has no competitor so that the market is monopolistic rather than competitive. The market outcome depends on the interaction between several variables. On the manufacturer side, the variables include price, promotion, warranty etc. On the consumer side, product choice (between no purchase/purchase; which of the competing brands to purchase) depends on several variables such as product features, perceived risk, brand, reputation, etc. The importance of warranty can be seen from the following illustrations:

1. Warranties have played an important role in the automobile sector. As discussed in Example 3.3, the warranty for automobiles was 90 days in the 1930s and this has steadily increased over the years. In 2002, Suzuki offered a 7-year, 100,000 mile warranty on the power train and a 3-year, 36,000 mile bumper to bumper warranty. A report in the *New York Times* [2] commented that it was the best auto warranty then available. The *Times* also reported that "Hyundai sales have quadrupled over the last four years because of affordable prices and a 10-year or 100,000 miles warranty" [3]. This increase in sales is partly due to improvements in reliability resulting from technological advances, but also due to the use of warranty as a marketing tool.

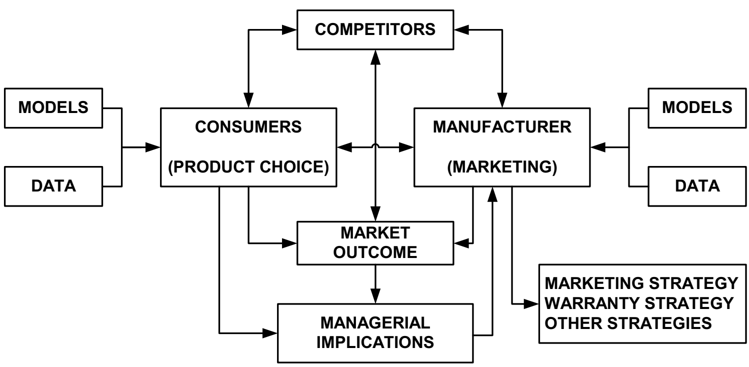


Figure 10.1. An overview of warranty and marketing

2. According to Roger Hobbie, General Service Manager at Eaton, “Warranty is a marketing tool ... they are statements about the product ... they foster a better understanding between Eaton and the end user.” [4]
3. “In today's ultra-competitive, value-conscious market, builders need to find new ways to earn buyer confidence,” says Andy Kireta Sr., Vice President for Plumbing Tube, Pipe and Fittings at Copper Development Association. “The warranty gives builders and consumers one more good reason to choose copper over materials that don't have the same record of reliability. The 50-year warranty says 'we're here today and we're here to stay,' and that's got to be attractive to any buyer of a new home.” [2]

Another important issue in marketing is the information available regarding the variables of importance to decision making. The two parties (manufacturer and consumer), in general, will have different information. This asymmetry in the information has a significant impact on the market outcome and the resulting implications for the two parties. Warranties play an important role in this context and we will discuss this later in the chapter.

In theoretical studies of the role of warranty in marketing, two questions are addressed:

1. Why do consumers demand warranties and extended warranties (given that a product with warranty costs more than one without warranty)?
2. What should be the warranty (and extended) strategies of the manufacturer so as to achieve the business goals or objectives (given this demand on the part of consumers)?

The starting point of any analysis is the consumer purchase decision. A microeconomic analysis of these issues considers market outcomes and resulting implications with regard to social welfare.[3] In marketing, the focus is on either total sales or sales over time. This information is used to manage other activities such as production rates, logistics etc.

10.3 Consumer Purchase Process

Figure 10.2 shows the consumer purchase process. This involves three stages: (i) pre-purchase, (ii) purchase and (iii) post-purchase.

The pre-purchase stage involves three phases as indicated in Figure 10.2. The starting point of any purchase is the recognition of the need for the product. This could be driven by several factors:

- Technology driven: A new product with superior performance appears on the market due to advances in technology that makes the existing product obsolete.

[2] See http://www.copper.org/newsreleases/2000/000114_warranty.html

[3] For further discussion of warranty from the microeconomics perspective, see Lutz [5].

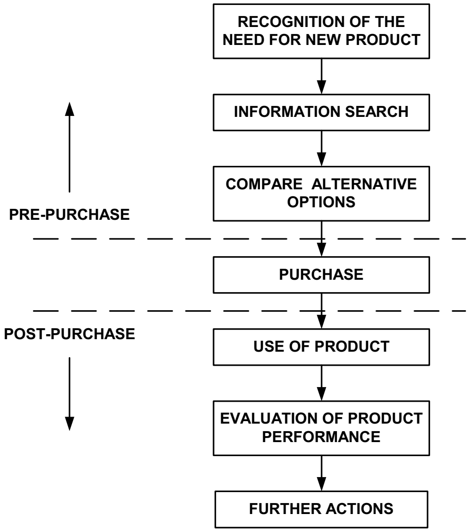


Figure 10.2. Consumer purchase process

- Customer (need) driven: The decision to purchase is the result of a perceived need.
- Market driven: The consumer is induced into purchasing a new product. This could be either due to the actions of other consumers or promotion by manufacturers.

The next phase for the consumer is to search for relevant information to reduce uncertainty regarding product reliability and performance and to reduce the associated risks. These are discussed in Section 10.4. Based on the information obtained, a consumer typically evaluates alternative options and this then leads to the final purchase decision.

The post-purchase stage deals with the evaluation of the product and with the resulting satisfaction or dissatisfaction. The satisfaction or dissatisfaction can be either with product performance and/or warranty servicing. Dissatisfaction impacts the sales through a negative word-of-mouth effect and is discussed in detail in Section 10.5.

10.4 Pre-purchase Behavior

Consumers need to resolve the uncertainty associated with the purchase of a new product. This uncertainty can be reduced through acquiring relevant information to assess product reliability and quality. Searching for this information is the next phase of the pre-purchase stage. Based on the information available, consumers compare alternatives (if there are several competing products) before deciding on the final purchase decision.

The purchase process for consumer products is different from that for commercial or industrial products, and for consumer products the process for non-durables is different from that for durables. For consumer durables, the process is often characterized by higher levels of involvement and search information when the items are expensive and the purchases are long-term.[4]

10.4.1 Purchase Uncertainty and Perceived Risks

Product uncertainty can arise from one or more of the following four sources:

1. *Technical uncertainty* relates to failure of a product to perform to the stated design specification. This is usually due to poor quality control during production. For durable products, poor quality control can result in shorter useful life or a higher failure rate. This in turn results in greater maintenance cost and reduced availability. This kind of uncertainty can be called *quality uncertainty*.
2. *Performance uncertainty* arises from a potential gap between the customer's perception of product performance and the actual product performance. For durable goods the uncertainty often relates to reliability aspects (such as useful life, average failure rate over the useful life, etc). In this case, the uncertainty can be called *reliability uncertainty*.
3. *Matching uncertainty* reflects the uncertainty resulting from a mismatch between the consumer's needs and the product's ability to satisfy them.
4. *Response uncertainty* refers to the uncertainty regarding product performance obtained from other users of the product.

Because of the above uncertainties, there is a risk associated with each purchase. The amount of perceived risk depends on the amount of uncertainty and the magnitude of the consequences that can result from choice of a particular product. The perceived risk can be one or more of the following:

1. *Financial risk* in which the consumer incurs financial loss.
2. *Performance risk* when the product fails to perform satisfactorily and meet the needs of the customer.
3. *Physical risk* resulting in damage to life and property.
4. *Social risk*.
5. *Psychological risk* .

The last two risks are usually associated with the purchase of consumer non-durables (for example, cosmetics). For consumer durables and commercial and industrial products, performance and financial risks are more important in the purchase decisions.

[4] For more on individual decision making, see Russo and Carlson [6].

10.4.2 Information, Cues and Signals

Most consumers are risk averse and as a result their willingness to try a new product is inversely related to the degree of perceived risk associated with the purchase of the product. One way of reducing the risk is through obtaining appropriate information to help evaluate the associated risks. This is not easy for consumer durables or for industrial and commercial products where consumers often learn through use and experience. In these cases, consumers rely on cues to assess product quality and reliability and to evaluate the associated risks.

Broadly speaking, cues can be divided into two categories – intrinsic and extrinsic. As the name suggests, intrinsic cues are inherent to the product and include things such as design features, performance, reliability, conformance, etc. In contrast, extrinsic cues are external to the product and include features such as brand name, price, dealer/retailer reputation, country of origin, advertisements, packaging, consumer magazines, recommendations of friends, etc. One needs to differentiate between high-scope and low-scope cues. The former have evolved over time such that their valence cannot be changed in a short time (for example, dealer reputation) whereas the latter are more transient and their valence can be changed (for example, price, advertising, warranty).

Signals, provided by one party (manufacturer or consumer) to another party, allow the recipient to draw inferences about the product. An issue of great relevance here is information asymmetry – for example, the manufacturer knows more about product reliability than do consumers; a consumer knows about his/her intentions regarding the usage mode and maintenance effort that the manufacturer is not fully aware of. This has implications for both consumers and manufacturers in the context of new products.

Studies of market signaling have looked at methods of conveying information regarding the unobservable product quality [7] and on the importance of relevance and credibility in conveying information of product reliability and quality [8].

10.4.3 Warranty and Product Choice

Warranties are seen as reducing perceived performance risk by providing protection against product defects leading to failures within the warranty period. Financial risk to the consumer is also reduced, as the repair costs to rectify failures occurring under warranty are covered by the manufacturer. Research supporting the expected effects of warranties on perceived and financial risk has been mixed [9].

According to marketing signal theory, warranties serve as signals to provide information about product quality and reliability. The underlying assumption is that consumers view the relationship between warranty and product reliability in terms of investments by manufacturers. Offering warranty results in additional cost and as a result manufacturers would invest in ensuring high reliability and better quality control if the product is sold with a long warranty. As a result, consumers tend to view warranty as being positively correlated with product reliability and quality. However, this is not always so, as indicated by the following:

> In 1995–1966 the NEC brand of personal printers came up with a two-year warranty compared with the industry standard one-year warranty offered on Hewlett-Packard printers. However, a 1996 survey of *PC Magazine* subscribers gave NEC a lower reliability rating compared to Hewlett-Packard, and the reported percentages of units needing repair was also higher for NEC. [10]

Cooper and Ross [11] make an even stronger statement:

> The extent of warranty appears to bear no general relation to the overall performance of a product. That is, the sellers of more reliable brands of a particular product may offer more, equal, or even less warranty protection than sellers of less reliable brands.

These inconsistencies arise because warranty is viewed as being the sole signal in transmitting information regarding product quality. In real life consumer's decisions about product quality and the associated risks are based on multiple cues. These include brand name, price, reputations of manufacturer and dealer, country of origin, information from friends, advertising, consumer magazines, packaging, etc. Consumers combine different signals to assess product reliability and quality and this in turn affects their purchase behavior.[5] In the end, the consumer's perception of product reliability and quality is determined by the effect of different signals and depends on the following [8]:

1. The relevant information content in each signal regarding the different dimensions of quality.
2. The relative credibility of different signals in conveying their information.
3. The propensity for each signal to enhance the credibility of the other signals.

In the remainder of this section, we look at the joint effect of warranty and other signals that influence consumer product choice.

---

[5] Hudson and Jones [12] discuss how consumers combine different uncertain signals to assess product quality. They look at several quality-related signals (such as price, brand name, shop, ingredients, country, friend, consumer magazine, shop assistant, advertisement, instructions, quality mark, guarantee or warranty and packaging) to explore the following: (i) the criteria against which individuals choose to use one signal more than another and (ii) under what circumstances they choose to use multiple signals. They use data from 1004 individuals in the UK and show that people use multiple signals, but they do so selectively. The most commonly used ones are, in descending order, brand name, quality mark and guarantee (warranty) when the sample population is treated as one. However, if the population is divided into different groups based on age, then for mature consumers (those aged 50 plus) the top three in ranking are, in descending order, brand name, guarantee (warranty) and quality mark so that guarantee jumps up to become the second most important signal.

10.4.4 Warranty and Brand

In the context of new products, a brand is a name, term, symbol, design, or some combination, which identifies the product (and associated services) of a particular manufacturer and gives it an advantage over the brands of its competitors.[6] The legal term for brand is *trademark*. A brand may identify one product, a family of products, or all products of manufacturer. A successful brand induces customers to prefer it to competitor's brands and thus build brand loyalty. Brands depreciate without investment in enhancing product quality, service and brand image.

Price and Dewar [8] examine the joint effect of brand and warranties by testing three hypotheses against empirical evidence in the literature. They conclude that "a signal's effect will be diminished when it lacks relevant information about a quality dimension or it lacks credibility, or both … and that a warranty can enhance brand signal credibility".

10.4.5 Warranty and Reputation

The combined effect of warranty as a signal and the reputation of the manufacturer on the consumer purchase decision was studied by Balachander [10]. He concluded that the product market may display positive correlation between warranty and reliability (as expected), or a negative correlation, depending on the circumstances. This is illustrated in the NEC and Hewlett-Packard example cited earlier. Another example of this is the following:

> In July 2002, Chrysler group started offering a fully transferable 7-year/ 70,00-mile Power-train Warranty on some of its models. GM, Ford Motor Company and Toyota Motor Corporation said that their models are more reliable and they don't need to follow Chrysler's warranty extension. [14]

Purohit and Srivastava [15] examine the joint effect of reputation (of manufacturer and retailer) and warranty in providing information about product quality using a "diagnosticity," a measure that refers to the perceived reliability of a cue in discriminating between alternative categorizations or interpretations. High-scope cues are perceived to be more credible and consequently more diagnostic relative to low-scope cues. In this context, warranty is considered to be a low-scope cue and reputation a high-scope cue. They conclude that warranty is used in product quality judgment only when the valence of the high-scope cues (manufacturer and/or retailer reputation) is positive. This suggests that the effect of a high-scope cue on perceptions of product quality is both direct and indirect.

10.4.6 Warranty and Hybrid Products

Hybrid products are products that are designed in one country (usually a developed country) and produced in another country (usually a developing country). Such products differ from products designed and produced in one country. Hybrid

---

[6] For more details on brands, see Chapter 14 of Baker [13].

products are becoming important as manufacturers become global in their operations. Consumers tend to perceive lower quality and reliability, and as a result higher risk, with hybrid products.

Tan and Leong [16] examine whether warranty has any mediating effect on consumers' evaluation of hybrid products and conclude that warranty plays an important role.[7] Tan *et al* [18] examine the country of design and the country of manufacture and the role of warranty in this context. Their conclusions are summarized in Table 10.1 and indicate when better warranty is effective in counteracting the negative effect of hybrid products.

10.5 Post-purchase Behavior and Warranty

As indicated in Figure 10.2, post-purchase involves use of the product and this in turn leads to an evaluation of product performance. The post-purchase process involves several elements as shown in Figure 10.3, with the final outcome being the intentions of customers. Some of the elements have been discussed in earlier chapters and in this section we discuss the remaining ones. We start with evaluation of product and service, following which we discuss customer satisfaction/dissatisfaction. We then conclude with a discussion of the different outcomes that may result from customer intentions.

10.5.1 Evaluation of Product and Service

Product performance can be either simple (working or not working) or complex, involving many variables (for example, in the case of an automobile engine this could include fuel efficiency, power output, mean time between failures, quietness of running, emission of undesirable pollutants etc). Consumer expectation regarding product performance can differ from that promised by the manufacturer. Also, in some cases it is easy to measure the performance objectively whereas in many other cases it might not be so (for example, the quality of sound from an automobile radio or CD player).

When the customer is not satisfied with product performance, we may have a warranty claim (provided the item is still covered under warranty).

Table 10.1. Effectiveness of better warranty and reputable warrantor in overcoming consumers' negative image of hybrid products

	Designed in reputable country; manufactured in less reputable	**Designed and manufactured in less reputable country**
Better warranty	Effective	Effective
Reputable warrantor	Partially Effective	Effective

[7] See also Ahmed and d'Astous [17].

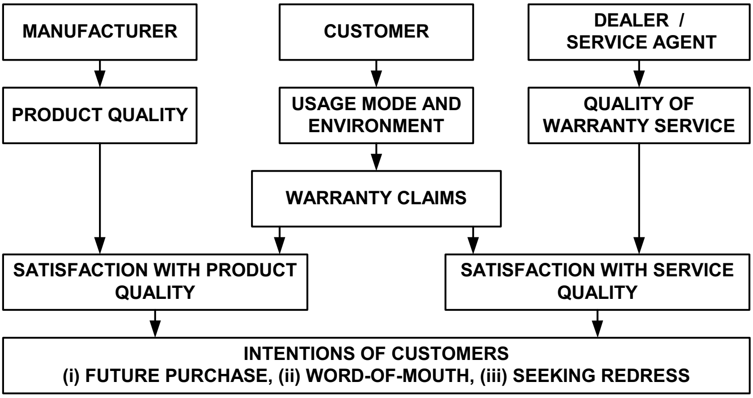


Figure 10.3. Post-purchase behavior

Service, in the context of product warranty, refers to all activities associated with the servicing of warranty claims. Customers also have expectations regarding the quality of service. According to *SERVQUAL*,[8] the five dimensions of service quality are:

- Tangibles: physical aspects – look and feel of premises, staff, etc.
- Responsiveness: provision of speedy service, willingness to serve, etc.
- Reliability: delivering promised service dependably and accurately
- Assurance: professional and courteous service which conveys trust
- Empathy: individualized, personal service.

As discussed in Section 2.3.3, product performance is one of many different notions of product quality. Customer evaluation of a product can involve several of these notions in addition to performance. As such, the evaluation of product and service can involve many different dimensions.

10.5.2 Satisfaction and Dissatisfaction

The following two statements indicate the importance of consumer expectations to manufacturers:

- "Customers do not buy products or services as much as they buy expectation." [20]
- "As autos get better, consumers are getting pickier about what they identify as a problem. Many automakers have started to take consumer expectations into account when they set out to design a new model. As a result, new autos today are better vehicles than cars produced just a few years ago." [21]

[8] See Zeithaml, Parasuraman, and Berry [19].

Consumers' perceived expectations regarding a product depend on several factors and can include many different notions of product quality and of service quality, value–price concept (a more costly product must perform better), manufacturer's reputation, product advertising, and so forth.

Satisfaction (or dissatisfaction) is linked to an evaluation or discrepancy between prior expectations and the actual (or perceived) product performance and quality of service. A customer is satisfied when performance exceeds expectations. The reverse situation leads to a dissatisfied customer.[9]

In the context of a product sold with warranty, a claim occurs when the item fails and is still under warranty. Each failure generates a level of dissatisfaction that tends to decrease with time. The timing of a failure has a significant effect on the level of dissatisfaction, as indicated in Figure 10.4, where the following four cases are illustrated [23]:

- Case (a): The first failure occurs very soon after purchase and hence leads to a high-level initial dissatisfaction.
- Case (b): Failure occurs late in the warranty period and the initial dissatisfaction level is medium to low.
- Case (c): Failure occurs very soon after the warranty has expired. In this case the dissatisfaction level is high for the simple reason that the customer has to pay for a repair, as opposed to not paying had the failure occurred just before the warranty expired.
- Case (d): Failure occurs well after the warranty has expired and in this case the initial dissatisfaction level is low.

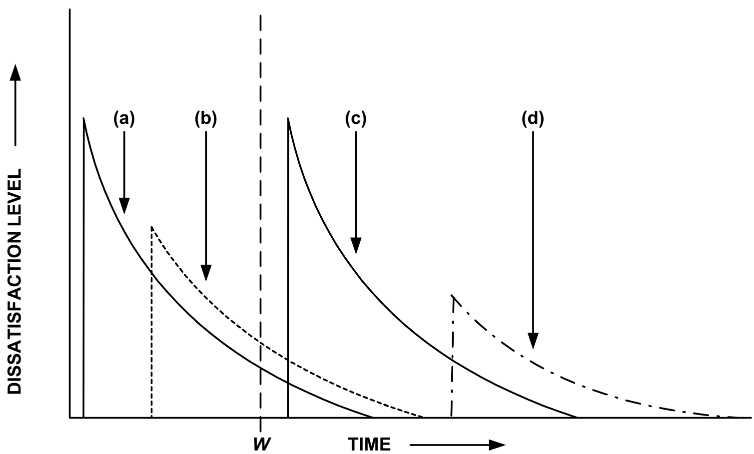


Figure 10.4. Dissatisfaction level versus timing of failures

[9] Most books on consumer behavior (e.g., Neal, Quester, and Hawkins [22]) discuss consumer satisfaction in detail.

The timing of failures and warranty expiration may have more complex effects on consumer reaction. The dissatisfaction resulting from multiple failures is cumulative so that failures occurring frequently can lead to the levels staying high for significant periods of time.

The level of dissatisfaction also depends on the whether the warranty claim is serviced or not and the manner in which it is serviced. We will look at some of the important issues involved in warranty servicing in Chapter 11.

Measuring customer satisfaction/dissatisfaction can be done through a properly designed questionnaire using a scale with discrete levels and ranging from strongly satisfied to strongly dissatisfied.[10] Another approach is through *critical incidents*, that is, events that are out of the ordinary in the mainstream of events that may occur [26]. Such an incident may cause a positive or negative adjustment to a customer's opinion of the quality of a product or its support services. This approach has been used to study consumer response to product quality in the case of automobiles [27].

10.5.3 Intentions of Consumers

Some of the possible reactions of dissatisfied consumers are shown in Figure 10.5. A very small fraction of consumers feel that they cannot suffer from consumer problems. These have a strong disinclination to be identified as being victims of product failure and will not take any action at all, even though they are dissatisfied. The remaining dissatisfied consumers would take actions to seek redress. Several paths for seeking redress are shown in Figure 10.5. When all options fail, or the consumer feels that seeking redress will not work, a consumer might decide on other actions such as warning others or boycotting the product. In either case, future sales are affected as a result of potential customers being turned away because of negative word-of-mouth reports or the loss of existing customers.

The significance of the word-of-mouth effect can be seen from the following statements:

- "Seventy-two percent of customers who switched to a competitor did so because of customer service problems."[11]
- "Sixty-one percent of customers polled say that their pre-purchase decisions were most influenced by the opinions of their friends, i.e., the importance of word-of-mouth"[12] "These "customer salespeople" are ten times more effective than any salesperson on payroll." [28]

These imply that word-of-mouth reports (positive or negative) have a significant influence on potential customers.

---

[10] Measuring satisfaction for consumer durables is different from that for industrial products. For more details regarding satisfaction with consumer durable products, see Oliver [24]. For industrial products, see Homburg and Rudolph [25].

[11] Based on a study by the Forum Corporation.

[12] Based on a General Electric Study, *The Information Challenge*.

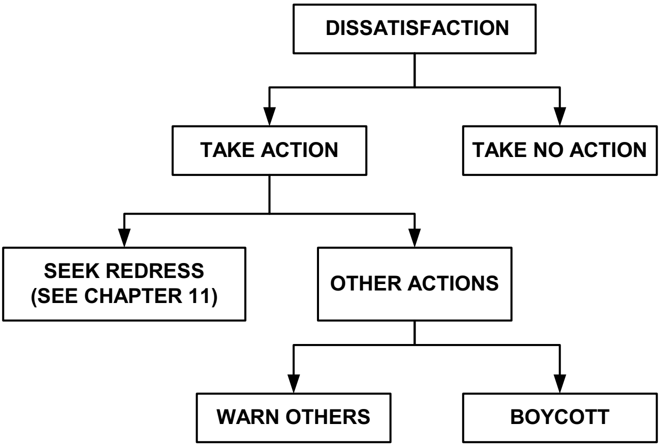


Figure 10.5. Consumer reaction to dissatisfaction

10.5.4 Customer Loyalty

Customer loyalty was mentioned briefly in Section 2.3.4. A definition of loyalty is the following:

> A deeply held commitment to re-buy or re-patronize a preferred product/service consistently in the future, thereby causing repetitive same-brand or same-brand-set purchasing, despite situational influences and marketing efforts having the potential to cause switching behavior. [24]

Satisfaction and loyalty are closely linked. Satisfaction is necessary, but not sufficient, for loyalty. Loyalty relates to repeat purchases and new purchases through referrals (word-of-mouth effect). According to Gitomer [28],

> The only way to measure loyalty is by the number of unsolicited referrals and re-orders received by the seller.

Customer loyalty impacts on profits:

> A 5% increase in customer retention leads to an increase in profits of 25–95% over 14 different industry sectors. [29]

Warranties can be used effectively to reduce the impact of dissatisfaction resulting from poor product performance and ensuring loyalty. This is discussed further in Chapter 13.

If customers are dissatisfied either with the product or service quality, then they are more likely to switch. In the simplest characterization, the probability of switching depends on the number of failures experienced in the warranty period. One form of this is indicated in Figure 10.6. A loyal customer may continue to purchase replacement items with near certainty up to a point (at N_1 failures) and then with decreasing probability to a point (at N_2 failures) where there is no chance of a repurchase, i.e., product switching is certain. In real life, the probability of repurchase is a more complex function that depends not only on the number of failures, but also on other factors such as the timing of failures, quality of service etc.

10.6 Market Outcome [Marketing Perspective]

In this section we look at the effect of warranty and other variables on product sales.

10.6.1 Total Sales

Total sales over the life cycle of a product depend on a number of marketing variables. Two that have significant impacts are price and warranty. Other variables that are important are advertising, quality of product, and reputation of the manufacturer. Many different static models have been proposed to model total sales for decision making at the front-end stage of a product life cycle.[13] One such model has been used in prediction of the effect of warranty on automobile sales in the USA [31]. Of particular interest in this context is *warranty elasticity*, that is, the ratio of relative change in sales to relative change in the length of the warranty period.[14] Warranty elasticity for Chrysler is claimed to be 0.143, which is considered to be in the typical range of advertising elasticities reported in the marketing literature [4].

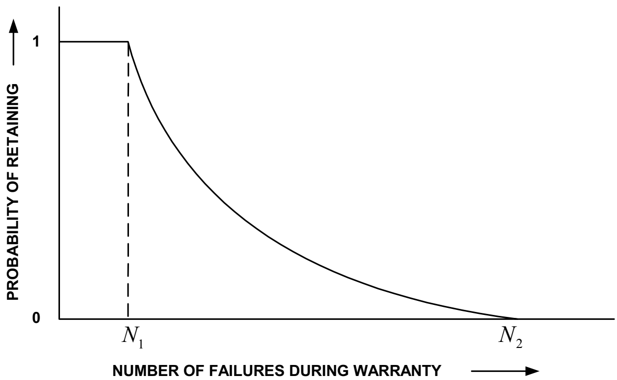


Figure 10.6. Probability of retaining customers versus number of failures

[13] Total sales L is modeled by a relationship $L = g(P, W, A, \ldots)$, where P is the sale price, W the length of the warranty, A the advertising effort (in \$), and so on. A simple model that has been used extensively is the Cobb–Douglas model given by $L = KP^{\alpha}W^{\beta}$. (See Murthy and Ravi Kumar [30].)

[14] More specifically, this is given by $[\partial L(P, W, A, \ldots)/\partial W]/[L/W]$. In the case of the Cobb–Douglas model, the warranty elasticity is given by β.

10.6.2 Dynamic Sales

Here one models the sales rate (sales per unit time) over time. The models vary from simple ones in which sales rate is modeled as a function of time, to fairly complicated models involving differential equations. In these models, warranty is modeled as a parameter that is intended to capture its advertising role.[15]

10.6.3 Pricing Warranty

The expected cost of servicing warranty is discussed in Chapter 7. This needs to be factored into the sale price, as warranty is integral to product sale. In contrast, extended warranties are optional warranties which consumers buy separately. The expected cost of servicing extended warranties can be obtained in a manner similar to that for normal warranties. Models for pricing based on consumer and manufacturer risks have been developed [33].

For many products, the price that providers of extended warranty (manufacturer or a third party) charge is well in excess of the fair actuarial price based on viewing warranty as an insurance. Extended warranties have generated huge profits.[16] This has led to legislation being introduced to curb such exploitation.[17]

10.7 Market Outcome [Microeconomics Perspective]

Economists model consumer choice as an optimization problem where consumers aim to maximize their expected utility taking into account the attitude to risk and the information available at the time of making the purchase decision.

Economists have identified four different reasons why offering warranty can increase producers' profits. The first three are applicable to both monopolistic as well as competitive markets whereas the last is only for the competitive case. They are as follows:

1. Warranties provide insurance against the risk of product failure.
2. Warranty may convince consumers that the product has high quality and reliability.

---

[15] The most well-known model is the diffusion model. Let $S(t)$ denote total sales till time t, with product launch being treated as $t = 0$. The simplest diffusion model is given by

$$dS(t)/dt = [a + bS(t)][L - S(t)],\ S(0) = 0$$

The parameter L represents total sales as discussed earlier. a and b are two other parameters. The latter captures the word-of-mouth-effect and the former represents the effect of direct advertising. As a result, all three parameters are functions of the warranty period W. For more on diffusion models, see Mahajan and Wind [32].

[16] Padmanabhan [34] discusses this topic in detail and gives the following statistics: Sears' revenue from extended warranties in 1991 was in excess of $1 billion; at least half of the profits of major appliance store chains are due to extended warranties, and major automobile manufacturers report revenue in excess of $100 million from sale of extended warranties.

[17] 2003 *Warranty Week* has several articles dealing with this problem in the UK.

3. When consumers are non-homogenous (with respect to some trait such as, for example, attitude to risk) then warranties can be used to segment the market.
4. To compete with each other using warranty as a marketing variable similar to other marketing variables such as price.

Lutz [5] considers the first three reasons, reviews the relevant literature for each of these, and discusses their managerial implications. It is important to note that the implications depend critically on the assumptions made with regard to the different consumer attributes discussed above. Although the models are stylized, they do provide some insight that can help managers in effective warranty management. We summaries some of the results reported in the literature:

- When consumers vary in their valuation of the product, high-valuation consumers are willing to pay a higher price for an extensive warranty in a competitive market with risk-neutral consumers. In a monopolistic market with risk-averse consumers, high-valuation consumers always pay a higher price but may purchase a product with lower quality or a lower warranty.
- When consumers vary in income, are risk averse, and take no maintenance actions, then high-income consumers are willing to pay more for the product. For this group, the manufacturer should charge more by offering an extensive warranty.
- When consumers vary in their degree of risk aversion, then less risk-averse consumers are willing to pay more for the product but less willing to pay more for warranty. In this case the manufacturer can segment the market by offering no warranty or small warranty for less risk-averse consumers and offer more extensive warranty to more risk-averse consumers who are willing to pay a higher price.
- Finally, when consumers vary in their usage intensity, high-usage consumers face a higher risk of failure. As such, they would prefer an extensive warranty at a higher price compared with low-usage consumers who would prefer less extensive warranty.

Padmanabhan [34, 35] looks specifically at extended warranties and their role in the segmentation of the market based on consumer heterogeneity. The managerial implications are similar to those discussed above but the focus is on providing a clear understanding of the role of base warranty and the segmentation role of the extended warranty.

10.8 Warranty Strategy

From a marketing perspective, warranties can be used either in an offensive manner or in a defensive manner [31]. Used in an offensive manner, warranties can help:

1. Accelerate the adoption of new products by reducing the perceived risk, and
2. Increase consumption of another product (tie-in promotions). An example of this is some credit cards offering extra warranty coverage for products purchased using the card.

This implies that an offensive strategy is appropriate for expensive durable products lasting for a long time (for example, domestic appliances, automobiles, etc), and for which the cost to repair failures is high and customers are risk averse. The goal is to maximize revenue or profits.

Used in a defensive manner, warranties can help:

1. Limit manufacturer's liability,
2. Avoid losing market share by matching the competitor's warranty terms, and
3. Correct consumer misperception about a product.

This implies that a defensive strategy is appropriate for products that do not have long durability (for example, batteries) and the goal is to maintain market share and improve customer satisfaction.

A warranty strategy involves deciding on several elements of the warranty, called the "*warranty program mix,*" [31] and involves making decisions with regard to the following:

- *Warranty type*: FRW, PRW or Combination; renewing or nonrenewing
- *Warranty length*: Duration of the warranty period
- *Warranty breadth*: This defines the extent to which a product is warranted. Some might have full coverage whereas others might have limited coverage. For example, some components of the product are covered for a longer period (e.g., the compressor in a refrigerator or the picture tube in a television) and the rest for a shorter period.
- *Product scope*: This deals with base warranty (offered with all products) and extended warranties (or service contracts) for some, sold at a higher price.
- *Market scope*: This is relevant when the product is marketed in different markets (for example, different countries) so that they take into account the local warranty legislation, consumer heterogeneity, etc.
- *Coverage*: This deals with issues such as whether material, parts, or both are covered under warranty and whether there are any deductibles.
- *Conditions*: These state the conditions to be met in order to invoke a warranty claim. An example is that consumers must register their product within a specified period subsequent to the purchase.

Warranty programs should be designed differently depending on whether the objective is offensive or defensive. The elements of the strategy for the two approaches are given in Table 10.2.

Table 10.2. Designing a warranty program mix

ELEMENTS	STRATEGY	
	Offensive	**Defensive**
Warranty type	FRW	PRW
Warranty length	Medium / long	Short / medium
Warranty breadth	Broad	Narrow
Product scope	All components covered over the warranty period	Some components not covered for the whole period
Market scope	Global	Limited (country, region)
Coverage	Parts and labor	Parts or labor
Conditions	Loose	Strict

The mix of the elements is, to some extent, a function of various product, manufacturer- and consumer-related factors. The product factors include product characteristics (such as failure rates of different components), repair costs for different components, etc. Manufacturer-related factors include product price, response to competitor's actions, and so forth. Finally, some of the consumer-related factors are ownership length, attitude to risk, warranty elasticity, price elasticity and warranty execution.

Other issues such as transferable warranties,[18] flexible warranties (in the case of two-dimensional warranties), and incentive warranties (where customers exercising due care and proper maintenance are rewarded through free servicing of claims beyond the warranty period) are options that manufacturers might explore as part of the warranty strategy.

References

[1] Webster, F. E. Jr. (2002), "The role of marketing and the firm," in *Handbook of Marketing*, B. Weitz and R. Wensley (eds), Sage Publications, London, pp. 66–82.

[2] *New York Times*, August 4, 2002.

[3] *New York Times*, January 16, 2003.

[4] Padmanabhan, V. (1996), "Marketing and Warranty," Chapter 15 in *Product Warranty Handbook*, W. R. Blischke and D. N. P. Murthy (eds), Marcel Dekker, New York, pp. 393–408.

[5] Lutz, N. A. (1996), "The Economic Theory of Warranties," Chapter 25 in *Product Warranty Handbook*, W. R. Blischke and D. N. P. Murthy (eds), Marcel Dekker, New York, 659–674.

[6] Russo, J. E. and Carlson, K. A. (2002), "Individual decision-making," in *Handbook of Marketing*, B. Weitz and R. Wensley (eds), Sage Publications, London, pp. 371–408.

[7] Kirmani, A. and Rao, A. R. (2000), "No pain, no gain: A critical review of the literature on signaling unobservable product quality," *Journal of Marketing* **64** (April), 66–79.

[18] For example, Daimler Chrysler offering a 7-year and 70,000 miles transferable warranty in response to Suzuki's 10 years and 100,000 miles non-transferable warranty.

[8] Price, L. J. and Dawar, N. (2002), "The joint effects of brands and warranties in signaling new product quality," *Journal of Economic Psychology* **23**, 165–190.

[9] Kelly, C. A. (1996), "Warranty and Consumer Behavior: Product Choice," Chapter 16 in *Product Warranty Handbook*, W. R. Blischke and D. N. P. Murthy (eds), Marcel Dekker, New York, 409–419.

[10] Balchander, S. (2001), "Warranty signaling and reputation," *Marketing Science* **47**, 1282–1289.

[11] Cooper, R. and Ross, T. W. (1985), "Product warranties and double moral hazard," *RAND Journal of Economics* **16**, 103–113.

[12] Hudson, J. and Jones, P. (2001), "Measuring efficiency of stochastic signals of product quality," *Information Economics and Policy* **13**, 35–49.

[13] Baker, M. J. (ed) (2000), *The Marketing Book*, Butterworth Heinmann, Oxford.

[14] *Bloomberg News*, September 6, 2002.

[15] Purohit, D. and Srivastava, J. (200x), "Effect of manufacturer reputation, retailer reputation and product warranty on consumer judgment of product quality: A cue diagnosticity framework," *Journal of Consumer Psychology*, (to appear).

[16] Tan, S. J. and Leong, W. Y. (1999), "Warranty strategy: a solution to hybrid product woes?" *International Marketing Review* **16**, 40–64.

[17] Ahmed, S. A. and d'Astous, A. (1995), "Comparison of country-of-origin effects on household and organizational buyers' product perceptions," *European Journal of Marketing* **29**, 35–51.

[18] Tan, S. J., Lee, K. S. and Lim, G. H. (2001), "Warranty and warrantor reputations as signals of hybrid product quality," *European Journal of Marketing*, **35**, 110–132.

[19] Zeithaml, V. A., Parasuraman, A., and Berry, L. B. (1990), *Delivering Quality Service*, The Free Press, New York.

[20] Levitt, Ted (1986), *The Marketing Imagination,* The Free Press, New York,

[21] Evanoff, T. "Today's cars are built to last", http://usatoday.com/money/autos /2002-12-12-newcars_x.html.

[22] Neal, C., Quester, P. and Hawkins, D. (1999), *Consumer Behavior*, McGraw Hill, New York.

[23] Lassar, W. H., Folkes, V. S., Grewal, D. and Costley, C. (1998), "Consumer affective reaction to product problems when the timing of warranty expiration varies," *Journal of Business Research*, **42**, 265–270.

[24] Oliver, R. L. (1996), *Satisfaction: A Behavioral Perspective on the Consumer*, McGraw Hill, New York.

[25] Homburg, C. and Rudolph, B. (2001), "Customer satisfaction in industrial markets: dimensional and multiple role issues," *Journal of Business Research* **52**, 15–33.

[26] Flanagan, J. C. (1954), "The critical incident technique," *Psychological Bulletin* **54**, 327–358.

[27] Archer, N. P. and Wesolowsky, G. O (1996), "Consumer response to service and product quality: A study of motor vehicle owners," *Journal of Operations Management* **14**, 103–118.

[28] Gitomer, J. (1998), "*Customer Satisfaction is Worthless: Customer Loyalty is Priceless,*" Bard Press, Austin.

[29] Reichheld, F. (1996), *The Loyalty Effect*, Harvard Business School Press, Cambridge, Mass.

[30] Murthy, D. N. P., and Ravi Kumar, K. (2000), "Total quality in a channel of distribution," *International Journal of Production. Economics*, **67**, 253–268.

[31] Menezes, M. A. J., and Quelch, J. A. (1990), "Leverage your warranty program," *Sloan Management Review* 31, 69–80.

[32] Mahajan, V., and Wind, Y. (1986), *Innovation Diffusion Models of New Product Acceptance*, Ballinger Publishing Company, Cambridge Mass.

[33] Chun, Y. H. and Tang, K. (1995), "Determining the optimal warranty price based on producer's and customers' risk preferences," *European Journal of Operational Research*, **85**, 97–110.

[34] Padmanabhan, V. (1996), "Extended Warranties," Chapter 18 in *Product Warranty Handbook*, W. R. Blischke and D. N. P. Murthy (eds), Marcel Dekker, New York, 439–452.

[35] Padmanabhan, V. (1995), "Usage heterogeneity and extended warranties," *Journal of Economics and Management Strategy* **4**, 33–53.

11

WARRANTY LOGISTICS

11.1 Introduction

Products offered with warranty must be serviced on failure, either by the manufacturer or his agent. Failure to deliver proper warranty service can have a negative impact on sales and hence negate the reasons for offering the warranty in the first place. This implies that product warranty logistics is very important for customer satisfaction as well for manufacturers' profitability. The outline of the chapter is as follows. We begin with a brief introduction to logistics in Section 11.2. This sets the background for topics discussed later in the chapter. Section 11.3 deals with product warranty servicing. The logistics issues in the servicing of warranty claims at the strategic level and subsequently at the operational and tactical levels are discussed in Sections 11.4 and 11.5, respectively. Section 11.6 deals with some related topics of relevance to product warranty logistics.[1]

11.2 Logistics: An Overview

11.2.1 Classification

Logistics can be broadly divided into the following three categories:

- **Supply chain logistics:** Supply chain logistics deals with the delivery of inputs from suppliers to the manufacturing plant and the delivery of finished goods to various demand centers. It deals with raw materials and components on the input side and finished products on the output side.
- **Service response logistics:** Service response logistics is the process of coordinating non-material activities necessary to the fulfillment of the service in an effective way. Service response logistics has a different focus from supply chain logistics in that supply chain logistics focuses on

[1] This chapter is based, to a large extent, on Murthy, Solem, and Roren [1].

physical supply and distribution of products, while service response logistics emphasizes building responsive organizations, that can respond to customer requests. This difference in emphasis is illustrated in Figure 11.1.

- **Product support logistics:** Product support logistics deals with the provisioning, procurement, materials handling, transportation and distribution, and warehousing of the items and the support infrastructure needed for carrying out these activities over the life of the product. Figure 11.2 shows the main elements of product support logistics.

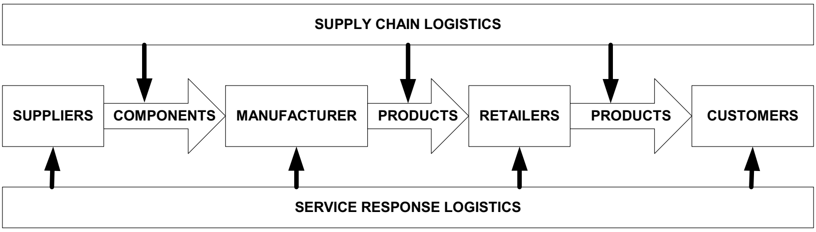


Figure 11.1. Supply chain logistics and service response logistics

11.2.2 Logistics Management

Logistics management[2] deals with decision-making at three different levels:

- *The strategic level* deals with decisions that have long-lasting effects on the firm. This includes decisions regarding the number, location and capacities of warehouses and manufacturing plants.
- *The tactical level* typically includes decisions that are updated anywhere between once every quarter and once every year. This embraces purchasing decisions, inventory policies and transportation strategies, including the frequency with which the retailers are visited.
- *The operational level* refers to day-to-day decisions such as scheduling, routing trucks, and measuring performance.

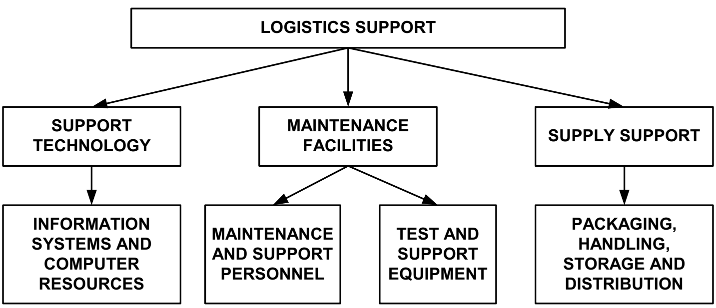


Figure 11.2. Elements of product logistic support

[2] There are many books dealing with logistics management. See, for example, Bowersox and Closs [2], Christopher [3], and Coyle, *et al.* [4].

Some of the key issues, all of which have been studied extensively, are the following:

- **Channels:** A manufacturer can choose between four main distribution channels for getting the product from the factory to customers. These are (i) manufacturer direct, (ii) company-owned dealerships, (iii) independent retailer, and (iv) some combination of the first three. The co-ordination between the different elements (manufacturer, wholesaler and retailer) is important in the context of both supply chain and service response logistics.[3]
- **Location:** The geographical placement of material stocking points is an important element of logistics strategy. In the context of supply chain logistics, fixing the number, location, and size of the warehouses, and assigning market demand to them, determines the paths by which products are directed to the marketplace. As a result, one has a distribution network with warehouses and manufacturing plants being the nodes. Decisions with regard to warehouse location must include all product movements and associated costs as they take place from plant location, through intermediate stocking points to customer locations, and finally back to the manufacturer for repair or replacement. Note that the supply chain can involve a multi-echelon structure for the warehouse locations. There can be more than one echelon for service facilities and the location of different echelon service centers is a problem of assigning these centers to different nodes of the network.[4]
- **Inventory levels:** The management of inventory levels for both supply chain and service support logistics deal with the ordering policies. There is a trade-off between the cost associated with, and the benefits derived from, having an inventory, and several strategies have been proposed and studied. In the case of supply chain logistics, two strategies are the "push-method" based on centralized control and the "pull-method" based on decentralized control. In the push-method, decisions to replenish warehouses are made by using forecast requirements within the warehouse territory and for the distribution system as a whole. In the pull-method, the decisions are made independently at each warehouse so that it can respond to the local market needs more effectively.[5]
- **Transportation:** Supply chain logistics deals with the transportation of raw material and components from suppliers to the manufacturing plant and the transportation of finished products from plants to retail markets via a hierarchy of warehouses and retail outlets. Similarly, service logistics and product support logistics also require transportation of material (parts, failed items, etc.) from one location to another. Transportation must be

[3] The linkage between product distribution and service support channels is discussed in Loomba [5]. For more on marketing channels, see Lewis [6].
[4] For more on the location problem, see Daskin [7], Dresner [8], Handler and Mirchandani [9], and Owen and Daskin [10].
[5] For more on inventories, see Hadley and Whitin [11], and Gupta and Korugan [12].

effectively managed if the firm is to satisfy its customers and achieve an acceptable rate of return on its investments. With rapidly rising fuel costs, and therefore transportation costs, this element takes on increasing importance in the overall strategy. The cost of transportation depends on the arcs of the distribution network that connect the plants and warehouses. In some cases, transportation is outsourced to an external independent agent.

- **Level-of-repair analysis:** In the context of product support service, a topic of relevance to warranty logistics is the level-of-repair analysis (LORA). This basically deals with the task of determining whether an item is to be treated as discardable (also called consumable) or as repairable. If the item is to be treated as repairable, the objective is to determine how and where it should be repaired in a multi-echelon repair facility.
- **Scheduling of repairs:** Product support involves repairing failed items. Products can be differentiated based on whether a failed item is brought to a service center or a repairman needs to go to the failed item. The scheduling of jobs is an important issue that not only has an impact on the overall cost of providing the service but also on customer satisfaction.

There is considerable research dealing with two or more of the above issues in an integrated manner.[6]

11.3 Product Warranty Servicing

Offering a warranty implies that the manufacturer must service claims resulting from product failures over the warranty period. The nature of servicing depends on the type of warranty. For consumer durables and standard industrial and commercial products, servicing involves either a refund (in the case of many PRW and all rebate policies) or repair or replacement of failed items or components (for FRW and some other policies).

The warranty servicing process is shown in Figure 11.3. Failures are a function of several variables and these include product reliability (influenced by design and manufacturing decisions of the manufacturer) and the usage mode and environment (influenced by the consumer). As a result, claims under warranty are a function of product reliability, usage mode and environment, the number of items sold and the terms of the warranty policy. The servicing of warranty requires service channels, repair facilities, spares, and equipment to carry out repair/replacement.

[6] See especially Nozick and Turnquist [13], and Jayaraman and Srivastava [14].

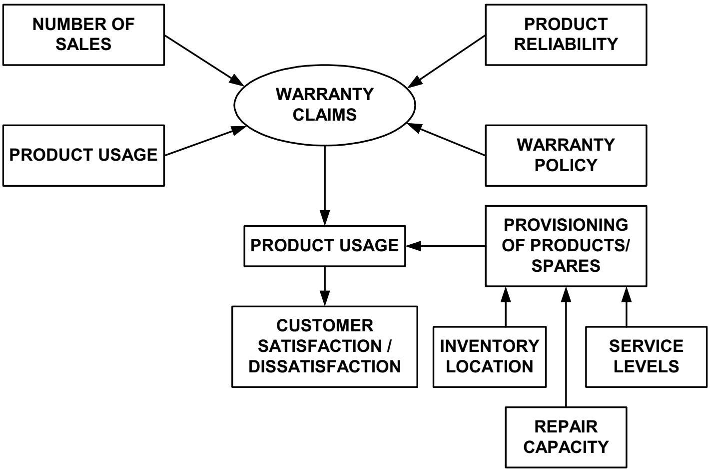


Figure 11.3. Warranty servicing process

11.3.1 Warranty Claims

We consider a product life cycle of length L and a warranty period of length W. Here the life cycle of interest is the period from the time the product is first introduced into the market to the instant when it is withdrawn from the market due to the appearance of a new and better product that replaces it. A typical form for the sales rate (sales per unit time) is as shown in Figure 11.4. It increases initially and then begins to decrease.

In the case where items are sold with non-renewing FRW policy, the warranty claims occur over the period from time 0, the time at which the product is introduced, until time $(L + W)$, the time at which the last items sold may fail and still be covered by warranty. Claims occur as random points along the time axis and are a function of the reliability of the item. If the failures are minimally repaired and the time to repair is small relative to the time between failures, then warranty claims over the warranty period for a single item can be modeled in a relatively straightforward way as discussed in Chapter 6.[7] The expected claims rate (expected number of claims per unit time) over the period of interest (from zero to $L + W$ in this case) can be determined from this and the sales rate. Figure 11.4 shows a typical plot of the expected warranty claims rate. The latter curve is similar to that of the sales rate, but lags behind it.

[7] Under the stated assumptions, the rate of occurrence of warranty claims for a single sale is identical to the ROCOF.

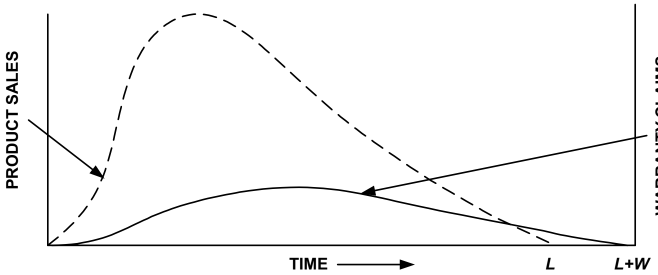


Figure 11.4. Sales rate and expected warranty claims

11.3.2 Warranty Logistics

Warranty logistics deals with all the issues relating to warranty servicing.[8] As mentioned earlier, this has a significant impact not only on the warranty servicing cost but also on customer satisfaction. Proper management of warranty logistics is very critical for business survival and success. This is becoming more important as customers demand greater assurance and most countries have either enacted or are in the process of enacting stricter legislation to protect consumer interests.

The manufacturer's ability to service warranty is affected by the geographical distribution of customers and by the level of their demand for prompt response. The manufacturer needs a dispersed network of service facilities that store spare parts and provide a base for field service. The service delivery network requires a diverse collection of human and capital resources and careful attention must be paid to both the design and the control of the service delivery system. This involves several strategic and operational issues.

The strategic issues are (i) the number of service centers and their location, (ii) the capacity and manning for each service center (to ensure desired response time for customer satisfaction), and (iii) whether to own these centers or out-source them so that the service is carried out by an independent agent. The tactical and operational issues are (i) transportation of the material needed for warranty servicing, (ii) spare parts inventory management, (iii) scheduling of jobs, and (iv) optimal repair/replace decisions.

The three different types of logistics discussed in Section 11.2 are all of relevance in the context of warranty logistics and the management of warranty servicing logistics requires input from many disciplines. In the following three sections, some of the important issues will be discussed and the challenges highlighted.

11.4. Strategic Issues

The main strategic issues in warranty logistics are the location of warehouses and

[8] There is a vast literature on servicing. See, for example, Cohen and Lee [15], and Klimberg and Van Bennekom [16].

service centers, and the channels for warranty servicing. When the channel involves an independent agent, several problems arise and these need to be understood and resolved properly.

11.4.1 Location of Service Centers and Warehouses

The location of both service centers (for carrying out repairs) and warehouses (for stocking spares needed) depend on the geographical distribution of customers who have bought the product and the type of product and its reliability characteristics.

11.4.1.1 Location of Service Centers

In general, most products are complex systems that can be decomposed into many different levels. When an item fails, the first task is to determine and identify the most likely cause of failure. For certain products (such as a large appliances in the home or an elevator in a multi-story building), this requires on-site evaluation and repair of the failed item. For others, the failed item is brought to either the retailer (in the case of many consumer durables) or to some designated service center. For most products, the failed item is made operational through appropriate actions at this level. However, in some instances, it is not possible to rectify a failure at this level due to the lack of resources such as special equipment and/or appropriately trained personnel. In this case, the failed component must be removed and shipped to a higher-level service center for rectification. Often, there can be more than two levels, depending on the complexity of the product and the type of resources needed for rectification. For example, in the case of a jet engine, this might involve a service facility at major airports (level 1) followed by a national (or regional) service center (level 2) and a service center at the manufacturing plant (level 3). If the item is to be treated as repairable, the objective is to determine where it should be repaired in a multi-echelon repair facility.[9]

Models to determine the number of levels, the location of the service centers and their capacities must take into account the following:

- Transportation time and cost for moving failed and repaired items between service centers
- The cost of operating the service centers (equipment and skilled persons needed at each center)
- The capacity needed at each service center.

The service center capacity requirement depends on the demand for services at the center. This in turn depends on the geographical distribution of sales and on product reliability.

---

[9] Alfredsson [17] deals with decisions with regard to LORA and the spare parts and test equipment needed to support a system. Barros and Riley [18] deal with optimization of the LORA. A related issue is the choice of best maintenance action from a set of desirable maintenance actions. This is discussed in Cassady, Murdock, and Pohl [19]. These have implications for spare parts support.

In solving the location problem, the following issues need to be addressed:

1. Coverage (so that all the customers are covered)
2. Distance that a failed item must travel
3. Distance that a repairman has to travel in case of a field visit or that a customer has to travel to bring a failed item to a service center or collection point.

Given the coverage, the model discussed in Chapter 6 can be used to determine the demand and the service capacity of the center.

11.4.1.2 Location of Warehouses

Depending on the geographical area of the market, the manufacturer might need to have a network of warehouses with a multi-echelon structure involving one or more levels. For example, a multi-national manufacturer might have a regional warehouse (level 4) receiving parts for the different component manufacturers and feeding to national warehouses (level 3) which in turn might feed to local distributed warehouses (level 2) which in turn feed parts to service centers (level 1).

Two key issues are the location of the warehouses and the capacity of each warehouse, defined through the quantities of different components that need to be stocked. As mentioned in Section 11.3, this problem has received some attention in the logistics literature. However, the models need to be modified to take into account the location of the service centers and the reliability characteristics of the product. The optimal location must take into account the following:

- Transportation time and cost for moving parts between warehouses (in the case of multi-echelon warehouses) and from warehouses to service centers
- The cost of operating the warehouses
- The capacity of each warehouse based on the demand for spares from the various service centers that are serviced by the warehouse.

11.4.2 Demand for Spares

The management of inventory levels for both supply chain and service support logistics deal with the ordering policies. There is a trade-off between the cost associated with, and the benefits derived from, having an inventory, and several strategies have been proposed and studied. Several methods have been developed to control the reordering of items.[10]

At the highest level of warehouse, the total demand for spares (of a component) over the product life cycle can be modeled as follows. If the replacement time of a failed component is small relative to the mean life of the component, then the demand for replacements over the warranty period can be modeled as a point process.

---

[10] These include the reorder point control, fixed interval control, and the min-max-control. For more details, see, for example, Candea and Hax [20], and Sherbrooke [21].

Example 11.1 [Photocopier]
The cleaning web of a photocopier must be replaced whenever it fails. In Example 6.8, we looked at modeling cleaning web failures based on failure data. A two-parameter Weibull distribution (with scale parameter 129 days and shape parameter 1.48) was suggested as a reasonable model when failure was measured in days. The expected number of replacements needed increases with age and is given in Table 11.1.

Suppose that the age profile of the machines that the service agent is servicing is as given in Table 11.2. Suppose that the photocopier is sold with a three-year warranty. Then the expected number of replacements needed to service failures under warranty is shown in Table 11.3. Note that this decreases in time, reflecting the fact that in the first year, the service agent is servicing 70 copiers and this drops to 60 in the second year (as copiers that are 3 years old are no longer covered under warranty) and to 50 in the third year.

Table 11.1. Expected replacements for photocopier

Age (years)	Expected total number of replacements	Expected annual replacement
1	2.87	2.87
2	6.00	3.13
3	9.13	3.13
4	12.26	3.13
5	15.39	3.13
6	18.52	3.13
7	21.65	3.13
8	24.78	3.13
9	27.91	3.13
10	31.04	3.13

Table 11.2. Age profile of photocopiers

Age	0	1	2	3
Number	30	20	10	10

Table 11.3. Expected number of replacements needed to service

Year	1	2	3
Expected number of replacements needed	180.0	156.5	86.1

■

11.4.3 Service Channels

The manufacturer can choose between many different distribution channels for moving the product from the factory to customers. Similarly, for warranty servicing a manufacturer can choose between the following two options:

1. Service provided by the manufacturer (through retail or service centers owned and operated by the manufacturer)
2. Service provided by an independent agent.

11.4.3.1 Independent Service Agents

Many manufacturers employ independent service agents to carry out the warranty servicing function under a properly drafted contract. Since the interests of the two parties are different, this raises several new issues. We highlight these issues by considering the following two contracts as illustrative examples:

Contract A: The manufacturer pays a lump sum to the agent and in return the agent has to service all claims during the warranty period at no additional cost to the manufacturer.
Contract B: The service agent charges the manufacturer for each warranty service.

Issues of relevance in this context include:

- *Informational asymmetry*: The manufacturer has better knowledge of product reliability compared with the agent and similarly the agent has better information regarding field failures than the manufacturer. This asymmetry can lead to each party deciding on actions that are optimal from their own individual perspective but overall sub-optimal.
- *Moral hazard*: This situation arises when the agent shirks in the effort expended (under Contract A) or carries out over-servicing (under Contract B) and the manufacturer is unable to observe the service agent's effort. In the former case, this can lead to customer dissatisfaction and that can affect the manufacturer's reputation and sales.
- *Monitoring*: The manufacturer can obtain new information by monitoring the agent's actions. Such information will allow the manufacturer to assess the warranty servicing carried out by the agent. However, this results in additional effort and cost to the manufacturer.
- *Adverse selection:* This issue arises when the manufacturer has to choose one or more service agents to carry out the warranty servicing from a pool of service agents. The service agents can misrepresent their ability and competencies and the manufacturer is unable to assess them prior to the signing of the contract. This can lead to the selection of inappropriate agents to service warranty.
- *Incentives*: The manufacturer can provide proper incentives to the service agents so that the actions of the agents are in the best interests of the manufacturer and avoid the need for monitoring. A proper contract provides the right incentives for the service agent to provide the optimal effort.
- *Agency cost*: The structuring, administering, and enforcing of contracts result in a cost that is referred to as the agency cost.
- *Risks*: The manufacturer and the service agents have partly differing goals and risk preferences and these impact on their individual actions.

Agency theory provides the framework to deal with the above issues. This has been studied extensively.[11]

Example 11.2 [Automobile]
Truby [24] reports that in the auto industry there have been battles between manufacturers and their dealers and examines problem between Ford and its dealers resulting from Ford's plan to reduce the payment to dealers for the labour cost involved in warranty servicing as part of its cost-reduction effort. Toyota spends, on the average, $300 less per car on warranty costs than Ford and Ford wants to close this gap.

Mechanics challenged Ford's contention that the Tarus sedan steering rack could be replaced and realigned in 1.3 hours, rather than the 4 hours currently allowed. One of the technicians working at a dealer commented that it was getting to a point where most didn't want to perform any warranty work.

■

Comment: Warranty cost depends on the reliability of the product, the terms of the warranty, and the cost of servicing the warranty. If the manufacturer focuses only on the last of these, it can lead to high customer dissatisfaction, not only with the product but also with the warranty servicing and ultimately with the company itself. Shortening the warranty period or otherwise decreasing warranty coverage can also reduce the cost. This also may lead to customer dissatisfaction, and may have the additional negative effect of reducing the company's competitive advantage. The most effective way of reducing the cost of warranty is therefore to increase product reliability. This, however, may require a considerable up-front investment in support of design and engineering efforts. Proper strategic planning requires that the trade-off between this investment and future warranty costs be given careful analysis.

11.5 Tactical and Operational Issues

The tactical and operational issues in warranty logistics deal mainly with activities at the service center level and issues such as spare part inventory levels, transportation of spares from warehouses to service centers, scheduling of jobs, and repair versus replacement decisions.

11.5.1 Spare Parts Inventory

The key issues in spare parts inventories are the following:

1. Which components should be carried as spare parts?
2. What should be the inventory levels?
3. When should the spares be reordered?

---

[11] See for example, Eisenhardt [22] and van Ackere [23]. The study of warranty servicing logistics based on agency theory is a topic that has not been studied.

4. What quantities of spares must be ordered?

These are linked to the expected numbers of failures of components over time and these, in turn, are related to the level of sales over time and to component reliability.

Most models dealing with spare part inventory assume very simple forms for the depletion of inventory. In the warranty-servicing context, the depletion of a particular component occurs in an uncertain manner and depends on sales rate over the region serviced by the servicing center and the reliability of the product. Optimal decisions with regard to inventory levels and ordering policies require taking into this into account.

11.5.2 Material Transportation

Supply chain logistics requires transportation of raw material and components from suppliers to manufacturing plants and the transportation of finished products from plants to retail markets via a hierarchy of warehouses and retail outlets. Similarly, service logistics and product support logistics also require transportation of material (parts, failed items, etc.) from one location to another. As a result, the disciplines of materials management and of operations management deal, in part, with transportation problems [25, 26]. Many issues relating to transportation have been studied. These include integrating inventory and transportation [27], contracts [28], and emergency transshipments [29].

Related more specifically to warranty servicing logistics, one can define three kinds of material transportation:

1. Transportation of failed units from a lower level to a higher level in the case of a multi-echelon service structure
2. Transportation of repaired items from service centers to customers or pick-up points where customers can collect them
3. Transportation of spares to and from warehouses.

The quantities to be moved are random entities and are related to sales and product reliability. Transportation can be carried out either by the manufacturer or by an independent agent. In the latter case, a contract between the manufacturer and the independent agent must take into account the following: cost of transportation, frequency of transportation, upper limits on quantities to be transported, time limits, penalties for delays in delivery and breaches of contract, and so on.

Note that the agency problems discussed in Section 11.4 are also relevant in this case and different contract options may be evaluated using the agency theory framework.

11.5.3 Scheduling of Jobs, Repairs and the Traveling Repairman Problem

Product support involves repairing failed items. Products can be differentiated based on whether a failed item is brought to a service center or a repairman needs to go the failed item. In the former case, the scheduling of jobs is an important issue that not only has an impact on the overall cost of providing the service but also on customer satisfaction. Scheduling of jobs has been extensively studied [30, 31, 32]. An important problem in this area is the scheduling of jobs so as to reduce the time spent in traveling between jobs. This is called the "traveling repairman problem," and a number of solutions have been proposed [33, 34, 35]. For products that are brought to the service center (or retail outlet) this is not a problem as items are processed using the first-come-first-served rule. However, should the warranty include penalties for delays, then the scheduling needs to take this into account as well.

11.5.4 Replace versus Repair Strategies

Whenever a repairable item fails under warranty, the manufacturer has the option of either repairing the failed item or replacing it by a new item. In the case of repair, the manufacturer needs to choose between different repair actions and this impacts on customer satisfaction as well as the warranty servicing cost.

11.5.5 Strategies Based on Age (and/or Usage) at Failure

Here the decision to repair or replace is based on the age of the item at failure in the case of one-dimensional warranties and on the age and/or usage in the case of two-dimensional warranties. The optimal strategy is selected to minimize the expected cost of servicing the warranty over the warranty period.[12]

Example 11.3[13]

Suppose that the failure distribution of the product is given by a Weibull distribution with scale parameter 1 year and shape parameter 2. The product is sold with FRW policy and W is the warranty period. The product is repairable and ρ is the ratio of replacement cost to cost of a minimal repair. The optimal replace–repair policy is complex to implement. A near optimal policy is characterized by the two parameters K and L ($0 \leq K \leq L \leq W$) and is as follows: All failures occurring in the interval $[0, K)$ are rectified by minimal repair. At the first failure in the interval $[K, L)$, the failed item is replaced by a new item and any subsequent failures in this interval are minimally repaired. Any failure in the interval $[L, W)$ is always minimally repaired.

The three options are: (1) always replace, (2) always repair and (3) near-optimal policy (given above) with K and L selected optimally to minimize the

[12] Blischke and Murthy [36] discuss two sub-optimal strategies for one-dimensional warranties. Jack and van der Duyn Schouten [37] deal with the optimal strategy. Jack and Murthy [38] examine a sub-optimal policy that is very close to the optimal strategy and involves at most one replacement over the warranty period. Iskandar and Murthy [39] extend the results of Blischke and Murthy [36] to two-dimensional warranties. Iskandar, Murthy, and Jack [40] deal with a strategy similar to that in Jack and Murthy [38] in the context of two-dimensional warranties.

[13] From Jack and Murthy [38].

expected warranty servicing cost. The optimizing values are denoted K^* and L^*. Table 11.4 gives the optimal solution for two different values of W and a range of ρ. As can be seen, when ρ is small "always replace" is the best strategy; for intermediate values the near-optimal policy is better and for large values, "always repair" is the best.

Table 11.4. Optimal choice between options 1–3

	W	
ρ	**2**	**3**
1.00	Always replace	Always replace
1.25	Always replace	Always replace
1.50	$K^* = 0.64$ $L^* = 1.87$	Always replace
1.85	$K^* = 0.65$ $L^* = 1.76$	$K^* = 1.21$ $L^* = 2.85$
2.00	$K^* = 0.66$ $L^* = 1.71$	$K^* = 1.21$ $L^* = 2.82$
2.50	$K^* = 0.71$ $L^* = 1.50$	$K^* = 1.21$ $L^* = 2.72$
3.00	Always repair	$K^* = 1.21$ $L^* = 2.62$
5.50	Always repair	Always repair

■

11.5.6 Cost Repair Limit Strategy

In general, the cost to repair a failed item is uncertain. Analogous to the notion of a failure rate function, one can define a repair cost rate function. Depending on the form of the distribution of time to repair, the repair cost rate can increase, decrease or remain constant. A decreasing repair cost rate is usually an appropriate characterization for the repair cost distribution [41]. Optimal repair limit strategies can be determined.[14]

11.6 Other Issues

In this section we briefly discuss several other issues of importance in the context of product warranty logistics.

11.6.1 Dispute Resolution

Disputes in the context of warranties arise when the manufacturer (or service agent) refuses to admit a warranty claim as a valid (or legitimate) claim. This may

[14] These are discussed in Blischke and Murthy [36] and Zuo, *et al.* [42].

occur for a variety of reasons (for example, misuse of the product, claim made after expiration of the warranty) or the customer may simply be unhappy with the warranty service provided. The latter is influenced by the warranty logistics and poor warranty logistics can lead to a greater number of disputes that need to be resolved.

There are several paths that a customer may use in seeking redress, as shown in Figure 11.5. The first course of action is to complain to the manufacturer through the retailer or service agent appointed to service warranty claims. This is a resolution process involving only two parties – manufacturer and dissatisfied consumer. If the resolution is satisfactory, then the problem is resolved. If not, the consumer might either complain to a third party (such as a consumer protection agency or a media channel) and then seek legal action should the problem remain unresolved, or go directly for resolution through legal action. If this leads to a resolution, no further action is necessary. If not, the consumer might pursue other actions. This is discussed in Section 10.5.3.

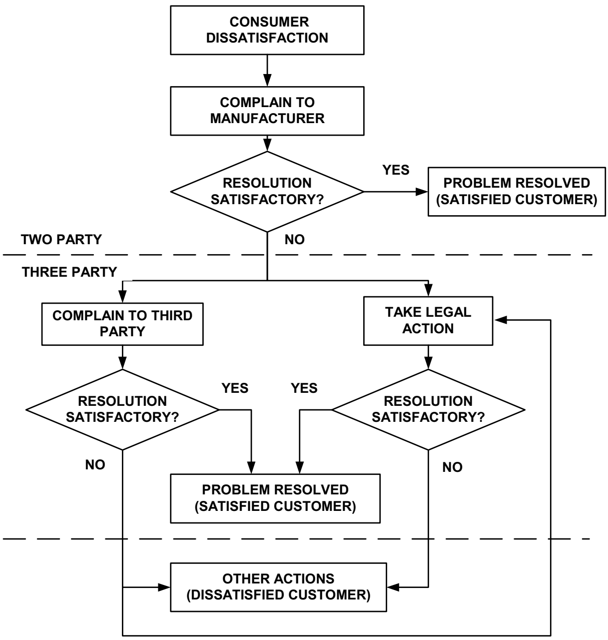


Figure 11.5. Complaint resolution process

Resolution involving a third party (small claims tribunal for relative inexpensive claims or the highest legal institution in the case of very costly claims) is discussed further in Chapter 13.

11.6.2 Customer Satisfaction

Customer dissatisfaction can arise due to poor performance of the purchased item and/or the quality of warranty service provided by the manufacturer. In either case, this has a negative impact on overall business performance, either due to dissatisfied customers switching to a competitor or losing potential new customers because of negative word-of-mouth publicity. The consequence of poor warranty servicing is more difficult and costly to rectify and hence it is very important that the manufacturer avoids this occurring in the first instance.

Figure 11.5 shows the key issues involved and their impact on customer satisfaction. A proper contract between the manufacturer and service agents and the monitoring of the agents' actions are very critical for ensuring high-level customer satisfaction.[15] There are several dimensions to service quality and many of these are intangible and can vary significantly from customer to customer. For example, customers can have undue expectations regarding product performance for a variety of reasons (exaggerated statements made during promotion, customer being not fully informed, etc.). However, other dimensions are more tangible and can be objectively assessed. These include response time to attend to a warranty claim, the time taken to rectify a failed item, delays resulting from lack of spares, workshop resources, etc. Through effective warranty logistics, the negative impacts resulting from these can be minimized.

11.6.3 Service Recovery

While retailers cannot eliminate complaints, they can learn to respond effectively to them. This response, termed service recovery, is defined as the process by which the firm attempts to rectify a service- or product-related failure. Recoveries are critical because customers perceiving poor recovery efforts may dissolve the buyer–seller relationship and purchase elsewhere.

Complaint handling is an important element of service recovery. It is often the manufacturer's (or service agent's) response to a failure, rather than a failure itself, that triggers discontent which in turn leads to dissatisfaction. It is important that the response be perceived as just, as this has a significant impact on satisfaction with the product and service and the firm itself [44]. Three kinds of justice are involved:

- *Distributive justice*: This focuses on the role of "equity" where individuals assess the fairness of exchange by comparing their inputs to outcomes. It is defined as the extent to which customers feel that they have been treated fairly with respect to the *final* outcome. The outcomes of distributive justice can be refunds, discounts, etc., to compensate for product or service failure.
- *Procedural justice*: This refers to perceived fairness of policies and procedures involving the recovery effort. An example of this is where the manufacturer (or service agent) provides a refund but the customer has to go through much hassle to get the refund.
- *Interactional justice*: This indicates the extent to which customers feel

[15] Service quality has been studied extensively. See, for example Haugen and Hill [43].

they have been treated fairly regarding their personal interaction with the service agents throughout the recovery process. This includes features such as honesty, courtesy, interest in fairness perceived by the customer.

The manner in which these affect satisfaction and the resulting consequences is shown in Figure 11.6. In two case studies (banking service and home construction sales), it was found that distributive justice is more pronounced in forming satisfaction with recovery among durable good (home construction) complaints than among service (banking) complaints. Interactional justice is more influential in forming satisfaction in the service case than for the durable good [44].

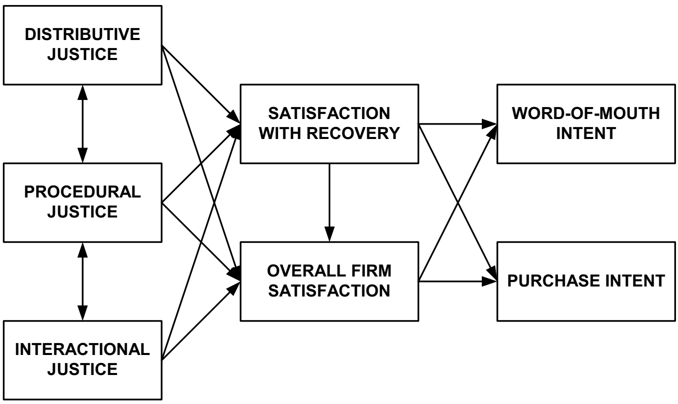


Figure 11.6. Outcome of service recovery

Example 11.4

Distributive justice has been used in the automobile industry to recover from problems associated with a product failing to perform as claimed. The following are an illustrative sample:

- Mazda RX-8 rotary-engine sports car failed to reach the advertised engine power (155 hp) and this caused customer dissatisfaction. Mazda attributed the drop in power (to 142 hp) to the last minute change in engine tuning to meet emission rules but had to act quickly to prevent damage to its reputation. It offered to buy back the car (at full sticker price plus taxes and other fees) irrespective of the mileage or to provide free scheduled maintenance for the fourth-year, 50,000-mile warranty period, plus $500.[16]
- Nissan claimed that its 2002 Infiniti would accelerate to 60 mph in 5.9 seconds. It achieved this result in ideal weather conditions, using a light base model and lightweight driver. It did not offer any compensation to customers to counteract the dissatisfaction [45].
- Ford Motors recalled 8,100 Ford Mustang Cobras after owners found the engines did not produce the advertised 320 hp. Ford blamed changes in

[16] Healey [45]. See http://www.usatoday.com/money/autos/2003-09-03-carbuyback_x.htm

mufflers and intake manifolds for the problem and installed new ones free on nearly all the Cobras [45].

- Some models produced by Honda (2000-01 Honda Odyssey minivans, 2000-01 Honda Accord cars with automatic transmission, 2000-01 Prelude and 2000-03 Acura CL and TL cars) had problems with transmissions slipping out of gear, not going into gear, abruptly downshifting or refusing to shift. Honda offered to extend the warranty from the usual three-year/36,000 miles to seven-years/100,000 miles to placate the dissatisfied customers.[17]

■

11.6.4 Use of Loaners

A critical issue in warranty servicing is the time to service a warranty claim. Quality warranty service requires that this should not exceed some specified value. In some warranty contracts, there is a penalty should this happen. One way for the manufacturer (or agent) to reduce the probability of this happening is to have a stock of loaners that are issued to the owners of failed items while they are undergoing repair. This implies additional servicing costs and the manufacturer must optimally decide on the number of loaners to be held in stock.[18]

11.6.5 Product Recall

Occasionally, a manufacturer finds it necessary to recall either a fraction or all of the items sold, for some rectification action. This can be either voluntary (driven by litigation or warranty cost considerations) or forced upon the company by the rulings of regulatory agencies. The recall of only a fraction of the total production arises when some batches contain defective items resulting from inferior component(s) that were not detected as part of quality control. A total recall situation arises because of poor design specifications that can lead to the product malfunctioning under certain conditions that are discovered only after the items have been produced and sold. In such cases, the manufacturer can be held responsible for damages caused under the terms of warranty for fitness and the recall is to replace the old problem components by newly designed ones.

11.6.6 Data Collection and Analysis

During the servicing of warranty a good deal of data is generated. These data are of several types:

- Product related: failure modes, time between failures, operating

---

[17] Healey [46], http://www.usatoday.com/money/autos/2002-09-20-honda-warranty_x.htm

[18] Karmakar and Kubat [47] deal with a simple model for decision making in the context of loaners.

environment, etc.

- Customer related: satisfaction with regard to the product, warranty service, etc.
- Servicing: spare parts inventories, utilization of service centers, transportation of material, etc.
- Economic: costs associated with different aspects of warranty servicing.

The data need to be collected properly and analyzed to extract information that can be used for improvement activities. Technical data are relevant for design changes, servicing data are important in the context of improving the warranty logistics, and customer and financial data are useful for improving the overall business performance. A warranty management system is needed to help the manufacturer to manage warranty from a product life cycle perspective and a critical element of this is a data collection system. We discuss this further in Chapter 14.

References

[1] Murthy, D. N. P., Solem, O., and Roren, T. (2003), "Product warranty logistics: Issues and challenges," *European Journal of Operational Research*, **156**, 110–126.

[2] Bowersox, D. J., and Closs, D. J. (1996), *Logistical Management: The Integrated Supply Chain Process,* McGraw-Hill, New York.

[3] Christopher, M. (1998), *Logistics and Supply Chain Management, Strategies for Reducing Cost and Improving Service,* 2nd edn, Financial Times Professional Ltd., London.

[4] Coyle, J. J., Bardi, E. J. and Langley, C. J., Jr. (1992), *The Management of Business Logistics,* West Publishing Company, St. Paul, Minnesota.

[5] Loomba, A. P. S. (1996), "Linkages between product distribution and service support functions," *International Journal of Physical Distribution and Logistics Management* **26**, 4–22.

[6] Lewis, E. H. (1968), *Marketing Channels: Structure and Strategy*, McGraw Hill, New York.

[7] Daskin, M. S. (1995), *Network and Discrete Location: Models, Algorithms, and Applications*, John Wiley and Sons, New York.

[8] Dresner, Z. (ed), (1992), *Facility Location: A Survey of Applications and Methods*, Springer-Verlag, New York.

[9] Handler, G., and Mirchandani. P. (1979), *Locations on Network: Theory and Algorithms*, The MIT Press, Cambridge, Massachusetts.

[10] Owen, S. H., and Daskin, M. S. (1998), "Strategic facility location," *European Journal of Operational Research* **111**, 423–447.

[11] Hadley, G., and Whitin, T. M. (1963), *Analysis of Inventory Systems,* Prenctice Hall, Englewood Cliffs, New Jersey.

[12] Gupta, S. M., and Korugan, A. (1998), "A multi-echelon inventory system with returns," *Computers and Industrial Engineering* **35**, 145–148.

[13] Nozick, L. A., and Turnquist, M. A. (2001), "Inventory, transportation, service quality and the location of distribution centers," *European Journal of Operational Research* **129**, 362–371.

[14] Jayaraman, V., and Srivastava, R. (1995), "A service logistics model for simultaneous siting of facilities and multiple levels of equipment," *Computers and Operations Research* **22**,191–204.

[15] Cohen, M. A., and Lee, H. L. (1990), "Out of touch with customer needs? Spare parts and after sales service," *Sloan Management Review* **31**, 55–66.

[16] Klimberg, R. K., and Van Bennekom F. C. (1997), "Aggregate planning models for field service delivery," *Location Science* **5**, 181–195.

[17] Alfredsson, P. (1997), "Optimization of multi-echelon repairable item inventory systems with simultaneous location of repair facilities," *European Journal of Operational Research* **99**, 584–595.

[18] Barros, L., and Riley, M. (2001), "A combinatorial approach to level of repair analysis," *European Journal of Operational Research* **129**, 242–251.

[19] Cassady, C. R., Murdock, W. P., and Pohl, E. A. (2001), "Selective maintenance of support equipment involving multiple maintenance actions," *European Journal of Operational Research* **129**, 252–258.

[20] Candea, D., and Hax, A. C. (1984), *Production and Inventory Management,* Prentice-Hall International, Englewood Cliffs, New Jersey.

[21] Sherbrooke, C. C. (1992), *Optimal Inventory Modeling of Systems: Multi-echelon Techniques,* John Wiley and Sons, New York.

[22] Eisenhardt, K. M. (1989), "Agency theory: An assessment and review," *Academy of Management Review* **14**, 57–74.

[23] Ackere A. van (1993), "The principal/agent paradigm: Its relevance to various fields," *European Journal of Operational Research* **70**, 88–103.

[24] Truby, M. (2003), "Ford warranty fight brews," *The Detroit News*, August 3, 2003.

[25] Tersine, R. J. (1994), *Principles of Inventory and Materials Management,* Prentice Hall, Englewood Cliffs, NJ.

[26] Nahmias, S. (1997), *Production and Operational Analysis,* McGraw-Hill, New York.

[27] Qu, W. W., Bookbinder, J. H. and Iyogun, P. (1999), "An integrated inventory-transportation system with modified periodic policy for multiple products," *European Journal of Operational Research* **115**, 254–269.

[28] Yano, C. A. (1992), "Optimizing transportation contracts to supply just-in-time deliveries: The case of one contracted vehicle per shipment," *IIE Transactions*, **24**, 177–183.

[29] Evers, P.T. (2001), "Heuristics for assessing emergency transhipments," *European Journal of Operational Research* **129**, 311–316.

[30] Hajri, S., Liouane, N., Hammadi, S., and Borne, P. (2000), "A controlled genetic algorithm by fuzzy logic and belief functions for job-shop scheduling," *IEEE*

Transactions on Systems, Man and Cybernetics, Part B (Cybernetics) **30**, 812–818.

[31] Jianer, C. and Miranda, A. (2001), "A polynomial time approximation scheme for general multiprocessor job scheduling," *SIAM Journal on Computing* **31**, 1–17.

[32] Ponnambalam, S. G., Ramkumar, V, and Jawahar, N. (2001), "A multiobjective genetic algorithm for job shop scheduling," *Production Planning and Control* **12**, 764–774.

[33] Afrati, F., Cosmadakis, S., Papadimitriou, C. H., Papageorgiou, G., and Papakostantinou, N. (1986), "The complexity of the traveling repairman problem," *Informatique-Theorique-et-Applications* **20**, 79–87.

[34] Yang, C. E. (1989), "A dynamic programming algorithm for the traveling repairman problem," *Asia–Pacific Journal of Operational Research* **6**, 192–206.

[35] Agnihothri, S. R. (1998), "Mean value analysis of the traveling repairman problem," *IIE Transactions* **20**, 223–229.

[36] Blischke, W. R., and Murthy, D. N. P. (1994), *Warranty Cost Analysis*, Marcel Dekker, New York.

[37] Jack, N., and van der Duyn Schouten, F. (2000), "Optimal repair–replace strategies for a warranted product," *International Journal of Production Economics* **67**, 95–100.

[38] Jack, N., and Murthy, D. N. P. (2001), "Servicing strategies for items sold with warranty," *Journal of Operational Research* **52**, 1284–1288.

[39] Iskandar, B. P., and Murthy, D. N. P. (2003), "Repair–replace strategies for two-dimensional warranties," *Mathematical and Computer Modeling*, **39**, 1233–1241.

[40] Iskandar, B. P., Murthy, D. N. P., and Jack, N. (2005), "A new repair–replace strategy for items sold with a two-dimensional warranty", *Computers and Operations Research*, **32**, 669–682.

[41] Mahon, B. H., and Bailey, R. J. M. (1975), "A proposed improved replacement policy for army vehicles," *Operational Research Quarterly* **26**, 477–494.

[42] Zuo, M. J., Liu, B., and Murthy, D. N. P. (2000), "Replacement–repair policy for multi-state deteriorating products under warranty," *European Journal of Operational Research* **123**, 519–530.

[43] Haugen, D. L., and Hill A. V. (1999), "Scheduling to improve field service quality," *Decision Sciences* **30**, 783–804.

[44] Maxham, J. G., III, and Netemeyer, R. G. (2002), "Modeling customer perceptions of complaint handling over time: the effect of perceived justice on satisfaction and intent," *Journal of Retailing* **78**, 239–252.

[45] Healey, J. R. (2003), *USA Today*, September 3.

[46] Healey, J. R. (2002), *USA Today*, September 20.

[47] Karmakar, U. S., and Kubat, P. (1983), "The value of loaners in product support," *IIE Transactions* **15**, 5–11.

12

Reliability Improvement Warranties

12.1 Introduction

The reliability improvement warranty (referred to as RIW) is a class of warranty policies that are applicable for expensive products that are especially built for customers. The products can be broadly divided into two groups: (i) new acquisitions by defense (such as military aircraft, tanks, ships, radar units, etc.) involving new state-of-the-art technologies, and (ii) complex systems (such as locomotives, power generating units, etc.) which are custom built to serve the needs of commercial or industrial customers. The intent of an RIW is to provide an incentive to the manufacturer to improve the reliability of the product, thereby reducing long-run repair and maintenance costs for the customer.

Including product reliability in the warranty coverage complicates the warranty process, since it requires the customer and manufacturer to agree to the precise reliability performance requirements and that the manufacturer ensure that these are achieved. This requires assessing reliability at different stages of the process and modifications to improve reliability if the agreed performance measures are not achieved. The measure usually used to assess product reliability and improvements therein is the mean time between failures (MTBF), and most RIWs include an MTBF guarantee, as illustrated by Policy 12 in Chapter 3. However, RIW can include any agreed-upon measure of reliability, as will be discussed later in this chapter. As a result, RIW policies are often quite complex.

In contrast to a consumer-type warranty, where the manufacturer decides on the warranty policy based on several factors, as discussed in Chapter 4, each RIW is a unique warranty contract, often covering only a few items and carefully negotiated by the customer and the manufacturer. As a result, the cost analysis (for both manufacturer and customer) of each RIW policy poses new challenges, depending on the reliability terms included in the policy. Furthermore, risk issues need to be addressed as well, and this adds an additional degree of complexity.

In this chapter, we deal with the major issues associated with RIW policies. The outline of the chapter is as follows. We start with a brief discussion of the background in Section 12.2, where we take a more detailed look at some of the specific features of such policies. The RIW process is discussed in Section 12.3, where we define the six different stages of the process and compare it with that for products sold with non-RIW policies. The first stage (Bid Process) is discussed in Section 12.4 and the last two stages (Engineering Change Proposal and Implementation) are discussed in Section 12.5. Management of the RIW process is discussed in Section 12.6.

Finally, it is worth noting that in the RIW literature, the manufacturer is often referred to as "contractor" and the customer as "buyer" as the buyer contracts with the contractor to build the product.

12.2 RIW Background[1]

12.2.1 History

The first use of this type of warranty was in purchases of aircraft by commercial airlines.[2] In military procurement in the United States, the RIW was initially called a "failure free" or "standard" warranty [4]. Some versions of this warranty had been introduced at about the same time as the inception of the airline RIW [5, 6]. The first actual use of an RIW, in 1967, was in procurement of a gyroscope for the F-111 aircraft. This warranty included a guaranteed MTBF provision, and it was apparently quite successful, with the target MTBF of 400 hours exceeded (the estimated actual MTBF was 531 hours) and a 40% reduction in maintenance costs per operational hour achieved [7].

The RIW came into wider use during the next several years with a guaranteed MTBF as the predominant feature [8]. The primary driver was the increasing pressure from Congress culminating with the passage of key legislation during 1983–1985 and particularly Section 794 of the FY 1984 Department of Defense Appropriation Act, which required that all weapons systems and components be covered by warranty in future procurements. The concern was not only with improving reliability and maintainability, but also ensuring that the government did not continue to carry the entire risk for errors in design and manufacture of weapons and other expensive systems.

Section 794 specifically required that contractors for weapons systems (1) guarantee that the design and manufacture of each component and the system itself conform to the contract performance requirements; and (2) guarantee that the systems and each component be free of all defects in materials and workmanship that would cause the system to fail to meet these requirements. In the event of any system failure, the contractor was to either repair or replace the system or any parts necessary to achieve the required performance at no cost to the government, or, if

---

[1] This section is based on Chapter 7 of Blischke and Murthy [1], where additional references to obtain more details can be found.

[2] The successful use of an RIW by Pan American World Airways in the purchase of Boeing 747s in the late 1960s is discussed in Hiller [2] and Shmoldas [3].

the contractor failed in this, to pay whatever cost the government incurred in obtaining the necessary repairs.[3]

RIW is now firmly established as a factor in defense acquisition. As it continues in use, its evolution will undoubtedly also continue. It is also finding greater acceptance in the context of complex industrial and commercial transactions.

12.2.2 RIW Concept

A broader term that has recently been used to describe any warranty or guarantee that includes an incentive to achieve or improve product performance or reliability is product performance agreement (PPA) [11]. This class of warranties includes many types of contracts, RIW being just one warranty in one of four classes:

1. Federal acquisition regulation agreements – covering inspection, supplies, design, performance specification, and technical data
2. Contractor repair agreements – covering re-warranty of repaired or overhauled equipment, reliability guarantees, repair/exchange agreements, and RIW
3. Field measurements agreements – covering MTBF verification tests, availability guarantees, RIW with MTBF guarantee, logistics and other cost guarantees, mean time to repair, and similar guarantees
4. Special features agreements – covering guarantees on characteristics such as ultimate life, commercial service life, software, test and repair improvement, and other unusual or unique features.

12.2.3 RIW Features

The original intent was to apply RIW in situations where operational (field), reliability, support costs, and potential reliability growth were all reasonably predictable. In such applications, many versions of RIW, with a wide variety of terms and features, were developed. Characteristics common to almost all applications include the following:

1. Complex equipment
2. Clearly defined performance requirements[4]
3. Ability to evaluate field or operational performance
4. Potential for reliability growth
5. Contractor provision of field maintenance and repair
6. Relatively long warranty terms (typically three to five years or more)
7. Requirement for engineering analysis of failures
8. Requirement for design changes to correct defects
9. A fixed price contract

---

[3] From Yuspeh [9]. See Appendices B–H of Brennan [10] for more details of RIW in the different branches of the USA Defense Forces.

[4] The RIW focuses mainly on reliability-related performance measures.

10. Contractor fees based on demonstrated reliability improvements.

Each bidding situation involving RIW may include many additional unique characteristics. Reliability, maintainability and supportability performance terms in an RIW policy 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).

For both guaranteed MTBF and guaranteed TAT, RIW contracts commonly require either spares be consigned (at contractor's expense) for use as replacements if the guarantee is not met or monetary compensation be paid by the contractor.

12.2.4 Assurance versus Incentive Warranties

If the objective of the warranty is only to ensure that the product or system performance meets some minimum level, then it is an assurance warranty. In this case the aim of the reliability 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 warranty contract includes incentive features to achieve this. This is accomplished by tying the payment to the performance level achieved by the contractor.

12.3 RIW Process

The RIW process is different from that for items sold with non-RIW policies discussed in Chapters 7–11. There the manufacturer makes all the decisions regarding warranty terms. The buyer is directly involved only in that a selection is made among products with different warranties, although this could have an indirect effect in that adverse selection in sufficient numbers may influence the manufacturer to improve warranty terms. In contrast, in the case of products sold with RIW policies, the buyer is actively involved in the process from the beginning and, in fact, may influence some crucial warranty decisions, since warranty terms are usually negotiated by the two parties. In addition, the focus of RIW is on the total life cycle of the product rather than just the warranty period as in the case of non-RIW policies. 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.

The RIW process involves six stages. These are shown in Figure 12.1 and are as follows:

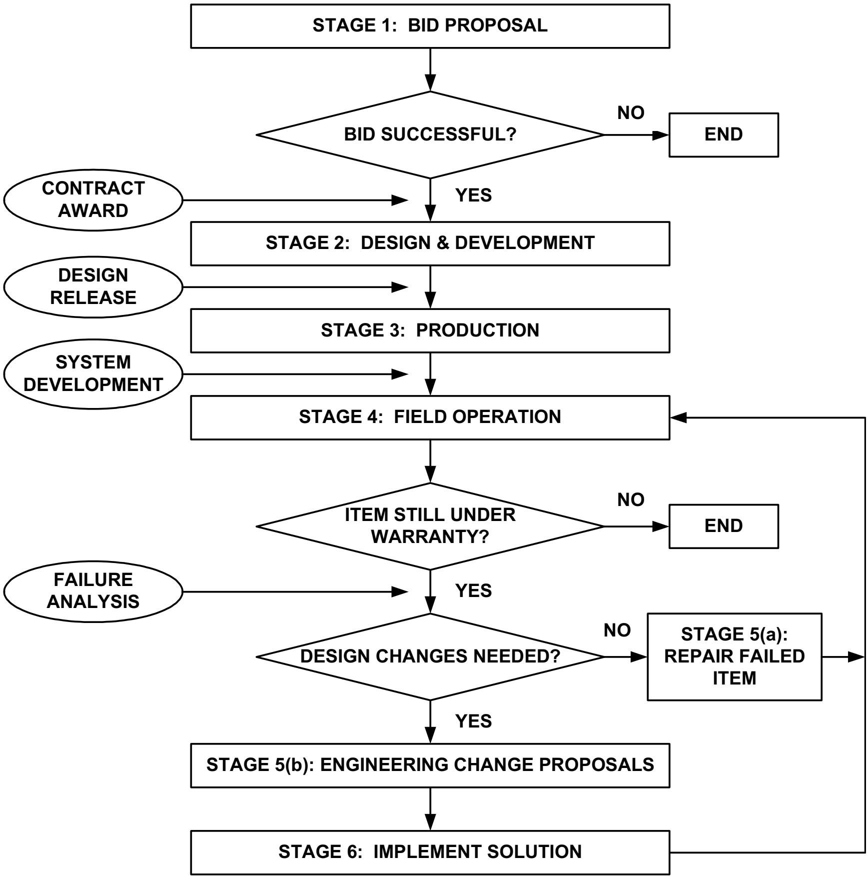


Figure 12.1. RIW Process

- **Stage 1** [Bid Proposal]: A bid is submitted in response to a Request for Proposal. This is discussed in Section 12.4.
- **Stage 2** [Design and Development]: The activities in this stage are the same as those discussed in Chapter 8. It is important to note that the contract might specify the type of testing to be carried out and the performance requirements to be met before the contractor can proceed to the next stage.
- **Stage 3** [Production]: The activities in this stage are the same as that discussed in Chapter 9. As before, the contract might specify the type of testing to be carried out and the performance requirements to be met before the item is released for field operation.
- **Stage 4** [Field Operation]: Here the items are put into use. The buyer is required to ensure that the items are used in a manner stated in the contract. Should the operating environment deviate from that for which the product has been designed (for example, the loads on some or all of the components of an item exceeding the design envelope), then it needs to be documented

by the buyer and reported to the contractor. Also, the buyer might need to record other information that will be of assistance in fixing problems that can arise later on.

- **Stage 5(a)** [Repair of Failed Items]: The activities to fix failed items are similar to those discussed in Chapter 11. This requires planning of various resources, including spares, workshop facilities, technicians, and so forth.
- **Stage 5(b)** [Engineering Change Proposals (ECP)]: This involves identification of failures and their causes and of modifications needed to prevent their future occurrence. The process is discussed in Section 12.5.
- **Stage 6** [Implementation]: This is concerned with actions required by Change Orders and is discussed in Section 12.5.

Figure 12.2 compares the stages of the warranty process for items sold with non-RIW policies with those for items sold with RIW policies. As can be seen, there are similarities as well as differences between the two.

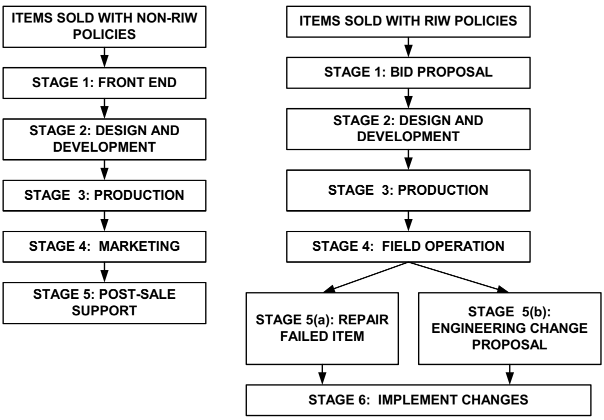


Figure 12.2. Comparison of the stages for items sold with non-RIW and RIW policies

12.4 Bid Proposal [Stage 1]

The first stage of the RIW process is the bidding stage. Figure 12.3 gives the activities in this stage. A typical scenario begins with the buyer issuing a "Request for Proposal" (RFP) to one or more manufacturers, informing them of the specifications, including performance requirements, for the new product, along with other information needed to prepare a bid on the project. Manufacturers respond through an initial bid proposal that indicates how the new product can be realized and gives some indication of the performance levels and crude estimates of various costs (such as development, production, operation etc). This is done using crude models based on limited data. The buyer carries out an evaluation of the proposals and decides on which ones are to be rejected and considers possible revisions to the performance requirements based on the bid proposals. The proposals not rejected go through a second stage where the process is repeated.

This iteration continues until one contractor is selected and both buyer and contractor are in agreement regarding performance and costs. Note that this process can involve several iterations, with successive iterations using more refined models and more detailed data. The end outcome is the final contract that states the terms of the RIW policy.

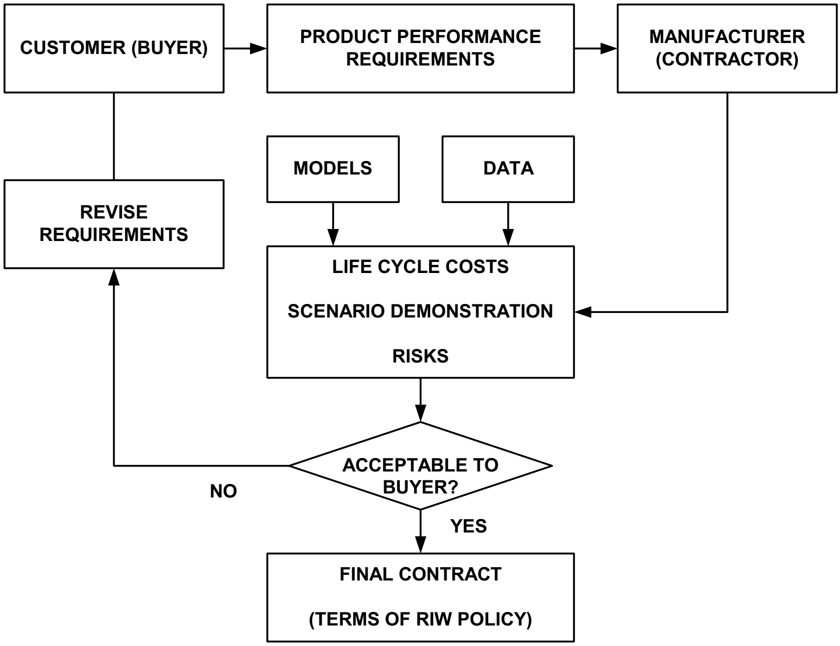


Figure 12.3. Stage 1 [Bid Proposal]

12.4.1 Contract

The contract needs to address the following issues.

12.4.1.1 Warranty Statement
This indicates which of the characteristics discussed in Section 12.2 are included. One or more of the following questions are addressed:

- What is the duration of the warranty period?
- Is it an assurance or incentive warranty?
- What are buyer and contractor obligations?
- What issues are covered?
- What are the exclusions?
- How are the spare parts issues addressed? Are they delivered at the start or over the operating life cycle of the product?

Note: This is not an exhaustive list and there may be many other questions.

12.4.1.2 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.

12.4.2 Costs

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

- Development cost
- Production cost
- Support cost (for spares, etc.)
- Warranty cost.

The contractor needs to take into account all of these costs in the pricing of the contract. The warranty cost must include the provision of replacements, repairs as well as upgrades. This depends on the duration and other terms of the warranty. Models are needed to predict these costs.

From the buyer's perspective, the cost of interest is the total life cycle cost. The buyer might look at alternate warranty options and needs to assess the benefits of warranty traded against the warranty costs.

All activities needed to build and support the product and, all the major factors that influence these activities must be converted into costs that are projected far enough into the future to cover the warranty period (in the case of the contractor) and beyond (in the case of the buyer).

12.4.3 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.

As an illustrative example, consider an incentive RIW policy with MTBF as the performance measure. In this case the contractor needs to decide on the optimal MBTF to maximize the expected profits subject to the requirement that it must be greater than MC, the minimum level for MBTF specified by the contract. Typical incentive payments and expected costs are shown in the top portion of Figure 12.4. The bottom portion shows the expected profit without taking into account the risks. In this case, the optimal MBTF the contractor should specify in the contract is M*, as indicated in the figure. A risk analysis will indicate that the technical and project risk increases with MTBF due to the need for greater development effort and the uncertainty associated with such development activities. In this case, the risk analysis might indicate that the optimal MBTF is smaller than M* if the risk at M* is too high.

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 assesses the probabilities of these occurring and the resulting consequences.

12.4.4 Dispute Resolution

For most RIW policies, 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 the 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. This topic is discussed further in Chapter 13.

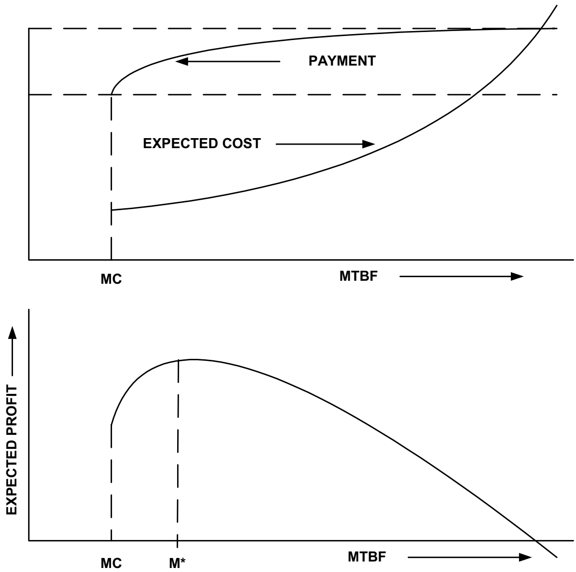


Figure 12.4. Optimal MTBF under incentive RIW

12.4.5 Models

The RIW process is complex and varies considerably from contract to contract. As a result, quite sophisticated models are needed to capture all of the elements of RIW. The models need to include development, testing, and operational factors and related costs, reliability growth, randomness (uncertainty of outcomes), risk, other project-specific elements, and, in addition, must look at these from a life cycle perspective and from the points of view of both buyer and contractor. General models that embody all of these features have not been developed. Typically, what is done is to develop comprehensive computerized databanks to record as much information as possible about the RIW project.[5]

Historically, a number of models, usually oriented to specific applications, have been developed. These are primarily descriptive models and look at life cycle costs. In this context, what is of interest is the cost of operating a unit over its lifetime, as discussed in Section 7.2.[6]

Examples

Most of the examples are from the defense sector. A few examples of applications[7] for which models were developed are:

- *Purchase of avionics by the military* [13]. A batch of items was purchased, with a subset of these put into service and the remainder used as spares. The model expressed cost to the buyer as a function of purchase price, expected cost of failures, and cost of maintenance, and included a number of breakdowns into lower level cost elements, incentives for reliability improvement, and other relevant factors.
- *Military electronic equipment* [14]. The model considered cost of RIW with guaranteed spares availability and turnaround time, and involved many related factors.
- *Complex system with guaranteed MTBF.*[8] Many features are modeled, including lower bounds on the MTBF, effect of retrofitting, fees for exceeding guaranteed MTBF, estimation of required number of spares, and so forth. Contracts also typically specify a methodology for estimating the actual MTBF based on field data and a procedure for establishing required engineering changes for improving reliability.

12.5 ECP and Implementation [Stages 5(b) and 6]

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

[5] For an example and discussion, see Glaser [12].
[6] This is discussed in Blischke and Murthy [1], Section 7.4.
[7] A number of other examples are discussed in Blischke and Murthy [1].
[8] There are many such examples. Cf. Balaban [15]. For another approach, see Kruvand [16].

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 12.5.

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 contractor incurs a penalty as per the terms of the contract.

However, if the root cause 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 contractor needs to carry out changes on all the items delivered or being held as spares.

It is worth noting that if an item is used in a mode that the product has not been designed for (for example, running a locomotive at speeds higher than designed or on poorly maintained tracks), then the warranty would become null and void. This implies that the buyer needs to ensure that proper operational and maintenance related data are kept in order to verify, if necessary, that the buyer's obligations are met.

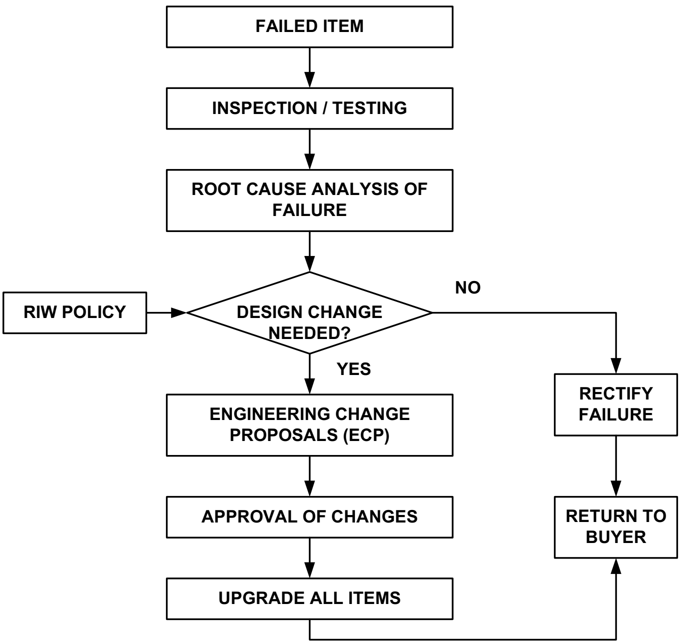


Figure 12.5. Stages 5 and 6 [Design Changes]

12.6 Management of the RIW Process

Some of the management issues for RIW are the same as for items sold with non-RIW policies and discussed in Chapter 4. However, there are some issues that are unique to RIW policies and we discuss these briefly in this section.

12.6.1 Warranty Negotiations

This is a critical element of Stage 1 for both commercial and government acquisitions. The negotiation process serves to clarify issues so as to arrive at an agreement that is acceptable to both parties (contractor and buyer). The negotiations can be involved, as the interests of the two parties are different and so are the information and knowledge needed to evaluate costs and risks.

12.6.2 Project Management

For a complex product, the contractor needs the involvement of several sub-contractors to provide different sub-systems. For example, in the case of an aircraft, the engine manufacturer would be one of the main sub-contractors. It is the responsibility of the contractor to confirm that the components obtained from sub-contractors conform to specifications. This implies that all design changes must be communicated effectively. This is achieved through "configuration management," which is managed by the contractor [17].

12.6.3 Data Management

The contractor needs a system to track and collect relevant data needed to estimate achieved performance at different stages of development, during production and during field operation. The input to this database must include the following:

- Product design: detailed design specifications of original configuration; design changes based on field performance data
- Product operation: usage, failures, failure modes, failure times, etc.
- Repair: actions, time needed for repair, costs, etc.

The buyer needs to keep track of operational-related data to ensure that the terms of the contract are not violated.

12.6.4 Warranty Administration

This deals with systems and procedures required to execute the various stages indicated in Figure 12.1. Brennan[9] deals with this topic in detail, particularly in the context of RIW and government acquisitions. It is important to specify requirements, procedures, and criteria for assessment of performance and to

[9] Brennan [10] deals with the planning, analysis and implementation of warranties.

perform a careful cost analysis at the outset. In the bid preparation stage, careful attention must be paid to all of these factors as well as to the cost and feasibility of various warranty terms. The last is especially important since a key feature of RIW acquisitions is that warranty terms will be negotiated. Brennan offers many guidelines regarding bid preparation, including discussion of

- Risks and benefits
- Warranty trade-offs
- Warranty costing
- Performance guarantees
- Warranty negotiating
- Determination of cost effectiveness.

When a contract is awarded, provision must be made for warranty implementation and administration. For the successful bidder, this involves staffing for this purpose and setting up procedures for information gathering, interfacing with the customer, interfacing with subcontractors (or, if the company is a subcontractor, with the prime contractor and other subcontractors), tracking progress, costs and problems, and evaluating company performance relative to the specifications made in the terms of the warranty. Administrative requirements are very program-specific, and many other factors may be involved. For effective administration and eventual profitability, detailed planning is needed early on, and a continuing program of data collection and analysis is essential. As mentioned previously, computerized data banks for this purpose are a very important tool.

References

[1] Blischke, W. R. and Murthy, D. N. P. (1994), *Warranty Cost Analysis*, Marcel Dekker, New York.

[2] Hiller, G. E. (1973), "Warranty and product support. The plan and use thereof in a commercial operation," *Proc. Failure Free Warranty Seminar*, U.S. Navy Aviation Supply Office, Philadelphia.

[3] Shmoldas, A. E. (1977), "*Improvement of Weapon System Reliability Through Reliability Improvement Warranties,"* Report 77-1, Defense Systems Management College, Ft. Belvoir, VA.

[4] Trimble, R. F. (1974),"*Interim Reliability Improvement Warranty (RIW) Guidelines"* HQ USAF Directorate of Procurement Policy Document, Dept. of the Air Force, Washington, D.C.

[5] Gregory, W. M. (1964), "Air force studies product life warranty," *Aviation Week and Space Technology,* 2 Nov. 1964.

[6] Klause, P. J. (1970), "Failure-free warranty idea lauded, wider use desired" *Aviation Week and Space Technology,* 9 Feb. 1970.

[7] Schmidt, A. E. (1976), "*A View of the Evolution of the Reliability Improvement Warranty,"* Report. 76-1, Defense Systems Management College, Ft. Belvoir, VA.

[8] Gandara, A., and Rich, M. D. (1977), "*Reliability Improvement Warranties for Military Procurement,"* Report No. R-2264-AF, RAND Corp., Santa Monica, CA.

[9] Yuspeh, A. R. (1986), "Legislation on weapon system warranties," 1986 *Proceedings Annual Reliability and Maintainability Symposium,* 438–442.

[10] Brennan, J. (1994), *Warranties*, McGraw Hill, New York.

[11] Fleig, N. G. (1986), "The United States Air Force Product Performance Agreement Center," 1986 *Proceedings Annual Reliability and Maintainability Symposium*, 449–453.

[12] Glaser, A. J. (1981), "A data information system for RIW contracts," *Proceedings Annual Reliability and Maintainability Symposium*, pp. 139–143.

[13] Balaban, H., and Reterer, B. (1974), "The use of warranties for defense avionic procurement," *Proceedings Annual Reliability and Maintainability Symposium*, pp. 363–368.

[14] Gates, R. K., Bortz, J. E., and Bicknell, R. S. (1976), "A quantitative analysis of alternative RIW implementations," *Proceedings National Aerospace and Electronics Conference*, pp. 1–8.

[15] Balaban, H. S. (1975), "Guaranteed MTBF for military procurement," *Proceedings 10th International Logistics Symposium*.

[16] Kruvand, D. H. (1987), "Army aviation warranty concepts," *Proceedings Annual Reliability and Maintainability Symposium*, pp. 392–394.

[17] Buckley, F. J. (1993), *Configuration Management*, IEEE Press, New York.

13

Financial, Societal, and Legal Aspects of Warranty

13.1 Introduction

In this chapter, we deal briefly with a number of additional aspects of warranty that are important in effective management. These include accounting, social and legal and other considerations beyond the immediate operational aspects of design, engineering, production, marketing, and post-sale services discussed in previous chapters.

Accounting is involved in analysis and management of warranty in several ways, including costing, determining when costs should be charged, provision for reserves to cover these costs, and assuring that regulatory constraints are satisfied and that accepted accounting principles are employed. Accounting issues are discussed in Section 13.2.

We also recognize that reliability and warranty issues may have a broad impact and hence are of concern beyond the corporation and its operation, sales, and the balance sheet. Excessive numbers of failures and warranty claims that may occur as a result of poor design, engineering, quality control, management, etc., can lead to disputes, lawsuits, and legislation, and may affect society as a whole. Consumers may react to the resulting dissatisfaction in various ways.

In a number of instances, concerns such as product safety, frequency and severity of failures, and warranties per se, have led to consumer movements advocating oversight and compensation to affected parties. In Section 13.3, we give a brief overview of some of the key consumerist activities with regard to warranty.

Warranty legislation at both the state and federal levels in the U.S. has aimed at regulating warranty practices, including what must be covered, corporate responsibilities, and even the language of written warranties. Much of this, in fact, has taken place in response to the campaigns of consumer activists. Key legislative actions have included the Universal Commercial Code, the Magnuson-Moss Warranty Act, and the so-called “lemon laws.” A brief survey of some key features of these legislative acts and their effect on corporations and management of warranties is given in Section 13.4.

Finally, we look at warranty and the courts in Section 13.5. When there are disputes between two parties regarding warranty, these may be resolved in many ways, from personal negotiation up to litigation. Lawsuits have ranged from individual to class action litigation. Many legal remedies in dispute resolution are specified in the Magnuson-Moss Act, which includes causes for action by consumers and well as warrantor's rights with regard to choice of compensation. In Section 13.5, we comment on a few important cases and related actions that have affected warranty, consumer recourse in this regard, and the impact of these on manufacturers.

13.2 Warranty and Accounting

13.2.1 Introduction

There are several accounting considerations of importance in the context of warranty. These include financial accounting and reporting requirements and procedures for warranties, which are discussed in Section 13.2.2, and the role of accounting in cost management planning and control, which is considered in the remainder of this section. Specifically, we look at external versus internal accounting, several issues in internal accounting, the link between quality and warranty in a cost context, and the trade-off between these in the context of strategic management.

13.2.2 Financial Accounting and Reporting[1]

Financial accounting and reporting is concerned with the acquisition and presentation of information in periodic financial statements for purposes of decision-making. Here we are concerned with recording and reporting requirement as specified by the Financial Accounting Standards Board (FASB) in the U.S. and the reporting requirements of the U.S. Internal Revenue Service (IRS). To meet the needs of external users such as investors and creditors, financial reports are prepared in accordance with a common set of standards and procedures called "generally accepted accounting principles" (GAAP), as specified by the FASB and other authoritative sources.[2] A key objective of this approach is to provide for consistency of standards, comparability of financial statements, and user confidence in and understanding of the results.

Financial reports are the main source of information regarding resources, claims to resources, and changes in either of these. With regard to warranties, financial accounting and reporting must conform to the stated intent of the FASB regarding recognition, measurement, and full disclosure.

In providing a warranty, a manufacturer agrees to assume some or all of the cost of repair or replacement of an item that fails within a specified period of time. Warranties are a contingency liability in the sense that they are an uncertain future

---

[1] The material of this section is based on Maschmeyer and Balachandran [1].
[2] See Maschmeyer and Balachandran [1], Section 26.2.

obligation. Accounting requirements associated with this obligation are specified by the FASB [2].

Likelihood of a loss due to warranty claims is specified by the FASB on a qualitative scale, as “probable,” “reasonably possible,” and “remote.” Depending on the assessed likelihood of the loss, accounting may be done by a cash or accrual method. The likelihood of loss also determines the level of disclosure to be included in financial statements. Under the accrual method of accounting, revenues and expenses are matched in an accounting period. Thus, loss contingencies in a given period are associated with that period’s sales, if the loss is probable and the amount of loss can be reasonably estimated. If the loss contingency does not fall into this category, the cash method of accounting is used. The largest effect of this is the time at which the expense and other liabilities are recognized in the financial report. In this case, some of the liabilities in a given period may relate to obligations incurred in prior periods.

Loss contingencies associated with warranty are similar to those in the insurance industry in that they are random future costs rather than current expenses. Thus a warranty is a type of insurance policy, and some of the mathematical models formulated for analysis of the insurance industry are appropriate here as well.[3]

Disclosure of warranty loss contingencies is done in the U.S. in accordance with the accounting profession’s policy of full disclosure. Thus, all financial information that is considered of significance to an informed reader is to be reported.[4] This includes the nature of the loss and an estimate of its magnitude. To make this specific, a recent requirement of the FASB, effective December 15, 2002, is that manufacturers “present, in tabular form, an accounting of their warranty reserve fund balance, the amount spent to satisfy current claims, and the amount added to finance future clams.” [5]

In accounting for warranty litigation, the action to be taken also depends on the likelihood of its occurrence. If a loss due to the litigation is probable and the amount of loss can reasonably be predicted, the expense is accrued as a loss contingency in the then current financial period. If not, only disclosure may be required.

Extended warranties and maintenance contracts that provide additional coverage and are priced separately are treated somewhat differently. GAAP provides accounting procedures for dealing with these [4]. The situation is somewhat more complex, depending on the terms and conditions of the agreement, and reporting requirements for tax purposes differ from the GAAP requirements, further complicating the issue.[6]

---

[3] For a discussion of this, see Frees [3].

[4] A list of types of information required is given in Figure 26.3 of Maschmeyer and Balachandran [1].

[5] *Warranty Week*, June 9, 2003. See this issue and that of June 2, 2003, for a discussion of the requirements. A tabulation of companies in compliance, organized by industry, is given in the June 9 issue.

[6] For additional details and discussion, see Maschmeyer and Balachandran [1], Section 26.2.5, and the references cited there.

Under current procedures, financial information of warranty costs may be included in the main body of a financial statement or in notes to the statements. Information may include expenses and liabilities related to the loss contingencies; methodology; revenues, expenses and liabilities related to extended warranties; reconciliations between tax liabilities and expenses between GAAP and IRS; and disclosures regarding litigations. The preparer is obligated to provide sufficient information so that the statements are not misleading.[7]

13.2.3 External versus Internal Accounting[8]

In addition to fulfilling financial reporting requirements, as discussed in the previous section, accounting for warranty also provides information for cost management decisions. In particular, warranty costs are of concern in managerial planning, control, and evaluation over the life cycle of a product. Here we look briefly at the difference between cost management accounting and the accounting required for external reporting purposes.

For users external to the company, e.g., present and future shareholders and creditors, reports are intended to provide information that is useful in evaluating investments and credit decisions, assessing the amounts and timing of these, and evaluating economic resources, obligations, and other circumstances of the company. These reports are usually provided quarterly or less frequently and are prepared in accordance with GAAP requirements.

Reports for internal use typically differ in both content and frequency of issuance. In the context of warranty, we are interested in management of warranty costs, including cost of quality and reliability, ultimate cost of processing and compensating claims, timing issues, and so forth. The cost management accounting used for this purpose differs from financial accounting in several ways: the reports are often prepared frequently and at irregular intervals as the need for information arises; they are tailored to meet specific needs (e.g., cost of warranty repairs for a specific product over a specified time period) and hence are non-uniform; they are not generally based on GAAP principles, but include data deemed useful for the purpose at hand; and they may include only specific products or product lines rather than information on the company as a whole.

In addition, some costs not reported under GAAP accounting may be of interest in warranty management. An example is the cost of lost sales because of customer dissatisfaction. This may affect decisions regarding the type and length of warranty to be offered, the repair/replacement policy to be used, and so forth. Design costs for increasing reliability and quality inspection to decrease the frequency of claims would also appear in internal management reports but not in financial statements. In short, all firms must comply with GAAP procedures for external accounting, but need to develop internal information systems that provide the information needed to optimize managerial decision-making. Finally, it is important to note that these

---

[7] See Maschmeyer and Balachandran [1], Section 26.3.
[8] Based on Section 29.2 of Maschmeyer and Balachandran [5].

needs change during the course of the product life cycle, and the information system must be modified accordingly.[9]

13.2.4 Product Warranty versus Quality Costs[10]

We have previously noted the trade-off between warranty costs and product quality. In principle, as more effort (at increased cost) is put into assuring the quality of a product, the number of warranty claims and the cost of servicing them will decrease. There are many other factors involved in this equation – for example, customers are dissatisfied not only on failure of an item leading to a warranty claim, but also with poor quality in the sense of performance being below expectations and for any of a number of other reasons, all of which can lead to decreased sales.

Accounting procedures recognize warranty as a component of the larger issue of cost of quality. Overall, quality costs are classified into four categories:[11]

- Prevention costs – including research and engineering, design, education, process controls, etc.
- Appraisal costs – including incoming materials inspection, in-process inspection, reliability testing, plant utilities, and many related items
- Internal failure costs – including costs of scrap and spoilage, rework labor, retest, reinspection, downtime cost, etc.
- External failure costs – including response to customer complaints, warranty repairs and replacements, product recalls, product liability, and so forth.

Cost models incorporating these four principal cost elements have been developed to relate the total cost of quality to the quality level of the product.[12] These provide a method of determining an optimal cost of quality.

Internal accounting procedures that provide the necessary reports for tracking costs in these four categories are very useful for resource allocation, detecting trends, determining trade-offs, and helping management in reducing overall quality cost and increasing product quality.

13.2.5 Strategic Warranty Cost Management[13]

Strategic management requires that costs be tracked over the life cycle of the product so that information on cost per unit and life-cycle cost per unit is available for trade-off studies. Traditional financial accounting does not provide this, and, in

---

[9] See Maschmeyer and Balachandran [5], Section 29.3.
[10] Based on Maschmeyer and Balachandran [5], Section 29.4.
[11] These are discussed in detail in Maschmeyer and Balachandran [5], Section 29.4.1.
[12] The traditional model describing this relationship is due to Juran and Gryna [6]. An expanded version is in Heagy [7].
[13] Based on Maschmeyer and Balachandran [5], Section 29.5.

fact, would tend to significantly understate product-specific costs on a life-cycle basis.[14]

For cost management by product or product line, both direct and indirect costs are allocated to specific products. Indirect costs are allocated on the basis of "activity-based cost accounting" [15] to assist in an equitable allocation.

The internal analysis for product cost management may be extended to external considerations by means of "target analysis" [8], a process that links engineering and other decisions to market requirements. The target analysis (i) determines customer requirements with regard to the desired function and quality of the product and the product warranty; (ii) determines unit target cost and quality; (iii) estimates quality from preliminary product designs and develops design modifications, material and process improvements until the desired quality is achieved; and (iv) estimates unit costs and, if these exceed target costs, continues redesign, etc., until the targets are met. If the targets are not met, the process iterates until an acceptable solution is reached.

13.2.6 Estimating Warranty Costs

Many models have been proposed for estimating and predicting warranty costs per unit. A number of these, based on failure models and related functions, were discussed in Chapter 7. From an accounting point of view, the objective is to estimate the repair and replacement costs for a product sold under warranty and then to aggregate these costs for all units sold under warranty during a particular accounting period. This enables management to compare actual with estimated warranty costs.

13.3 The Impact of Consumerism on Warranty[16]

13.3.1 Introduction

As discussed in Section 1.2, warranties in some form have been offered for a very long time. Typically, however, coverage was minimal and the warranty, whether implicit or explicit, did not offer adequate protection to the buyer. Growing dissatisfaction with warranty coverage, beginning in the early 20th century, led to consumer movements demanding changes to better protect the interests of the buyer. These, in turn, led to legislation and the consequent enforcement of regulations regarding the rights of buyers and responsibilities of manufacturers concerning warranty.

In this section, we look briefly at the consumer movements in the 20th century and their impact on warranty.

---

[14] ibid.
[15] ibid.
[16] Based on Burton [9]. See this source and the many references cited there for additional information.

13.3.2 Consumerist Warranty Concerns[17]

Beginning in the early 20th century, three separate consumer movements may be identified. The first, at the very beginning of the century, was concerned with the quality and safety of food and drugs and the growing power and influence of business trusts. The influence of the social reformers of the time led to the first consumer protection laws, the 1906 Pure Food and Drug Act and the Meat Inspection Act. This was followed, in 1914, with the establishment of the Federal Trade Commission (FTC), which was set up to regulate the trusts, and to deal with deceptive advertising and other unfair business practices. The first consumer movement effectively ended with the onset of World War I.

After World War I, consumers experienced a significant increase in real income. Increased affluence provided a market potential that led to a large increase in consumer goods, including many appliances and increasing numbers and complexity of automobiles. Consumer expectations also increased significantly during this period, fueled, in part, by misleading, deceptive or non-informative advertising. The second consumer movement began in response to this situation, and led, in the 1930s to the Consumer's Union, publishers of the well-known *Consumer Reports.* The movement led to many consumer benefits, including the New Deal of President Franklin Roosevelt, additional protection through Food and Drug amendments, and strengthening of the FTC. This movement ended at the onset of World War II.

The period immediately following World War II was characterized by mass consumption, which came as a result of wartime deprivation of consumer goods, built up savings, and the vast production capability of the U.S. The demand was so great that consumers paid little attention to quality. As a result, the third consumer movement of the 20th century did not begin until the 1960s, partly as a result of a near approval of a birth-defect causing drug (thalidomide) and partly as a result of congressional hearings at which Ralph Nader became famous for his testimony on auto safety. The third consumer movement that resulted was influential in the passage of many laws intended to protect the consumer, including Truth-in-Lending legislation in 1969, and the Equal Credit Opportunity, Fair Trade, Consumer Product Safety, and the National Traffic and Motor Vehicle Safety Acts in the 1970s.

13.3.2 Impact of the Consumer Movements on Product Warranty[18]

In the early part of the 20th century, products were much simpler and could easily be repaired. This was an era of self-reliance and the buyer generally made any needed repairs. It was also an era of *caveat emptor*, as had been the case for centuries, and meaningful warranty protection was not offered. Furthermore, the real needs were for safe food and drugs, and the efforts of the first consumer movement were in these areas. As a result, very little attention was paid to warranty and no warranty legislation arose during this period.

---

[17] Burton [9], Sections 28.2.1, 28.3.1, and 28.4.1.

[18] Burton [9], Sections 28.2.2, 28.3.2, 28.4.3 and 28.4.4.

The second consumer movement also paid little attention to warranty. There was little pressure for legislation and the courts did not provide warranty protection to consumers through the notion of implied warranty. Again, health and safety issues were of most concern to consumers.

In spite of consumer dissatisfaction with warranties, consumer advocates also did not pursue warranty protection issues during the early part of the third consumer movement. From 1945 to 1975, the popular press published few articles on warranty, and texts devoted very little space to the subject. Warranty problems that finally led to consumerist activity and eventual legislation during the third consumer movement concerned automobiles. For some years prior to 1960, the standard automobile warranty was 90 days/4,000 miles. In 1960, Ford increased this to 1 year/12,000 miles, starting a competition with other manufacturers, with warranty as a marketing tool. Thus began a "warranty war," which had near disastrous results for some automakers and led to a retreat, with progressively decreasing warranty coverage.

In addition to decreasing and then fluctuating warranty terms, during this period better warranties were rarely an indication of higher quality. In fact, there were serious problems with defects, not only in their frequency of occurrence, but in obtaining service. Cars were becoming more complex and more difficult to repair, and repair service was frequently inadequate. Consumer complaints became a major factor and investigations into the nature of automobile warranties were undertaken.

During this period, there was also dissatisfaction with regard to appliance warranties. These led to a study by the FTC that concluded that repair service under warranty was not satisfactory to consumers.

With regard to both automobiles and appliances, consumers were also not satisfied with the warranty terms offered, particularly those regarding disclaimers. In addition, it was found that consumers were at a distinct disadvantage in any warranty-related dispute. Finally, warranties were found to be confusing and consumers frequently misunderstood the coverage that was being provided.[19] Eventually, this did finally lead to consumer action and warranty legislation.

13.3.3 Passage of the Magnuson-Moss Act

In the 1970s, action by consumerists, through Consumers Union, articles in *Consumer Reports,* US Public Interest Research Group, and others, led to increasing pressure on Congress to enact consumer protection legislation. The FTC was also pressured to increase its role in protecting consumers' interests by issuing stronger rules. The resulting key legislation was the Magnuson-Moss Act, which was passed in 1974 and became effective in 1975. This act, due in great part to the influence of the third consumer movement, both strengthened and reformed the FTC and provided a legislative foundation for comprehensive warranty protection. In the next section, this and related legislation are discussed in some detail.

[19] For a discussion of four consumer studies on warranty, see Rothschild [10].

13.4 Warranty Legislation (USA)

13.4.1 Introduction

In the previous section, we discussed consumerism and its influence in securing one of the most important pieces of consumer warranty legislation, the Magnuson-Moss Act. The second important major legislative action in this area is the Uniform Commercial Code (UCC). In this section, we look briefly at both of these, highlighting the aims and effects of each and providing some details with regard to provisions of the acts, benefits to consumers, and impact on manufacturers.

Both the UCC and Magnuson/Moss are Federal legislation. In the U.S., individual states have also passed legislation governing warranties. These will be briefly discussed. We also comment on a number of other areas of warranty legislation of interest to manufacturers, including commercial warranties, warranties in military and non-military government acquisition, and international law regarding warranty.

13.4.2 The Uniform Commercial Code (UCC)[20]

The UCC, set forth by the U.S. National Conference of Commissioners on Uniform State Laws, covers both express and implied warranties. Implied warranties are unwritten guarantees created by state law. Express warranties may be created by the seller of a product in a number of ways. Both implicit and express warranties are discussed in some detail in Chapter 3 and a listing of the sections of the UCC warranty provisions is given in Table 3.1.[21]

In establishing a warranty policy, it is important that a company be aware of the many UCC regulations and the complexities therein. For example, implied warranties are warranties that are not written, but some disclaimers and exclusions must be in writing. Furthermore, express warranties must contain a "promise," but need not contain the words "warranty" or "guarantee," and need not be in writing.[22]

We note, incidentally, that one of the purposes of the UCC was to provide uniform coverage from state to state. In fact, many states enacted variations of the code, and, though there are strong similarities in these, the intended uniformity did not occur.

13.4.3 The Magnuson-Moss Act

The most important single legislative act governing warranties is the Magnuson-Moss Warranty and Federal Trade Commission Improvement Act of 1975 [13], commonly called simply the Magnuson-Moss Act. Many studies prior to passage of the legislation (over a period of more than 10 years) had concluded that there were many problems with consumer warranties, including inadequate coverage, complex language, excessive numbers of disclaimers, shoddy products having

---

[20] Based on Section 4.2 of Kelley [11].
[21] For further background and discussion of the UCC, see Mosier and Wiener [12].
[22] See Kelley [11] and the references cited there for details.

misleadingly generous warranty terms, and warranty service that was poorly done or difficult to obtain. The intent of the legislation was to address the following perceived consumer needs: (1) better understanding of warranty terms, (2) the need to ensure that a minimal level of protection is provided, (3) availability of procedures for consumer remedies, including dispute resolution, up to and including class action, and (4) higher reliability products.[23]

The terms and conditions required by the Magnuson-Moss Act are discussed in detail in Chapter 3 and in the references cited there and previously in this chapter. The Act does not require that a seller provide a warranty, and it covers only consumer goods, not commercial goods or any services. It does cover catalog and mail-order sales and has special provisions dealing with these.[24] The Act specifies that disclosure be made of what is to be covered in the warranty, and that written warranties on items with a selling price of $15 or more must be conspicuously labeled as “Full” or “Limited Warranty.” (A full warranty must be FRW or full rebate if the product continues to malfunction after a reasonable number of attempts at fixing it.[25] As a result of this requirement, after enactment of Magnuson-Moss most companies began to label their warranties “Limited.”) A list of additional specific provisions of the Magnuson-Moss Act is given in Table 3.2. Again, this is essential knowledge for a manager formulating warranty policy.

13.4.4 Other Legislation[26]

In this section, we look briefly at warranty legislation beyond Federal actions governing consumer transactions.

13.4.4.1 Commercial Warranty Legislation

Sections of the Uniform Commercial Code also cover commercial warranties.[27] Coverage includes warranty of title (where the seller guarantees that the title is clear and the goods are free of any known liens), express warranties, implied warranties of merchantability and fitness.

The Magnuson-Moss Act covers warranties on consumer products used for commercial purposes. As a result, some manufacturers have developed a single warranty satisfying the requirements of the Act for products that are sold in both the consumer and commercial markets. (Retailers that purchase consumer products for resale are not considered “consumers” under the Act.)

13.4.4.2 State Warranty Legislation

Warranties are regulated on the basis of variations of the UCC by all 50 states, and many have also enacted legislation similar to that establishing the FTC as well as Fair Business Practice Statutes. These apply to warranties on consumer and

---

[23] This is discussed in detail by Mosier and Wiener [12].
[24] See Kelley [11], Section 4.2.2.
[25] See Kelley [11], Table 4.3, for a summary of the differences between limited and full warranties.
[26] From Kelley [11], Section 4.2, and Blischke and Murthy [14], Chapter 7.
[27] See McGuire [15] for further information.

commercial goods. The Magnuson-Moss Act does not supersede state laws that regulate warranties.

13.4.4.3 U.S. Military Acquisition and Other Government Warranty Requirements

Warranty requirements in the government sector are similar to those for consumer and commercial goods, in that they specify coverage and duration of the warranty and the responsibilities of the seller. There are, however, some important differences. In much of government procurement, products are required to satisfy some very specific needs that do not apply to other buyers. In addition, service is often done by the government agency rather than by the seller. As a result, special legislation may be enacted governing a specific procurement and manufacturers must meet the particular requirements of the pertinent law.

Military acquisition, in addition to purchase of ordinary consumer goods, involves both the development and purchase of many highly specialized types of weapons and equipment. Historically, most of these products were not covered by warranty. The RIW, discussed in Chapters 3 and 12, was introduced in the mid-1960s and it and other forms of warranty received increasingly wider use through the 1970s and into the 1980s, primarily as a result of increasing pressure from Congress to control costs. This led, in the period 1983–1985, to legislation requiring that essentially all weapons systems and components in future procurements be covered by warranty.[28] The resulting laws require that contractors for weapons systems guarantee (1) that the design and manufacture conform to performance specifications, and (2) that the system and all components be free of all defects in materials and workmanship that would cause them to fail to meet design requirements. In case of failure, the contractor is required to repair or replace the system or any parts necessary to meet the requirements at no cost to the government, or, on failure to do this, pay the government whatever cost it incurred in obtaining the repairs.

13.4.4.4 International Warranty Legislation

Warranties are contractual obligations, and laws governing these vary widely from country to country. Contracts may be enforced by either common law, under which warranties must be a part of the contract, or by civil law, where contracts carry implicit warranties that may be enforced [16]. Common law contracts are generally more detailed. A breach of contract often occurs as a result of a misunderstanding or misinterpretation of the contract terms. Companies dealing in foreign markets should consult with legal counsel familiar with the laws of the countries in which the transactions take place.

[28] Section 794 of the FY 1984 Department of Defense Appropriation Act. See Blischke and Murthy [14], Section 7.2 for additional details.

13.4.5 The TREAD Act

The TREAD Act,[29] requires manufacturers of motor vehicles and equipment sold in the U.S. to submit quarterly reports to the National Highway Traffic Safety Administration (NHTSA) that summarize all claims made against them for incidents that involve deaths or serious injuries, property damage data, communications to customers and others, information on incidents that happen in a foreign country to vehicles that are substantially similar to vehicles sold in the U.S., and other information that helps the agency identify potential safety-related defects. The legislation requires manufacturers to record, aggregate and report a broad collection of data regarding dozens of components and safety systems on a quarterly basis starting December 1, 2003. This data includes field reports, production statistics, injuries and fatalities, complaints, warranty claims, and much more.[30]

13.4.6 Implications of Warranty Legislation for Business

The Uniform Commercial Code and Magnuson-Moss Warranty Act have had a significant impact on warranty and have major implications for business. The following are important considerations in this regard when formulating company warranty policy:[31]

- *Be aware of federal and state laws when offering written warranties*. Federal requirements are specified in the UCC and Magnuson-Moss, but state codes vary, and it is necessary to keep up with changes in any state in which a company is doing business. States vary in whether tort law or contract law governs product warranties and both are used in courts. For international business, laws of the country must be consulted.
- *Be in control of disclosure of warranty information by the company and its agents in advertising and other promotional activities*. This assures that required prepurchase disclosures are made and that advertising conforms to the terms of the warranty offered. Failure to disclose warranty information where required is a violation of the law whether or not it is the fault of the manufacturer.
- *Disclose warranty terms in simple, easily understandable language.* This is required on consumer products under Magnuson-Moss. Beyond that, it leads to fewer dissatisfied costumers by avoiding misunderstandings of warranty terms and coverage.
- *Encourage customers to read and compare written warranties.* This is a good marketing ploy if the warranty is better than the industry standard, or is perceived to be so. It is in the best interest of the company, in any case,

[29] The TREAD Act was introduced into Congress as H.R. 5164, and signed into law by President Bill Clinton on Nov. 1, 2000 as Public Law 106-414.
[30] See *Warranty Week* issues of March 31, 2003 and April 7, 2003 for more details.
[31] From Kelley [11], Section 4.4.

that the buyer understands what is covered by the warranty. This reduces claims that result from misinterpretation of the warranty and the confusion and conflict that these entail.

- *Establish informal mechanisms to resolve warranty disputes.* State the procedures for resolving complaints that arise when products fail under warranty, so that the buyer is made aware of the steps to be taken in obtaining a solution. This may increase customer satisfaction and also identify problem areas in sales and service. Solution of such problems may avoid future complaints, thereby increasing customer satisfaction and increasing sales.
- *Keep abreast of the warranty literature.* Many warranty studies are published every year, in economics, business, law, production, engineering, and many other areas. Tracking current research will help in learning about new laws and regulations regarding warranty and enforcement. *Warranty Week*, published on the internet, is an invaluable tool for keeping abreast of current information.

13.5 Warranty-related Litigation

13.5.1 Introduction[32]

In this section, some legal issues that have arisen as a result of litigation in federal and state courts are briefly discussed. Actions under both the UCC and Magnuson-Moss are included.

13.5.2 Litigation Under the UCC and Other State Laws

Traditionally, state law has regulated consumer protection. The most important source of these regulations is the UCC. Other sources include the various so-called state "lemon laws," the Uniform Deceptive Trade Practices Acts of 1964 and 1966, and the Uniform Consumer Sales Practices Act of 1970.

Under the UCC, consumers have the following three recourses in the event of breach of warranty:

- Rejection of the goods, which right is forfeited if the goods are used
- Recovery of damages in the amount of the difference between their value as received and the value originally warranted, unless the seller limits recovery to repair or replacement of the defective item
- Revocation of acceptance of a defective item, which is allowed only if done on a timely basis and if the defect significantly impairs the usefulness of the item for its intended purpose.

---

[32] Based on Kowal [17]. The author discusses litigation from consumer and manufacturer perspectives.

Under the UCC code, the seller is allowed to disclaim all express and implied warranties, as long as certain requirements are satisfied.[33] In addition, a seller is allowed to limit or modify the buyer's remedies for breach of contract, unless the limitation is overly one-sided or is the result of excessive bargaining power of the seller.

State lemon laws came about in response to complaints regarding the automobile industry, particularly failure to abide by express written warranties.[34] This occurred after Magnuson-Moss, when manufacturers, instead of full warranties, offered limited warranties that did not provide for full replacement or refund of the purchase price. Because of the high cost of litigation, the buyer had little recourse in cases where the product was completely unsatisfactory. Nearly all states have since adopted lemon laws to provide buyers with additional remedies. In all cases, lemon laws apply only to new noncommercial automobiles and have various conditions and restrictions, depending on the state. Generally, before initiating litigation, a consumer must first make use of an informal dispute resolution procedure set up by the manufacturer, or, in some cases, an arbitration program set up by the state. The state laws do not cover products other than motor vehicles.

13.5.3 Litigation under Magnuson-Moss

Litigation under the Magnuson-Moss Act may be filed in either state or federal court. If filed in a state court, they are subject to the state's jurisdictional requirements. In federal court, lawsuits must meet the requirements that each claim exceeds $25, the total of all claims in the action exceeds $50,000, and, if a class action, there must be at least 100 defendants. As a result, most claims have been filed in state courts, and the federal courts have dealt only with the most significant abuses of warranty law.[35]

One provision of the Act that is unusual in the U.S. is that in most cases a successful plaintiff consumer may recover the cost of litigation, unless the court rules that this would be inappropriate. The aim of this is to provide consumers who have been injured relatively easy access to legal assistance. (Successful manufacturers, suppliers, retailers or warrantors are excluded and cannot recover legal fees or expenses incurred in defense or appeal of warranty actions.) In most cases, courts have awarded recovery of legal expenses to the successful consumer plaintiff.

The Act is applicable only to "consumers" who have purchased "consumer products" not for resale. The Act and various litigations have defined what is meant by these terms.[36] The consumer has four choices regarding cause under the Act:

---

[33] See Kowal [17], Section 5.3.2.
[34] Kowal [17], Section 5.3.3.
[35] See Kowal [17], Section 5.2 for additional details and other sources of information.
[36] See Kowal [17], Section 5.2.5.

1. Damage caused by failure to comply with the Act (e.g., failure to disclose whether full or limited, availability of warranty prior to sale, failure to provide for informal dispute settlement procedures);
2. Breach of full or limited warranty;
3. Breach of any implied warranty as set by the UCC of the state; and
4. Breach of a service contract.

With some conditions, the warrantor is allowed to select from three remedies:

1. Repair of the product;
2. Replacement of the product; and
3. Refund.

These options are intended to counterbalance those of the consumer.

Most consumers seek compensation for one or more of three types of damages due to breach of warranty:

1. Claims for personal injury (generally under state law)
2. Compensation for economic loss
3. Punitive damages (not recoverable under the Act, but allowed in some states).

The Act encourages consumers and manufacturers to attempt to settle any dispute by use of "informal dispute settlement mechanisms" without resorting to litigation, and specifies procedures for establishing these. A decision reached by use of an informal mechanism, however, is not legally binding and does not preclude a dissatisfied consumer from pursuing litigation.

In the Act, a "supplier" is defined to be "any person engaged in the business of making a consumer product directly or indirectly available to consumers" and a "warrantor" is defined to be "any supplier or other person who gives or offers to give a written warranty or who is or may be obligated under an implied warranty." Key defenses for a supplier or warrantor are:

1. The "right to cure" defense – the consumer must afford the seller or warrantor an opportunity to repair or replace the item or to offer a refund;
2. The "written warranty" defense – some of the remedies of the Act are only available if a written warranty has been given.[37]

The Act also includes disclosure requirements. If a written warranty is offered, the terms must be made available to the buyer prior to the purchase. This may be done in four ways:

1. Displaying the text of the warranty next to the product,
2. Maintaining binders containing the warranty in the department in which the item is sold,

[37] See Kowal [17], Section 5.2.7 for details.

3. Showing the package of the product on which the warranty is written, and
4. Placing a sign listing the warranty terms in close proximity to the product.

Failure to disclose the warranty terms is in violation of both the FTC regulations and the Act. For further information, see Kowal [17] and the references cited there, and for the latest developments in this area, see *Warranty Week* and consult with attorneys knowledgeable in the area of warranties.

13.5.4 Implications for Business

The implications of warranty legislation for business were discussed in Section 13.4.5. Many of the concerns discussed apply to warranty litigation as well. However, manufacturers have certain advantages over consumers in avoiding litigation in federal courts. First, it is very difficult to obtain federal jurisdiction. Secondly, manufacturers can avoid litigation by setting up a proper informal dispute resolution mechanism, which must be used by the consumer prior to litigating in a federal court. Finally, manufacturers have the right to cure any defects before they can be sued under federal law. Nonetheless, manufacturers must take the necessary steps to avoid costly warranty litigation, which is especially so because of the right of recovery of attorney's fees and expenses. To avoid federal litigation, it is also important to comply with FTC presale disclosure requirements.

State litigation is potentially more of a problem for manufacturers. It is easier to bring suit in state courts. In addition, many state warranties are automatically implied when an item is sold in the state, whether or not it is in writing. Finally, there are many more state statues regarding warranties, including UCC regulations, deceptive practices acts, and lemon laws. Again, manufacturers must be aware of the large number of state consumer protection laws and local judicial practices with regard to interpretation of these laws.

References

[1] Maschmeyer, R. A., and Balachandran, K. R. (1996), "Financial Accounting and Reporting for Warranties," Chapter 26 in Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[2] FASB (1975), *Accounting for Contingencies*, Statement of Financial Accounting Standards No. 5, FASB, Stamford, CT.

[3] Frees, E. W., (1996), "Warranty as a Contingent Claim," Chapter 30 in Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[4] FASB (1990), *Accounting for Separately Priced Extended Warranty and Product Maintenance Contracts,* Financial Accounting Series, FASB Technical Bulletin No. 90-1, Financial Accounting Standards Board, Stamford, CT.

[5] Maschmeyer, R. A., and Balachandran, K. R. (1996), "Cost Management Planning and Control for Product Quality and Warranties," Chapter 29 in Blischke, W. R., and

Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[6] Juran, J., and Gryna, F. (1980), *Quality Planning and Analysis*, McGraw-Hill, New York.

[7] Heagy, C. (1991), “Determining optimal quality costs by considering cost of lost sales,” *Cost Management* **65**: 64–72.

[8] Turney, P. (1991), *Common Cents, The ABC Performance Breakthrough*, Cost Technology, Hillsboro, OR.

[9] Burton, J. S. (1996), “Warranty Protection: A Consumerist Perspective,” Chapter 28 in Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[10] Rothschild, D. P. (1976), “The Magnuson-Moss Warranty Act: Does it balance warrantor and consumer interests?” *George Washington Law Review*, **44**, 335–380.

[11] Kelley, C. A. (1996), “Warranty Legislation,” Chapter 4 of Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[12] Mosier, G. C., and Wiener, J. L. (1996), “Warranties and Public Policy,” Chapter 27 in Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

[13] Public Law No. 93-637 (15 U. S. C. 2301).

[14] Blischke, W. R., and Murthy, D. N. P. (1994), *Warranty Cost Analysis,* Marcel Dekker, New York.

[15] MeGuire, E. P. (1980), *Industrial Product Warranties: Policies and Practices*, The Conference Board, New York.

[16] Litker, M. (1988), *International Dimensions of the Legal Environment of Business*, PWS-Kent Publishing, Boston.

[17] Kowal, R. S. (1996), “Warranty and the Courts,” Chapter 5 in Blischke, W. R., and Murthy, D. N. P., Editors (1996), *Product Warranty Handbook*, Marcel Dekker, New York.

14

Warranty Management Systems

14.1 Introduction

Warranties play a very important role in the marketing of new products. They provide assurance to consumers and serve as a promotional tool for manufacturers to promote product reliability and quality and, to differentiate their products from those of competitors. However, this is achieved at a cost and, as discussed in Chapter 7, the cost of servicing warranty is a significant item that affects the manufacturer's bottom line. This implies that manufacturers need to manage warranties effectively to survive and grow in a fiercely competitive world with demanding consumers and increasing warranty legislation.

A warranty management system (WMS) is a tool that manufacturers can use to manage warranties effectively. This chapter deals with this topic and looks at various issues relating to WMS. The outline of the chapter is as follows. In Section 14.2 we briefly review warranty management and indicate three stages in its evolution. Section 14.3 looks at the four key elements of WMS, (i) database, (ii) models, (iii) mathematical tools and techniques, and (iv) interface. Some of the issues for each of these are discussed in the subsequent four sections (Sections 14.4 to 14.7). Finally, we conclude with a brief discussion of some of the commercial WMS packages that are currently available.

14.2 Warranty Management

14.2.1 Evolution of Warranty Management

As mentioned in the Preface, warranty management has evolved over time and one can identify three stages in the evolutionary process.

14.2.1.1 Stage-1: [Warranty Administration]

Here the focus of warranty management was on the administration of warranty claims. It involves the following steps:

- Receiving claims from service agents
- Processing claims to check for the validity of claim (so as to prevent fraud)
- Arranging for reimbursement
- Part management (to update the part inventory of service agents).

The aim was to control warranty servicing costs through detection of fraud (by customers and/or service agents) and to ensure a certain level of customer satisfaction through efficient servicing of valid claims by service agents. The approach to warranty was reactive and warranty was viewed mainly as a cost element with an accounting emphasis.

14.2.1.2 Stage-2: [Operational Improvement]

Here the focus moved to understanding the causes that lead to warranty claims and the resulting costs and customer dissatisfaction for a product that has been launched. Failures depend on product reliability and this is influenced by decisions made during design and production. Warranty data collected from service centers is used for improvements to reduce the warranty servicing costs and to increase customer satisfaction. This involves the following:

1. Evaluating product reliability in the field and then initiating changes to the production processes for improving quality of conformance and/or redesigning weak components for improving component reliabilities
2. Assessing customer dissatisfaction and then initiating changes to warranty servicing to reduce any dissatisfaction.

As can be seen, the thrust of warranty management has shifted from simply the accounting focus of Stage 1 to focusing on the cost of warranty as well as customer satisfaction. The emphasis on improvement fits well into the TQM (Total Quality Management) paradigm.

14.2.1.3 Stage-3: [Strategic Management]

Here the manufacturer looks at warranty from a strategic management perspective. Product warranty management needs to be done in the overall product life cycle context, as discussed in Chapter 4. This implies defining a warranty strategy, in conjunction with all other technical and commercial strategies, so as to achieve the overall business goals.

According to Jim Ericson [1], “Warranty management today is about faster cycles for engineering design and redesign, better consumer response, recovering costs, improving channel relationships, and building a service business with much higher margins than traditional manufacturing. Today, the customer demands the warranty, but the manufacturer needs it more.”

In early stages of the product life cycle, a manufacturer's warranty management goal must be to reduce the cycle time of uncovering the root cause of defects in products so that changes can quickly be made. For the latter stages of the product life cycle, warranty management must deal with various aspects of warranty logistics and achieve a balance between costs and customer satisfaction.

The complexity of modern business demands quicker and more effective decision-making. "Product life cycles are shorter, you're revamping your product line quicker than ever before," says Joseph Mejaly, director of customer support at ArvinMeritor North America. "You have a proliferation of products and part numbers you need to support at a higher level." Second, he says, "As companies move through acquisition or growth or merger, they look a lot different than they did five years ago." [1]

A big part of this is getting a grip on the complexity of a modern manufacturing business, various partners in the delivery chain and the customers. Speed is critical, as product life cycles are getting shorter. All the processes must be well planned and controlled to ensure overall success. The strategic warranty management approach proposed in earlier chapters provides a framework to achieve this.

Another side of warranty management is the revenue potential in extended warranties. "We've found that the margins for aftermarket parts and service can be an 85 percent margin business, compared to 25–35 percent for traditional OEMs," says Mark Demers, Vice President of Marketing and Business at Entigo. "Why do you think Circuit City and Best Buy push customers so hard?" [1]

The key elements for warranty management are shown in Figure 14.1. Effective warranty management requires taking into account the interaction between these elements and the effect of warranty on these interactions. These interactions are apparent throughout the chart. For effective management and efficient operation, impacts of each element on other activities must be recognized and responded to. In the top portion of the figure, for example, each element impacts on every other, and this pattern is found in other segments as well. More importantly, the complexity of the actual system as a whole is, in fact, even greater than is apparent in the overview represented in Figure 14.1. Because of this, the systems approach as discussed in Chapter 5 is an essential tool for analysis.

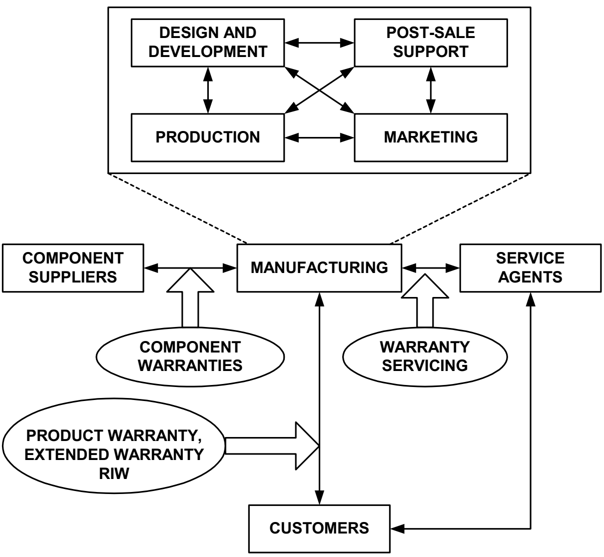


Figure 14.1. Key elements for warranty management

Strategic warranty management requires finding solutions to a variety of decision problems. Data and models play a critical role in this, as indicated in Figure 14.2. Decision-making involves using information to solve problems. The link between data, information and solution is shown in Figure 14.3, which also indicates the other elements that are needed for effective decision-making. Data collection is discussed in detail in Chapter 6. The use of models allows the decision-maker to understand the *qualitative* links between various aspects, and with the use of statistical methods of data analysis *quantify* those links and provide levels of confidence in the solutions proposed.

14.2.2 Current Scene

The warranty management practice at most manufacturing businesses is still at Stage 1. This is reflected in the fact that the majority of the warranty management systems currently available are suitable only for this kind of warranty management. A growing number of businesses are moving into Stage 2 and a few warranty management systems that will be useful at this stage have appeared over the past few years. Stage 3 warranty management is still in its infancy.

14.3 Designing a Warranty Management System

A warranty management system is a tool that can be used to evaluate alternate options in finding solutions to a variety of warranty related problems through proper decision-making. In the case of new products, it allows the evaluation of alternate warranty strategies and then deciding on the best one. In the case of existing products, it allows for evaluation of alternate options to decide on the best strategy for improvement in business performance. It uses data and models to assist management in the development of effective strategic and operational strategies.

The aim of a WMS is to assist decision-makers with finding solutions to a variety of warranty-related problems at the different stages of the product life cycle for (i) formulating warranty strategy for new products and (ii) continuous improvements to reduce warranty costs for products on the market.

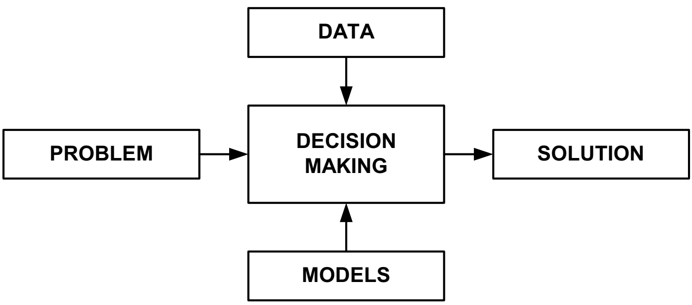


Figure 14.2. Decision, problem and solution

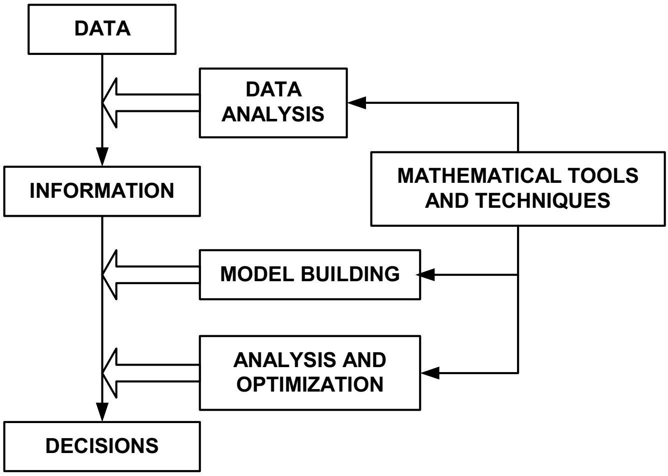


Figure 14.3. Data – information – decision

The WMS has four essential components, each of which needs to interact with each other, as shown in Figure 14.4. These are

- Database
- Models
- Mathematical tools and techniques
- Interface.

We discuss these in some detail in the next four sections.

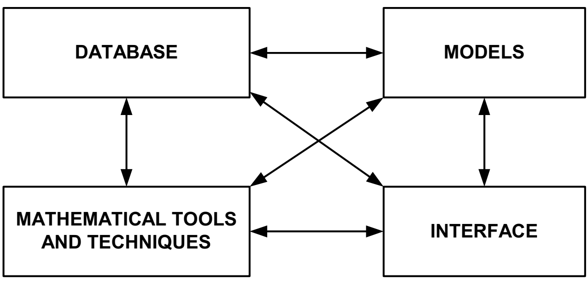


Figure 14.4. Components of a warranty management system

14.4 Databases

Data from many different sources are needed for decision-making during the formulation of various strategies. A WMS must be able to incorporate data and information from these sources. In the early stage of product development, much of the data and information will be subjective (e.g. based on the judgement of experts) or come from historical records of similar systems or components. As the development progresses, better data becomes available due to design definition, prototype testing, and trial manufacturing runs. Once the product enters the market, new data relating to product performance, sales, etc., becomes available.

For each generation of products, many types of data are generated over the product life cycle. These need to be combined with data from external sources (vendors, industry groups) to make proper decisions. As such, the WMS database needs to contain all in-house data relating to different generations of products.

The inputs to the database can be divided into two groups – internal and external, as shown in Figure 14.5. External data are data relating to partners in the supply chain (such as component suppliers, service agents, dealers), to competitors and to customers. Internal data are the data generated by groups responsible for the four stages of the product life cycle. Also shown in the figure are the outputs resulting from the database and the other elements of the WMS.

14.4.1 Database Management

A database must be maintained and managed for it to be of value to users. A database management system (DBMS) provides the procedures and mechanisms for maintaining and managing a database. Three main functions of a DBMS are file maintenance, database administration, and information retrieval. The relationship between these functions is illustrated in Figure 14.6.

File maintenance involves adding records to tables, updating data in tables, and deleting records from tables. The users of the database are responsible for maintaining the quality of the data that is in the database. In the context of the WMS, file maintenance is carried out by operational users at each of the phases of the product life cycle. Engineers would input the results of prototype tests into the WMS, financial personnel would input weekly or monthly cost data, service personnel would enter data relating to fault types and repair activities and so on.

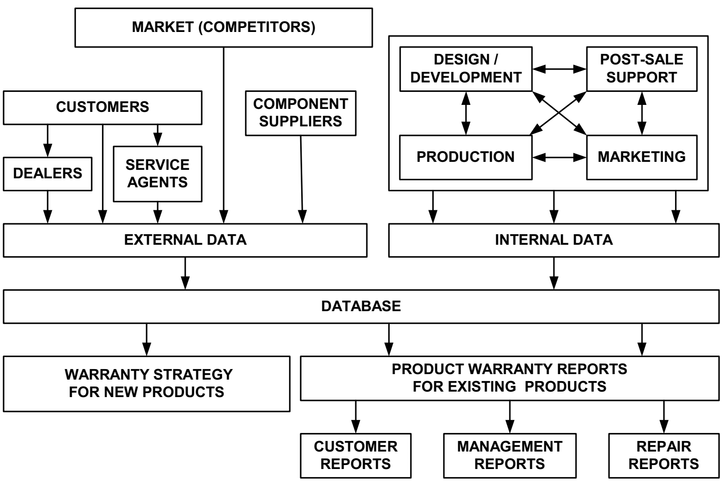


Figure 14.5. Database – inputs and outputs

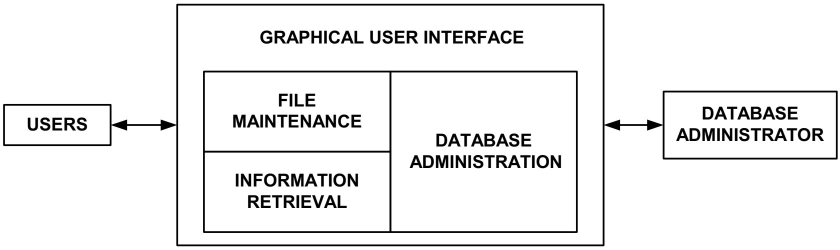


Figure 14.6. Database management system

Database administration involves the creation, deletion and restrictions on the use of tables. During development of the database, tables are created for storing data. As the design of the database evolves, some tables may become obsolete and require deletion, while additional tables may be required in order to support additional features. It is important that only certain personnel have the ability to make such changes, so that the downstream effects are managed. The database administrator may be a dedicated position or it may be a part-time role of an operational 'supervisor,' depending on the size of the organization.

Information retrieval involves the input of certain search criteria and the extraction of useful information based on the data within the database. The system must allow the user to input requirements (targets, objectives, models, etc.) and view the output results. Operational users will require the ability to access information based on their inputs. Strategic users (the managerial decision-makers) will need to retrieve strategic information linking multiple modules so that trade-off decisions can be made.

14.4.2 Data Warehousing

A data warehouse is a centralised repository of useful data. It is designed for strategic decision support because it allows the past to be researched and relevant trends to be identified. It is largely built up from data extracted from operational databases. The structure should be

- Time dependent
- Non-volatile
- Subject oriented
- Integrated.

Each record in the database has a date associated with it so that historical trends can be ascertained.

The database must be a static, historical 'snapshot' of the operational data. Before data enters the data warehouse from operational databases, the data needs to be "cleaned" so that it is ready for queries.

Only data that is relevant to the decision support purpose should be extracted from operational databases for use in the warehouse. A data warehouse by definition will be large, so extraneous data should be avoided. Data for day-to-day use should be accessed through the operational databases.

The data entering the data warehouse must be consistent and integrated from all appropriate sectors of the organisation. A single entity may be referred to by different names across the many operational databases, but since the purpose of the warehouse is to facilitate analysis, there must be only one name for each entity.

14.5 Models

Many different kinds of models are needed to assist in the decision-making in the different phases of the product life cycle. This element of WMS is a library of the different models that have been developed either internally or externally. The models can be grouped into four categories as indicated below and the list of models in each that we indicate is not exhaustive.

14.5.1 Design and Development Stage

Some important models include:

- Failure / reliability models
- Development time / reliability growth models
- Development cost models.

14.5.2 Production Stage

Key production models include:

- Production cost models
- Production quality models
- Plant maintenance models.

14.5.3 Marketing Stage

Many aspects of marketing are modelled. Models used are:

- Risk models
- Demand / sales models
- Marketing cost models
- Market share models
- Total cost models
- Revenue models
- Profit models.

14.5.4 Post-Sale Servicing Stage

Many models in this area have been developed, including:

- Warranty cost models
- Repair / renewal models
- Warranty execution models
- Product usage models
- Warranty reserves models
- Warranty servicing models.

The operational user should to be able to select models from within each category and have the parameter values estimated from data sets stored in the system. Conservative default values (and probability profiles) should be offered if data sets are not available (or judgement values solicited).

Often several models need to be linked to find a solution to a specific decision problem. Also, the WMS must have the flexibility that allows for upgrading of models and the addition of new models to the system.

14.6 Mathematical Tools and Techniques

This element contains packages needed for carrying out data analysis and model building, analysis and optimization. Some of the packages are standard commercial packages whereas others might be specialized packages.

Advances in computer technology have resulted in packages that can handle large and complex data sets and carry out the analysis using modern techniques such as data mining, expert systems, artificial intelligence, etc. These are important in looking for the underlying patterns in the data set.

A large number of statistical packages are available for various tasks of model building (such as model selection, parameter estimation, model validation). Similarly, a large number of software packages are available for model analysis and optimisation.

One of the main sources of new data on an ongoing basis in later phases is the warranty reports generated regularly. In this connection, the user should be aware of the many difficulties often encountered in warranty data, as discussed in Chapter 6.[1] We reiterate that it is important in the warranty phase to assure that useful data of as high quality as feasible be obtained. It is also important that proper and adequate data analysis techniques be used in evaluating, summarizing, and interpreting the data.[2]

---

[1] Some of the shortcomings of claims data and the reasons for them are discussed in Iskandar and Blischke [2] and Suzuki *et al.* [3].

[2] Some of these are illustrated in Iskandar and Blischke [2]. For additional discussion, see Suzuki *et al*. [3] and Lawless [4].

14.7 Interfaces

Two interface requirements are that the WMS should have a user interface and an application interface. The user interface facilitates the flow of information from the user to the WMS and back, while the application interface provides the link between a variety of external programs and databases that may be called upon to analyze or upload data to and or download data from the WMS.

14.7.1 User Interface

As a decision support tool, the WMS can be viewed as composed of four modules. These are indicated in Figure 14.7. The modules relate to the four phases of the product life cycle and interact with each other. The problem or objective is first specified, and then data and models from the WMS are used to provide information and assistance to solve the problem or to achieve the desired objective.

The WMS should present a variety of model options (and state the assumptions underlying each model). If an appropriate model is not available, the WMS should guide the user through a model-building process whereby data are imported from the appropriate source (e.g., database or expert opinion), analysed, and parameters estimated. The input values (decision variables or other data) should be clearly displayed as well as the output values and confidence bounds.

Once the component models have been selected, they need to be linked so as to assist in the solving of the problem. This linking is facilitated using a graphical representation, such as a flowchart, whereby icons for different models could be dragged-and-dropped. The output from one model would become the input for the next. Selecting an element of the flowchart would then open it up for more detailed configuration, with the option of viewing underlying data or model assumptions.

The user should be able to specify the form of the outputs. These could be viewed for each of the component models (to ensure they are performing as expected, or to focus on certain problem areas) or at the objective function (macro) level. Graphs illustrating distributions of variables and the limits on parameters should be available.

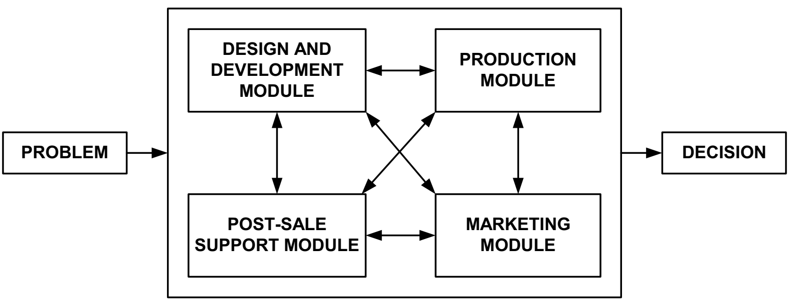


Figure 14.7. Four modules of a WMS

It is important for the interface to be easy to learn and easy to use, allowing the operator to define the problem and the elements that are expected to have an impact on the system being studied. In other words, time should be spent solving the problem, not navigating the tool. Two common options are a menu system or a graphical user interface (GUI). A combination of the two could be used to make the most of the two types.

14.7.2 Application Interface

The interface between external applications (such as analysis software packages and operational databases) and the warranty management system should have the ability to extract data from the WMS so that more sophisticated analyses can be performed. It should also have the ability to return data from the external software in such a way that the results are linked to the original data and can be easily referenced if using a model based on that data.

If the decision-maker, for example, requires a reliability model, then the parameter value estimates should be readily available. If the underlying data have been updated (additional testing performed, for example), then there should be some flag displayed that will show potential users that the analysis package should be revisited to refresh the estimates.

14.8 Commercial Software Packages

As mentioned earlier, the bulk of the commercially available warranty management systems are designed for Stage 1 warranty management and a few are designed for management at the level of Stage 2. According to D. F. Blumberg Associates, "The market for standalone warranty/claims processing solutions this year is $194 million, with another $110 million in Internet-based warranty portals. The overall market, still in its infancy, is experiencing 19 percent (annual) growth." In this section, we briefly discuss a few warranty management systems currently on the market and designed for Stage 2 warranty management. The material reported here is based on information downloaded from the websites for the various systems. These sites should be contacted for access to the latest updates and any relevant new products offered by the respective vendors.

14.8.1 WarrantyNet

This is a software package from IBM. Guy Vales, vice president of e-business and Web application development, states:

> Warranty records contain valuable information – what was bought and where, how often a product is serviced, what repairs are needed – that can help businesses track market trends earlier in the supply cycle than with traditional market analysis. We also realized that for consumers, warranties are a defense against faulty products and serve a crucial customer service role. From recall notification to product and warranty coverage information,

> WarrantyNet.com provides consumers with assistance to enhance their ownership experience.

Some of the key features of WarrantyNet.com are:

- It provides web-based warranty management solutions that allow consumers and corporate buyers to register, store and forward their warranty information to manufacturers and other warranty providers.
- It allows buyers to locate dealers and repair shops, and obtain recall information.
- It allows buyers to purchase extended warranties on items such as cars, computers, automobiles and home appliances via a reverse auction service that provides a greater choice of extended warranty plans.
- It enables manufacturers, retailers and other warranty providers to process online and offline warranty information for central electronic storage and processing, helps warranty providers to transform warranty data into business intelligence that may be used to market more effectively, provide better customer service, reduce fraud, track repair trends, increase service revenue from extended warranties and provide recall information to customers.
- It provides an information base for use in defining customer profiles, management of recalls, warranty information management, customer relations management, and management of retailers, repair shops, etc.

14.8.2 SAP

According to Kerstin Geiger, head of the Industry Business Unit Automotive, SAP AG, the developers of this system:

> Processing warranty claims is a complex business that involves different business partners. Customer satisfaction and retention heavily depends on the professional way of resolving these claims as fast as possible in an automated manner, while keeping process costs low.

Some of the key features of the system are:

- Warranty Claims Processing with mySAP™ Automotive is intended to help customers process large volumes of warranty claims, while reducing processing costs and increasing customer satisfaction and loyalty.
- It meets the specific needs of the automotive industry by linking complex business processes into a logical flow. The solution flexibly integrates the warranty process into vehicle sales, financials, controlling, spare parts management, and engineering to create efficient processes.
- Features include portal-based integration, which increases speed and cuts processing costs, use of rules to automatically check and process claims,

reducing administration costs, and intelligent control of processes which reduces the amount of manual processing.

- With warranty processing, information can later be used to track the processing of the claim in detail and analyze damage symptoms. The resulting evaluations can be used to introduce preventive measures for improving the product.

14.8.3 Entigo/SAS

According to Jim Ericson [5]:

> Entigo's expertise goes well past administrative task work around warranties; the underlying goals of warranty management are deeply tied to engineering design and cost recovery, as well as improved customer service and better channel management.

In commenting on the SAS/Entigo approach, Mark Demers of Entigo Corp. states that

> SAS and Entigo provide the industry's first end-to-end warranty management and analysis solution that helps manufacturers reduce warranty costs and risk. The SAS and Entigo solution encompass the entire warranty life cycle – including the automation and management of claims registration, processing, policy administration, settlement, supplier recovery – and integrates warranty data with key customer, product, and manufacturing information for problem identification and root cause analysis. This solution enables automotive manufacturers to predict and reduce warranty costs by streamlining processes, enhancing claim accuracy, accelerating problem identification and resolution cycle time, managing recoverable costs resulting in improved product quality, customer satisfaction and enhanced brand value.

Entigo Warranty solves operational problems in claims management, supplier recovery, and returns processing for manufacturing companies. It is a family of products that covers the entire spectrum of warranty management, from registering products in the sales channel to sharing warranted parts costs with key suppliers. Some of the key features of the system are:

- The system includes a core Universal Claims Server (UCS) that optimizes the business processes of product registrations, warranty policies, and claims management.
- Supporting the UCS, Entigo provides enterprise warranty applications that support the business processes of claims exchange, claims adjudication, extended warranty, returns management, supplier recovery, parts management, and integration management.
- The UCS and its 10 management modules offer a complete end-to-end enterprise warranty management system.

- Entigo Warranty provides intelligent claims processing, allowing manufacturers and channel partners to submit and view all claims associated with user groups. It also automatically validates and classifies claims against product registration information and warranty campaigns or programs, tracks standard repair time, logs actual labor and much more.

14.8.4 Jetliner Warranty Management

The Boeing Company has developed a warranty management system for processing and analyzing warranty claims on its jetliners. Boeing's online service for processing jetliner warranty claims is available through the company's MyBoeingFleet.com Web portal which was set up with the goal of becoming a single point of entry for airlines to transact virtually all of their support-related business with Boeing. According to Sandra Donckers, warranty claims manager at Boeing Commercial Airplanes,

> Online filing of warranty claims will cut as much as two days off the typical six-day processing time. It eliminates the need at our end to collect, distribute and manually re-key the data into our system and also reduces the chance for errors.

Some of the key features of the system are:

- Airline employees can simply enter the pertinent information directly into the warranty claims section in the MyBoeingFleet portal.
- Other advantages include automated tracking of warranty information, immediate claim receipt acknowledgements, and fewer delays in receiving claim remedies.
- Claims stemming from vendor-designed items are handled with the individual vendors. For customer convenience, the warranty section on the MyBoeingFleet portal includes links to vendors and, if available, to their online claims services.
- MyBoeingFleet allows customers to retrieve maintenance, engineering and flight operations information, and to collaborate on service-related issues affecting the worldwide Boeing fleet. The portal also provides access to the Boeing PART Page for ordering and tracking spare parts and offers many other features that enhance the speed and convenience of fleet support.

References

[1] Ericson, J. (2002), "The word on warranties," *Line 56*, Thursday, May 23, 2002.

[2] Iskandar, B. P., and Blischke, W. R. (2003), "Reliability and Warranty Analysis of a Motorcycle Based on Claims Data," Chapter 27 in Blischke, W. R., and Murthy, D. N. P. (Editors), *Case Studies in Reliability and Maintenance*, John Wiley and Sons, New York.

[3] Suzuki, K., Karim, Md. R., and Wang, L. (2001), "Statistical Analysis of Reliability Warranty Data," Chapter 21 in Balakrishnan, N., and Rao, C. R. (Editors), *Handbook of Statistics, Volume 20, Advances in Reliability*, Elsevier Science, Amsterdam.

[4] Lawless, J. F. (1998), "Statistical analysis of product warranty data," *International Statistical Review* **66**, 40–60.

[5] Ericson, J. (2002), "Entigo taps New Chairman/CEO." *Line 56*, Thursday, October 10, 2002.

15

Conclusion

Warranty is important in the context of new products. It provides assurance to customers that the product will perform satisfactorily as well as the recourse available to the customer in the event that the product performance is not satisfactory. Customer satisfaction with the product depends on how well the actual performance meets expectations and also on the service provided in servicing warranty claims resulting from unsatisfactory product performance. Customer satisfaction, in turn, impacts product sales and the revenue generated. The cost of servicing warranty is significant and depends on management decisions made during the different phases of the product life cycle.

Warranty management is an important issue for manufacturers. As discussed in Chapter 14, there are three stages in the evolution of warranty management. These are:

- **Stage-1 [Administration]**: Here the focus of warranty management is the on the administration of warranty claims. The aim is to control warranty-servicing costs through detection of fraud (by customers and/or service agents) and efficient servicing of valid claims.
- **Stage-2 [Operational improvement**]: Here the focus has moved to understanding the causes that lead to warranty claims and the resulting costs and customer dissatisfaction for a product. Warranty data collected from service centers is used for improvements to reduce the warranty-servicing costs and to increase customer satisfaction.

In both of these, warranty is viewed as an afterthought and warranty management is neither integrated into the overall new product management nor strategic in focus. Warranty impacts the commercial side (marketing, financial) of a business, as sales and revenue generated are influenced by warranty terms and the cost of servicing warranty claims affects overall profits. Warranty claims depend on product reliability and are influenced by the technical side (design and production) of the business. Warranty can no longer be viewed as an afterthought – rather it should be viewed as an important element of a new product and must be managed strategically.

- **Stage-3 [Strategic warranty management]**: Here the manufacturer looks at warranty from a strategic management perspective. Product warranty management must be done in the overall product life cycle context, as discussed in Chapter 4. This implies defining a warranty strategy, in conjunction with all other technical and commercial strategies, so as to achieve the overall business goals.

This book has dealt with strategic warranty management. Management at this level involves two issues – strategy formulation and strategy implementation. Strategy formulation needs to be done jointly by senior level managers (CEO, functional managers such as Marketing Manager, Production Manager, etc.) and middle level managers (responsible for sections such as material acquisition, product development, etc). Strategy implementation needs to be done jointly by middle level managers and junior level managers (responsible for management of operational activities). Different kinds of data are needed for strategy formulation and strategy modification and refinement over time. This is shown in Figure 15.1.

There is an increasing trend towards outsourcing of design, where some or all of the design activities are carried out by external designers. This has implications for warranty since claims result from poor product performance. Also, most manufacturers buy some or all of the components from external component suppliers. The quality of components affects product performance, and as a result, component conformance is very critical since claims increase with the degree of nonconformance.

Customers not only need assurance regarding product performance but also the product must meet the customer needs regarding the support services, including warranty servicing. Since different customers have different needs, warranties need to be flexible to met customer needs. Warranty servicing is important since it impacts on customer satisfaction and this in turn has a major influence on sales and revenue. External service agents are employed to service warranty claims and the quality of service (provided by the agents) impacts on customer satisfaction.

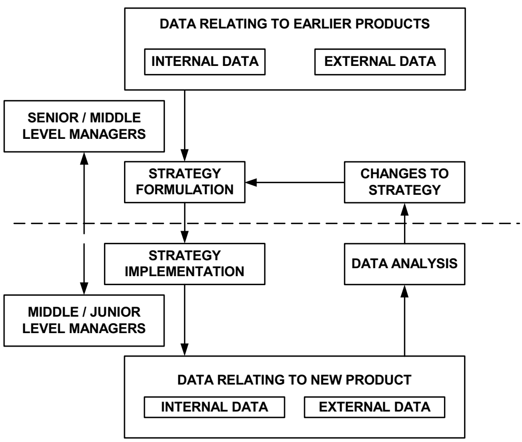


Figure 15.1. Strategic warranty management

Figure 15.2 (which is a slight modification of Figure 14.1) shows the interactions between the different key elements of the process. The overall system can be viewed as defining a **warranty chain** involving several external parties. A manufacturing process is comprised of several units or sections. Five of these that are important in the context of warranty management are shown in the box at the top of the figure. (There are many other units, such as legal, human resources, and so forth that are not shown in the box.) The link between these units and product warranty is discussed in Chapters 7–11. The dashed lines in Figure 15.2 show the links between four of these units and the different external parties involved. Some of the important issues in this context are:

1. *Product performance*: This depends on the decisions made by the designer and may have a significant impact on warranty costs. When external designers are involved, how does one apportion the warranty costs resulting due to design problems? If the problem is due to poor design from an external designer, the costs should be borne by the external designer, but it is often difficult to establish whether the internal or the external designers are responsible for a particular design problem.
2. *Component conformance*: Nonconforming items result in higher warranty cost. When a warranty claim occurs and the reason for it is identified as nonconformance of a component supplied by an external party, how are the warranty costs to be shared?
3. *Warranty servicing*: The service agent might not deliver the appropriate level of service quality and this impacts on customer satisfaction. How is the resulting cost to be shared between the two parties (manufacturer and service agent)? Increased monitoring will minimize the risk of the service agent shirking on the quality of service. However, this adds to the total cost to the manufacturer.

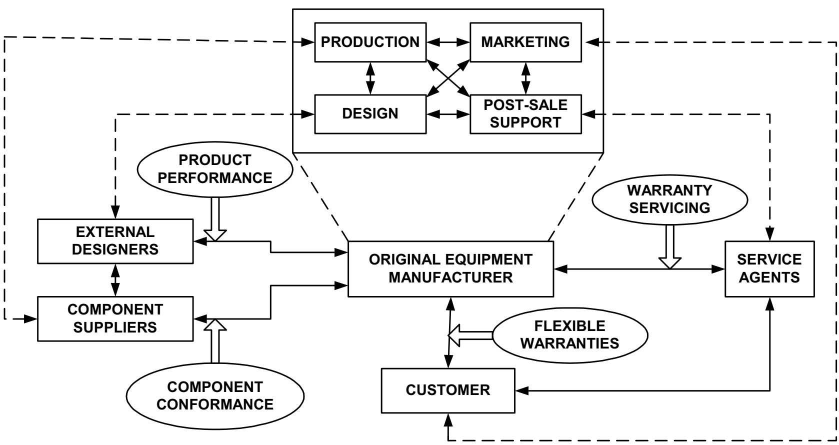


Figure 15.2. Warranty chain

4. *Flexible warranties*: Warranties need to be designed to meet the needs of the customer rather than those of the manufacturer. Also this is a potential revenue-generating source as customers (especially industrial and commercial) are willing to pay extra for better warranty service.

Through proper contracts, the manufacturer can ensure that the external parties carry their share of the warranty costs as well as the indirect costs resulting from product failures attributable to the external parties involved.

Strategic warranty management deals with all of these and other issues in warranty, in an integrated manner, taking into account all the implications. How should a business proceed with the implementation of Stage 3 warranty management? We indicate a multi-step process that businesses can use to achieve this goal.

- Step 1: Create a Warranty Management Department headed by a senior level manager with the title "Warranty Manager".
- Step 2: Carry out a review of the company's current approach to warranty management to identify if the business is at Stage 1 or Stage 2 warranty management and formulates a plan for moving to Stage 3.
- Step 3: Carry out an audit of the different information and management systems in use, to determine the kinds of data being collected, and to assess their relevance for strategic warranty management.
- Step 4: Set up a warranty management system. This must link with the various existing systems in use and must contain the modules discussed in Chapter 14. Make provision for the warranty management system to be continuously updated so that the company can effectively manage warranty for new products as they are developed and sold.
- Step 5: Initiate programs, either internally or with the assistance of external consultants, so that the competencies needed at all three levels of management (senior, middle and junior) exist.

In relation to Step 5 above, requirements of managers at the various levels are:

1. The CEO needs to understand the warranty chain, the need for strategic warranty management, and the need for warranty strategy as part of the overall strategy for each new product.
2. Senior level managers (responsible for the different functional units) need to understand the warranty chain so that they can formulate warranty strategy that is coherent and consistent with other technical and commercial strategies at the front-end stage of the product life cycle.
3. Middle level managers (across the different functional units) need to have the skills to evaluate alternate strategies and help senior level managers in strategy formulation. In addition, they need to have the skills to guide and monitor implementation of the strategies by junior level managers.
4. Junior level managers (across the different functional units) need to have a good understanding of the issues at the operational level so that the

strategies can be implemented and the data needed for effective management are collected.

It is difficult to suggest a checklist that would suit all businesses as they differ in the overall organization, the product, technology, goals, resources, etc. The following list is a sample of the kinds of things that managers at each level need to know and do.

CEO

- Must accept that warranty is an important element of new product development and critical for business success
- Must agree to a warranty strategy as an important element of new product development strategy
- Must understand that warranty strategy is an integrative element that links the technical and commercial aspects of new product development
- Must set up a Warranty Management Department headed by a senior level manager (with the title "Warranty Manager") responsible for strategic warranty management
- Must ensure that senior level functional managers (across different functional units) understand the link between warranty and the activities in their respective functional units and the importance of the warranty management department.

Senior Level Managers

Senior managers in charge of different functional units must:

- Closely interact with the Warranty Manager to ensure that the functional strategies are coherent with the warranty strategy
- Ensure that the functional oriented databases are properly linked to the WMS for effective transfer of relevant data
- Ensure that middle and junior level managers have the skills and techniques needed
- Develop alternate strategies for analysis by middle level managers
- Recommend strategies for consideration by the CEO
- Evaluate the implications of warranty for the various functional strategies.

Warranty Management Department

Warranty Manager

The Warranty Manager is responsible for:

- Setting up the warranty management system (WMS) and continuously updating it
- Formulation of warranty strategy in conjunction with other senior level managers.

Middle level managers

Responsibilities include:

- Analysis of different kinds of data relevant for warranty management
- Interface with external parties (as well as with middle level managers in different functional units within the business) to resolve problems
- Initiating improvement actions
- Supervising junior level managers in relation to data collection.

Junior level managers

Requirements are:

- Must have the skills and techniques needed for data collection and analysis
- Implement improvement changes suggested by middle level managers
- Liaise with their counterparts in various functional units.

This implies that the Warranty Management Department is an interdisciplinary group with people having backgrounds in engineering, reliability, statistics, marketing, legal, IT and management.

Author Index

Subject Index