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B.S. Dhillon

Applied Reliability and Quality

Fundamentals, Methods and Procedures

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This book is affectionately dedicated
to my colleague Professor Stavros Tavoularis
for helping me to trace my ancient Scythian ancestry
that resulted in the publication of a book on the matter
and for challenging me to write 30 books.

Foreword

In today's technological world nearly everyone depends upon the continued functioning of a wide array of complex machinery and equipment for our everyday safety, security, mobility, and economic welfare. We expect our electric appliances, hospital monitoring control, next-generation aircraft, data exchange systems, banking, and aerospace applications to function whenever we need them. When they fail, the results can be catastrophic. As our society grows in complexity, there is a need to understand the critical reliability challenges. In other words, people want to know how reliable of their products by understanding how to quantify the reliability and quality of existing systems.

This volume, **Applied Reliability and Quality**, which is a well-written introduction in 11 chapters, is designed for an introductory course on applied reliability and quality for engineering and science students as well as a suitable for a short training course on applied engineering reliability. The book consists of four parts. The first part discusses some fundamental elements of probability and statistics including probability properties, basic statistics measures, and some common distribution functions. The second part presents various introductory aspects of reliability engineering and their applications in medical devices, electrical power, and robotic and computer systems. It also includes various methods such as Markov, fault tree, and failure modes and effect analysis. The third part describes some fundamental concepts of quality control and assurance and its applications in healthcare, software engineering, textiles, and the food industry. Finally, the last part provides a comprehensive list of literature references for readers who are interested in obtaining additional information on this subject.

Each chapter provides a basic introduction to applied engineering reliability and quality, an unusually diverse selection of examples, and a variety of exercises designed to help the readers further understand the material.

Hoang Pham
Series Editor

Preface

Today, billions of dollars are being spent annually world wide to develop reliable and good quality products and services. Global competition and other factors are forcing manufacturers and others to produce highly reliable and good-quality products and services. Needless to say, nowadays reliability and quality principles are being applied across many diverse sectors of economy and each of these sectors has tailored reliability and quality principles, methods, and procedures to satisfy its specific need. Some examples of these sectors are robotics, health care, electric power generation, Internet, textile, food, and software.

There is a definite need for reliability and quality professionals working in diverse areas to know about each other’s work activities because this may help them, directly or indirectly, to perform their tasks more effectively. At present to the best of author's knowledge, there is no book that covers both applied reliability and quality within its framework. More specifically, at present to gain knowledge of each other’s specialties, these specialists must study various books, articles, or reports on each of the areas in question. This approach is time consuming and rather difficult because of the specialized nature of the material involved.

This book is an attempt to meet the need for a single volume that considers applied areas of both reliability and quality. The material covered is treated in such a manner that the reader needs no previous knowledge to understand it. The sources of most of the material presented are given in the reference section at the end of each chapter. At appropriate places, the book contains examples along with solutions, and at the end of each chapter there are numerous problems to test reader comprehension. This will allow the volume to be used as a text. A comprehensive list of references on various aspects of applied reliability and quality is provided at the end of this book, to give readers a view of the intensity of developments in the area.

The book is composed of 11 chapters. Chapter 1 presents need for applied reliability and quality, reliability and quality history, important reliability and quality terms and definitions, and sources for obtaining useful information on applied reliability and quality. Chapter 2 reviews various mathematical concepts considered useful to understand subsequent chapters. Some of these concepts are arithmetic mean, mean deviation, standard deviation, Laplace transform definition, Newton method, Boolean algebra laws and probability properties, and probability distributions. Chapter 3 presents various introductory aspects of both reliability and quality.

Chapter 4 is devoted to robot reliability. It covers topics such as robot failure causes and classifications, robot reliability measures, robot reliability analysis methods, and models for performing robot reliability and maintenance studies. Chapters 5 presents medical equipment reliability-related topics such as medical equipment reliability improvement procedures and methods, human error in medical equipment, guidelines for reliability and other professionals to improve medical equipment reliability, and organizations and sources for obtaining medical equipment failure-related data.

Chapter 6 is devoted to power system reliability and covers topics such as service performance indices, loss of load probability, models for performing availability analysis of a single generator unit, and models for performing availability analysis of transmission and associated systems. Chapter 7 presents various aspects of computer and Internet reliability including computer system failure causes and measures, fault masking, software reliability evaluation models, Internet failure examples and outage categories, and Internet reliability models. Chapters 8 and 9 are devoted to quality in health care and software quality, respectively.

Chapter 10 covers various important aspects of quality control in the textile industry including quality-related issues in textiles, textile quality control department functions, textile test methods, and quality control in spinning and fabric manufacture. Chapter 11 is devoted to quality control in the food industry. It covers topics such as factors affecting food quality, basic elements of a food quality assurance program, the hazard analysis and critical control points (HACCP) concept, fruits and vegetables quality, and food processing industry quality guidelines.

This book will be useful to many people including design engineers, manufacturing engineers, system engineers, engineering and manufacturing managers, reliability specialists, quality specialists, graduate and senior undergraduate students of engineering, researchers and instructors of reliability and quality, and professionals in areas such as health care, software, electric power generation, robotics, textile, food, and the Internet.

The author is deeply indebted to many individuals including colleagues, friends, and students for their invisible inputs and encouragement throughout the project. I thank my children Jasmine and Mark for their patience and invisible inputs. Last, but not least, I thank my other half, friend, and wife, Rosy, for typing various portions of this book and other related materials, and for her timely help in proofreading.

Ottawa, Ontario B.S. Dhillon

Contents

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Introduction

1.1 Need for Applied Reliability and Quality

Today, billions of dollars are being spent annually worldwide to develop reliable and good quality products and services. Global competition and other factors are forcing manufacturers and others to produce highly reliable and good quality products and services. Needless to say, reliability and quality principles are being applied across many diverse sectors of the economy, and each of these sectors has tailored reliability/quality principles, methods, and procedures to satisfy its specific need. Some examples of these sectors are robotics, health care, electric power generation, the Internet, textile, food, and software.

As a result, there is a definite need for reliability and quality professionals working in diverse areas such as these to know about each others' work activities because this may help them, directly or indirectly, to perform their tasks more effectively. In turn, this will result in better reliability and quality of end products and services.

1.2 Reliability and Quality History

This section presents an overview of historical developments in both reliability and quality areas, separately.

1.2.1 Reliability History

The history of the reliability field may be traced back to the early 1930s, when probability principles were applied to electric power generation-related problems in the United States [1–5]. During World War II, Germany applied the basic reliability concepts to improve reliability of their V1 and V2 rockets. Also during World War II, the United States Department of Defense recognized the need for reliability improvement of its equipment. During the period between 1945–1950, it performed various studies concerning the failure of electronic equipment, equipment maintenance and repair cost, etc. The results of three of these studies were as follows [6]:

- An Army study indicated that between two-thirds and three-fourths of the equipment used by the Army was either out of commission or under repair.
- An Air Force study performed over a period of five years revealed that repair and maintenance costs of the equipment used by the Air Force were approximately ten times the original cost.
- A Navy study conducted during maneuvers revealed that the electronic equipment used was functional about 30% of the time.

As the result of studies such as these, the US Department of Defense established an ad hoc committee on reliability, in 1950. In 1952, this committee became a permanent group known as the Advisory Group on the Reliability of Electronic Equipment (AGREE). In 1957, the Group released its report, called the AGREE report, that ultimately resulted in the release of a specification on the reliability of military electronic equipment [6].

In 1954, a National Symposium on Reliability and Quality Control was held for the first time in the United States. Two years later, in 1956, the first commercially available book on reliability was published [7]. The first master's degree program in system reliability engineering was started at the Air Force Institute of Technology of the United States Air Force (USAF) in 1962.

All in all, ever since the inception of the reliability field many people and organizations have contributed to it and a vast number of publications on the subject have appeared [8, 9]. A more detailed history of the developments in the reliability field is available in [8, 10].

1.2.2 Quality History

The history of the quality field may be traced back to the ancient times to the construction of pyramids by the ancient Egyptians (1315–1090 BC). During their construction quality-related principles were followed, particularly in regard to workmanship, product size, and materials. In the 12th century AD quality standards were established by the guilds [11].

However, in the modern times (*i. e.*, by 1907) the Western Electric Company was the first to use basic quality control principles in design, manufacturing, and installation. In 1916, C.N. Frazee of Telephone Laboratories successfully applied statistical approaches to inspection-related problems, and in 1917, G.S. Radford coined the term "quality control" [12]. In 1924, Walter A. Shewhart of Western Electric Company developed quality control charts. More specifically, he wrote a memorandum on May 16, 1924, that contained a sketch of modern quality control chart. Seven years later, in 1931, he published a book entitled *Economic Control of Quality of Manufactured Product* [13].

In 1944, the journal *Industrial Quality Control* was jointly published by the University of Buffalo and the Buffalo Chapter of the Society of Quality Control Engineers. In 1946, the American Society for Quality Control (ASQC) was formed, and this journal became its official voice.

Over the years, many people and organizations have contributed to the field of quality and a vast number of publications on the topic have appeared [8, 14]. A large number of publications on four applied areas of quality are listed at the end of this book. A more detailed history of the developments in the field of quality is available in [8, 11, 14, 15].

1.3 Reliability and Quality Terms and Definitions

There are a large number of terms and definitions currently being used in reliability and quality areas. Some of the commonly used terms and definitions in both these areas are presented below, separately [16–22].

1.3.1 Reliability

- **Reliability.** This is the probability that an item will perform its stated mission satisfactorily for the specified time period when used under the stated conditions.
- **Failure.** This is the inability of an item to function within the stated guidelines.
- **Hazard rate (instantaneous failure rate).** This is the rate of change of the number of items that have failed over the number of items that have survived at time t.
- **Availability.** This is the probability that the equipment is operating satisfactorily at time t when used according to specified conditions, where the total time considered includes active repair time, operating time, logistic time, and administrative time.
- **Redundancy.** This is the existence of more than one means to accomplish a stated function.
- **Maintainability.** This is the probability that a failed item will be restored to its satisfactory working state.
- **Reliability engineering.** This is the science of including those factors in the basic design that will assure the specified degree of reliability, maintainability, and availability.
- **Reliability demonstration.** This is evaluating equipment/item capability to meet stated reliability by actually operating it.
- **Reliability model.** This is a model to predict, assess, or estimate reliability.
- **Reliability growth.** This is the improvement in a reliability figure-of-merit caused by successful learning or rectification of faults in equipment/item design, manufacture, sales, service, or use.

1.3.2 Quality

- **Quality.** This is the degree to which an item, function, or process satisfies the needs of users and customers.
- **Quality control.** This is a management function, whereby control of raw materials' and manufactured items' quality is exercised to stop the production of defective items.
- **Quality plan.** This is the documented set of procedures that covers the in-process and final inspection of product.
- **Quality control program.** This is an overall structure that serves to define the quality control system objectives.
- **Quality control engineering.** This is an engineering approach whereby technological skills and experiences are utilized to predict quality attainable with various designs, production processes, and operating set-ups.
- **Control chart.** This is the chart that contains control limits.
- **Random sample.** This is a sample of units in which each unit has been chosen at random from the source lot.
- **Sampling plan.** This is a plan that states the sample size to be inspected and provides acceptance and rejection numbers.
- **Process inspection.** This is intermittent examination and measurement with emphasis on the checking of process variables.
- **Quality assurance.** This is a planned and systematic sequence of all actions appropriate for providing satisfactory confidence that the product/item conforms to established technical requirements.
- **Quality measure.** This is a quantitative measure of the features and characteristics of an item or service.
- **Quality management.** This is the totality of functions involved in achieving and determining quality.
- **Average incoming quality.** This is the average level of quality going into the inspection point.

1.4 Useful Information on Applied Reliability and Quality

There are many sources for obtaining applied reliability and quality-related information. Some of the most useful sources for obtaining such information, on both reliability and quality, are presented below, separately, under many different categories [8, 9, 23].

1.4.1 Reliability

Organizations

- Reliability Society, IEEE, P.O. Box 1331, Piscataway, New Jersey, U.S.A.
- SOLE, the International Society of Logistics, 8100 Professional Place, Suite 111, Hyattsville, Maryland, U.S.A.
- American Society for Quality Control, 310 West Wisconsin Avenue, Milwaukee, Wisconsin, U.S.A.
- National Aeronautics and Space Administration (NASA) Parts Reliability Information Center, George C. Marshall Space Flight Center, Huntsville, Alabama, U.S.A.
- Reliability Analysis Center, Rome Air Development Center, Griffis Air Force Base, Rome, New York, U.S.A.
- System Reliability Service, Safety and Reliability Directorate, UKAEA, Wigshaw Lane, Culcheth, Warrington, U.K.

Journals

- *Reliability Engineering and System Safety*
- *International Journal of Quality and Reliability Management*
- *IEEE Transactions on Reliability*
- *Engineering Failure Analysis*
- *Quality and Reliability Engineering International*
- *Software Testing, Verification, and Reliability*
- *Risk Analysis*
- *Microelectronics Reliability*
- *Journal of Machinery Manufacture and Reliability*
- *Journal of Risk and Reliability*
- *Reliability Review*
- *International Journal of Reliability, Quality, and Safety Engineering*
- *Journal of the Reliability Analysis Center*
- *Lifetime Data Analysis*
- *Reliability Magazine*
- *IEEE Transactions on Power Apparatus and Systems*

Conference Proceedings

- *Proceedings of the Annual Reliability and Maintainability Symposium*
- *Proceedings of the ISSAT International Conference on Reliability and Quality in Design*

- *Proceedings of the Annual International Reliability, Availability, and Maintainability Conference for the Electric Power Industry*
- *Proceedings of the European Conference on Safety and Reliability*

Books

- *Grant Ireson, W., Coombs, C.F., Moss, R.Y., Editors, Handbook of Reliability Engineering Management, McGraw Hill Book Company, New York, 1996.*
- *Dhillon, B.S., Reliability Engineering in Systems Design and Operation, Van Nostrand Reinhold Company, New York, 1983.*
- *Ohring, M., Reliability and Failure of Electronic Materials and Devices, Academic Press, San Diego, California, 1998.*
- *Kumar, U.D., Crocker, J., Chitra, T., Reliability and Six Sigma, Springer, New York, 2006.*
- *Thomas, M.U., Reliability and Warranties: Methods for Product Development and Quality Improvement, Taylor and Francis, Boca Raton, Florida, 2006.*
- *Billinton, R., Allan, R.N., Reliability Evaluation of Power Systems, Plenum Press, New York, 1996.*
- *Dhillon, B.S., Design Reliability: Fundamentals and Applications, CRC Press, Boca Raton, Florida, 1999.*
- *Shooman, M.L., Probabilistic Reliability: An Engineering Approach, McGraw Hill Book Company, New York, 1968.*
- *Dhillon, B.S., Medical Device Reliability and Associated Areas, CRC Press, Boca Raton, Florida, 2000.*

Standards and Other Documents

- MIL-STD-785B, Reliability Program for Systems and Equipment, Development, and Production, US Department of Defense, Washington, D.C.
- MIL-STD-721C, Definition of Terms for Reliability and Maintainability, US Department of Defense, Washington, D.C.
- MIL-HDBK-338, Electronic Reliability Design Handbook, US Department of Defense, Washington, D.C.
- MIL-HDBK-217F, Reliability Prediction of Electronic Equipment, US Department of Defense, Washington, D.C.
- MIL-STD-790E, Reliability Assurance Program for Electronic Parts Specifications, US Department of Defense, Washington, D.C.
- MIL-STD-1629A, Procedures for Performing a Failure Mode, Effects, and Criticality Analysis, US Department of Defense, Washington, D.C.
- MIL-STD-2155, Failure Reporting, Analysis and Corrective Action System (FRACAS), US Department of Defense, Washington, D.C.
- MIL-HDBK-189, Reliability Growth Management, US Department of Defense, Washington, D.C.

- MIL-HDBK-781, Reliability Test Methods, Plans, and Environments for Engineering Development, Qualification, and Production, US Department of Defense, Washington, D.C.
- MIL-STD-781D, Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution, US Department of Defense, Washington, D.C.
- MIL-STD-756, Reliability Modeling and Prediction, US Department of Defense, Washington, D.C.

1.4.2 Quality

Organizations

- American Society for Quality Control, 310 West Wisconsin Avenue, Milwaukee, Wisconsin, U.S.A.
- European Organization for Quality, 3 rue du Luxembourg, B-1000, Brussels, Belgium.
- American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania, U.S.A.
- American National Standards Institute (ANSI), 11 W. 42nd St., New York, New York, U.S.A.
- Government Industry Data Exchange Program (GIDEP), GIDEP Operations Center, U.S. Department of Navy, Naval Weapons Station, Seal Beach, Corona, California, U.S.A.
- National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia, U.S.A.

Journals

- *Quality Progress*
- *Quality in Manufacturing*
- *Benchmarking for Quality Management and Technology*
- *International Journal of Quality and Reliability Management*
- *Journal of Quality in Maintenance Engineering*
- *Journal of Quality Technology*
- *Quality Forum*
- *Quality Today*
- *International Journal of Health Care Quality Assurance*
- *Managing Service Quality*
- *Quality Assurance in Education*
- *The TQM Magazine*
- *International Journal for Quality in Health Care*
- *Quality Engineering*

- *Six Sigma Forum Magazine*
- *Software Quality Professional*
- *Techno-metrics*
- *Quality Management Journal*
- *Journal for Quality and Participation*
- *The Quality Circle Journal*
- *Quality Assurance*
- *Industrial Quality Control*
- *Quality Review*

Conference Proceedings

- *Transactions of the American Society for Quality Control (Conference Proceedings)*
- *Proceedings of the European Organization for Quality, Conferences*
- *Proceedings of the Institute of Quality Assurance Conferences (U.K.)*

Books

- *Beckford, J., Quality, Routledge, New York, 2002.*
- *McCormick, K., Quality, Butterworth Heinemann, Boston, 2002.*
- *Kirk, R., Healthcare Quality and Productivity: Practical Management Tools, Aspen Publishers, Rockville, Maryland, 1988.*
- *Alli, I., Food Quality Assurance: Principles and Practices, CRC Press, Boca Raton, Florida, 2004.*
- *Schroder, M.J.A., Food Quality and Consumer Value: Delivering food that satisfies, Springer, Berlin, 2003.*
- *Vardeman, S., Jobe, J.M., Statistical Quality Assurance Methods for Engineers, John Wiley and Sons, New York, 1999.*
- *Gryna, F.M., Quality Planning and Analysis, McGraw Hill Book Company, New York, 2001.*
- *Rayan, T.P., Statistical Methods for Quality Improvement, John Wiley and Sons, New York, 2000.*
- *Shaw, P., et al., Quality and Performance Improvement in Healthcare: A Tool for Programming Learning, American Health Information Management Association, Chicago, 2003.*
- *Galin, D., Software Quality Assurance, Pearson Education Limited, New York, 2004.*
- *Meyerhoff, D., editor, Software Quality and Software Testing in Internet Times, Springer, New York, 2002.*
- *Kemp, K.W., The Efficient Use of Quality Control Data, Oxford University Press, New York, 2001.*

- *Hartman, MG., Editor, Fundamentals Concepts of Quality Improvement, ASQ Quality Press, Milwaukee, Wisconsin, 2002.*
- *Smith, G.M., Statistical Process Control and Quality Improvement, Prentice Hall, Inc., Upper Saddle River, New Jersey, 2001.*
- *Bentley, J.P., An Introduction to Reliability and Quality Engineering, John Wiley and Sons, New York, 1993.*
- *Kolarik, W.J., Creating Quality: Process Design for Results, McGraw Hill Book Company, New York, 1999.*
- *Evans, J.R., Lindsay, W.M., The Management and Control of Quality, West Publishing Company, New York, 1989.*

Standards and Other Documents

- *ANSI/ASQC A3, Quality Systems Terminology, American National Standards Institute (ANSI), New York.*
- *MIL-HDBK-53, Guide for Sampling Inspection, US Department of Defense, Washington, D.C.*
- *ANSI\ASQC B1, Guide for Quality Control, American National Standards Institute (ANSI), New York.*
- *MIL-STD-52779, Software Quality Assurance Program Requirements, US Department of Defense, Washington, D.C.*
- *ANSI/ASQC E2, Guide to Inspection Planning, American National Standards Institute (ANSI), New York.*
- *MIL-HDBK-344, Environmental Stress Screening of Electronic Equipment, US Department of Defense, Washington, D.C.*
- *MIL-STD-2164, Environment Stress Screening Process for Electronic Equipment, US Department of Defense, Washington, D.C.*
- *MIL-STD-105, Sampling Procedures and Tables for Inspection by Attributes, US Department of Defense, Washington, D.C.*
- *ANSI/ASQC A1, Definitions, Symbols, Formulas, and Table for Quality Charts, American National Standards Institute (ANSI), New York.*
- *ANSI/ASQC B2, Control Chart Method for Analyzing Data, American National Standards Institute (ANSI), New York.*
- *ANSI/ASQC A2, Terms, Symbols and Definitions for Acceptance Sampling, American Standards Institute (ANSI), New York.*

1.5 Problems

1. Define and compare reliability and quality.
2. List at least five areas of applied reliability.
3. Discuss historical developments in the area of quality.

4. Define the following terms:
   - Reliability growth
   - Hazard rate
   - Reliability engineering
5. What is the difference between quality control and quality control engineering?
6. Define the following quality-related terms:
   - Quality plan
   - Quality management
   - Process inspection
7. What is the difference between quality assurance and quality control?
8. List five important organizations for obtaining reliability-related information.
9. Write an essay on the history of the reliability field.
10. Discuss at least three important organizations for obtaining quality-related information.

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2

Reliability and Quality Mathematics

2.1 Introduction

Since mathematics has played a pivotal role in the development of quality and reliability fields, it is essential to have a clear understanding of the mathematical concepts relevant to these two areas. Probability concepts are probably the most widely used mathematical concepts in both reliability and quality areas. The history of probability may be traced back to the sixteenth century, when a gambler's manual written by Girolamo Cardano (1501–1576) made reference to probability.

However, it was not until the seventeenth century when Pierre Fermat (1601–1665) and Blaise Pascal (1623–1662) solved the problem of dividing the winnings in a game of chance correctly and independently. Over the years many other people have contributed in the development of mathematical concepts used in the fields of reliability and quality. More detailed information on the history of mathematics and probability is available in [1, 2]. More specifically, both these documents are totally devoted to the historical developments in mathematics and probability. This chapter presents mathematical concepts considered useful to understand subsequent chapters of this book.

2.2 Arithmetic Mean, Mean Deviation, and Standard Deviation

These three measures are presented below, separately.

2.2.1 Arithmetic Mean

This is expressed by

$$m = \frac{\sum_{i=1}^{n} DV_i}{n} \tag{2.1}$$

where

n is the number of data values.

DVi is the data value i; for i = 1, 2, 3, …, n.

m is the mean value (*i. e.*, arithmetic mean).

Example 2.1

The quality control department of an automobile manufacturing company inspected a sample of 5 identical vehicles and discovered 15, 4, 11, 8, and 12 defects in each of these vehicles. Calculate the mean number of defects per vehicle (*i. e.*, arithmetic mean).

Using the above-specified data values in Equation (2.1) yields

$$m = \frac{15+4+11+8+12}{5}$$
$$= 10 \ defects \ per \ vehicle$$

Thus, the mean number of defects per vehicle or the arithmetic mean of the data set is 10.

2.2.2 Mean Deviation

This is one of the most widely used measures of dispersion. More specifically, it is used to indicate the degree to which a given set of data tend to spread about the mean. Mean deviation is expressed by

$$m_{\mathrm{d}} = \frac{\sum_{i=1}^{n} \left| DV_i - m \right|}{n} \tag{2.2}$$

where

n	is the number of data values.
DVi	is the data value i; for i = 1, 2, 3, …, n.
m_d	is the mean value deviation.
m	is the mean of the given data set.
$\lvert DV_i - m \rvert$	is the absolute value of the deviation of DVi from m.

Example 2.2

Find the mean deviation of the Example 2.1 data set.

In Example 2.1, the calculated mean value of the data set is 10 defects per vehicle. By substituting this calculated value and the given data into Equation (2.2), we get

$$\begin{aligned} m_d &= \frac{\left[|15-10|+|4-10|+|11-10|+|8-10|+|12-10|\right]}{5} \\ &= \frac{[5+6+1+2+2]}{5} \\ &= 3.2 \end{aligned}$$

Thus, the mean deviation of the Example 2.1 data set is 3.2.

2.2.3 Standard Deviation

This is expressed by

$$\sigma = \left[\frac{\sum_{i=1}^{n} (DV_i - m)^2}{n} \right]^{1/2} \tag{2.3}$$

where

σ is the standard deviation.

Standard deviation is a commonly used measure of data dispersion in a given data set about the mean, and its three properties pertaining to the normal distribution are as follows [3]:

- 68.27% of the all data values are within $m + \sigma$ and $m - \sigma$.
- 95.45% of the all data values are within $m - 2\sigma$ and $m + 2\sigma$.
- 99.73% of the all data values are within $m - 3\sigma$ and $m + 3\sigma$.

Example 2.3

Find the standard deviation of the data set given in Example 2.1.

Using the calculated mean value, *m*, of the given data set of Example 2.1 and the given data in Equation (2.3) yields

$$\sigma = \left[\frac{(15-10)^2+(4-10)^2+(11-10)^2+(8-10)^2+(12-10)^2}{5}\right]^{1/2}$$

$$= \left[\frac{5^2+(-6)^2+1^2+(-2)^2+2^2}{5}\right]^{1/2}$$

$$= 3.74$$

Thus, the standard deviation of the data set given in Example 2.1 is 3.74.

2.3 Some Useful Mathematical Definitions and Formulas

There are many mathematical definitions and formulas used in quality and reliability fields. This section presents some of the commonly used definitions and formulas in both these areas.

2.3.1 Laplace Transform

The Laplace transform is defined by [4] as

$$F(s) = \int_0^\infty f(t)e^{-st}\,\mathrm{d}t \tag{2.4}$$

where

t is time.

s is the Laplace transform variable.

$F(s)$ is the Laplace transform of function, $f(t)$.

Laplace transforms of four commonly occurring functions in reliability and quality work are presented in Table 2.1. Laplace transforms of other functions can be found in [4, 5].

Table 2.1. Laplace transforms of four commonly occurring functions

$f(t)$	$F(s)$
$e^{-\theta t}$	$\frac{1}{s+\theta}$
$\frac{\mathrm{d}f(t)}{\mathrm{d}t}$	$s\,F(s)-f(0)$
c (constant)	$\frac{c}{s}$
t	$\frac{1}{s^2}$

2.3.2 Laplace Transform: Initial-Value Theorem

If the following limits exist, then the initial-value theorem may be stated as

$$\lim_{t\to 0} f(t) = \lim_{s\to\infty} s\,F(s) \tag{2.5}$$

2.3.3 Laplace Transform: Final-Value Theorem

Provided the following limits exist, then the final-value theorem may be stated as

$$\lim_{t\to\infty} f(t) = \lim_{s\to 0} s\,F(s) \tag{2.6}$$

2.3.4 Quadratic Equation

This is defined by

$$a\,y^2 + b\,y + c = 0 \quad \mathit{for}\ a \neq 0 \tag{2.7}$$

where
a, b, and c are constants.

Thus,

$$y = \frac{-b \pm \left(b^2 - 4\,ac\right)^{1/2}}{2\,a} \tag{2.8}$$

If a, b, and c are real and $M = b^2 - 4ac$ is the discriminant, then the roots of the equation are

- Real and equal if $M = 0$
- Complex conjugate if $M < 0$
- Real and unequal if $M > 0$

If y_1 and y_2 are the roots of Equation (2.7), then we can write the following expressions:

$$y_1 + y_2 = \frac{-b}{a} \tag{2.9}$$

and

$$y_1 \; y_2 = \frac{c}{a} \tag{2.10}$$

Example 2.4
Solve the following quadratic equation:

$$y^2 + 13y + 40 = 0 \tag{2.11}$$

Thus, in Equation (2.11), the values of a, b, and c are 1, 13, and 40, respectively. Using these values in Equation (2.8) yields

$$y = \frac{-13 \pm \left[13^2 - 4(1)(40)\right]^{1/2}}{2(1)}$$

$$y = \frac{-13 + 3}{2}$$

Therefore,

$$y_1 = \frac{-13+3}{2} = -5$$

and

$$y_2 = \frac{-13-3}{2} = -8$$

Thus, the roots of Equation (2.11) are $y_1 = -5$ and $y_2 = -8$. More specifically, both these values of y satisfy Equation (2.11).

2.3.5 Newton Method

Newton's method is a widely used method to approximate the real roots of an equation that involves obtaining successive approximations. The method uses the following formula to approximate real roots of an equation [6, 7]:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}, \; for \; f'(x_n) \neq 0 \tag{2.12}$$

where
the prime ($'$) denotes differentiation with respect to x.
x_n is the value of the nth approximation.

The method is demonstrated through the following example.

Example 2.5
Approximate the real roots of the following equation by using the Newton's approach:

$$x^2 - 26 = 0 \tag{2.13}$$

As a first step, we write

$$f(x) = x^2 - 26 \tag{2.14}$$

By differentiating Equation (2.14) with respect to x, we get

$$\frac{\mathrm{d}f(x)}{\mathrm{d}x} = 2x \tag{2.15}$$

Inserting Equations (2.14) and (2.15) into Equation (2.12) yields

$$x_{n+1} = x_n - \frac{x_n^2 - 26}{2x_n} = \frac{x_n^2 + 26}{2x_n} \tag{2.16}$$

For $n = 1$ in Equation (2.16) we chose $x_1 = 5$ as the first approximation. Thus, Equation (2.16) yields

$$x_2 = \frac{x_1^2 + 26}{2x_1} = \frac{(5)^2 + 26}{2(5)} = 5.1$$

For $n = 2$, substituting the above-calculated value into Equation (2.16), we get

$$x_3 = \frac{x_2^2 + 26}{2x_2} = \frac{(5.1)^2 + 26}{2(5.1)} = 5.099$$

Similarly, for $n=3$, substituting the above-calculated value into Equation (2.16), we get

$$x_4 = \frac{x_3^2 + 26}{2\,x_3} = \frac{(5.099)^2 + 26}{2\,(5.099)} = 5.099$$

It is to be noted that the values x_3 and x_4 are the same, which simply means that the real root of Equation (2.13) is $x = 5.099$. It can easily be verified by substituting this value into Equation (2.13).

2.4 Boolean Algebra Laws and Probability Properties

Boolean algebra is named after mathematician George Boole (1813–1864). Some of the Boolean algebra laws that can be useful in reliability and quality work are as follows [8, 9]:

$$A.B = B.A \tag{2.17}$$

where

A is an arbitrary event or set.

B is an arbitrary event or set.

Dot (.) between A and B or B and A denotes the intersection of events or sets. However, sometimes Equation (2.17) is written without the dot, but it still conveys the same meaning.

$$A + B = B + A \tag{2.18}$$

where

$+$ denotes the union of sets or events.

$$A(B + C) = AB + AC \tag{2.19}$$

where

C is an arbitrary set or event.

$$(A + B) + C = A + (B + C) \tag{2.20}$$

$$AA = A \tag{2.21}$$

$$A + A = A \tag{2.22}$$

$$A(A + B) = A \tag{2.23}$$

$$A + AB = A \tag{2.24}$$

$$(A + B)(A + C) = A + BC \tag{2.25}$$

As probability theory plays an important role in reliability and quality, some basic properties of probability are as follows [10–12]:

- The probability of occurrence of event, say X, is

$$0 \leq P(X) \leq 1 \tag{2.26}$$

- Probability of the sample space S is

$$P(S) = 1 \tag{2.27}$$

- Probability of the negation of the sample space is

$$P(\overline{S}) = 1 \tag{2.28}$$

where

$\overline{S}$ is the negation of the sample space S.

- The probability of occurrence and non-occurrence of an event, say X, is

$$P(X) + P(\overline{X}) = 1 \tag{2.29}$$

where

$P(X)$ is the probability of occurrence of event X.

$P(\overline{X})$ is the probability of non-occurrence of event X.

- The probability of an interaction of K independent events is

$$P(X_1 X_2 X_3 \ldots. X_K) = P(X_1)P(X_2)P(X_3)\ldots.P(X_K) \tag{2.30}$$

where

X_i is the ith event; for $i = 1, 2, 3, \ldots., K$.

$P(X_i)$ is the probability of occurrence of event X_i; for $i = 1, 2, 3, \ldots., K$.

- The probability of the union of K independent events is

$$P(X_1 + X_2 + X_3 + \ldots. + X_K) = 1 - \prod_{i=1}^{K} \left(1 - P\left(X_i\right)\right) \tag{2.31}$$

For $K = 2$, Equation (2.32) reduces to

$$P(X_1 + X_2) = P(X_1) + P(X_2) - P(X_1)P(X_2) \tag{2.32}$$

- The probability of the union of K mutually exclusive events is

$$\begin{aligned} P(X_1 + X_2 + X_3 + \ldots. + X_K) &= P(X_1) \\ + P(X_2) + P(X_3) + \ldots + P(X_K) \end{aligned} \tag{2.33}$$

2.5 Probability-related Mathematical Definitions

There are various probability-related mathematical definitions used in performing reliability and quality analyses. Some of these are presented below [10–13]:

2.5.1 Definition of Probability

This is expressed by [11]

$$P(Y) = \lim_{m \to \infty} \left[\frac{M}{m} \right] \tag{2.34}$$

where

$P(Y)$ is the probability of occurrence of event Y.

M is the total number of times Y occurs in the m repeated experiments.

2.5.2 Cumulative Distribution Function

For a continuous random variable, this is expressed by

$$F(t) = \int_{-\infty}^{t} f(y)\,\mathrm{d}y \tag{2.35}$$

where

t is time (*i. e.*, a continuous random variable).

$F(t)$ is the cumulative distribution function.

$f(t)$ is the probability density function (in reliability work, it is known as the failure density function).

2.5.3 Probability Density Function

This is expressed by

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} = \frac{\mathrm{d}\left[\int_{-\infty}^{t} f(y)\mathrm{d}y \right]}{\mathrm{d}t} \tag{2.36}$$

2.5.4 Expected Value

The expected value, $E(t)$, of a continuous random variable is expressed by

$$E(t) = M = \int_{-\infty}^{\infty} t\, f(t)\, \mathrm{d}t \tag{2.37}$$

where
$E(t)$ is the expected value of the continuous random variable t.
$f(t)$ is the probability density function.
M is the mean value.

2.5.5 Variance

This is defined by

$$\theta^2(t) = E(t^2) - \left[E(t)\right]^2 \tag{2.38}$$

or

$$\theta^2(t) = \int_{0}^{\infty} t^2 f(t)\mathrm{d}t - M^2 \tag{2.39}$$

where
$\sigma^2(t)$ is the variance of random variable t.

2.6 Statistical Distributions

In mathematical reliability and quality analyses, various types of probability or statistical distributions are used. Some of these distributions are presented below [13, 14].

2.6.1 Binomial Distribution

The binominal distribution is named after Jakob Bernoulli (1654–1705) and is used in situations where one is concerned with the probabilities of outcome such as the total number of occurrences (*e. g.*, failures) in a sequence of, say m, trials [1]. However, it should be noted that each trial has two possible outcomes (*e. g.*, success and failure), but the probability of each trial remains constant.

The distribution probability density function is defined by

$$f(x) = \binom{m}{x} p^x\, q^{m-x},\ for\ x = 0, 1, 2, \ldots., m \tag{2.40}$$

where

$f(x)$ is the binomial distribution probability density function.

$$\binom{m}{x} = \frac{m!}{x!(m-x)!}$$

x is the number occurrences (*e. g.*, failures) in m trials.

p is the single trial probability of success.

$q = 1 - p$, is the single trial probability of failure.

The cumulative distribution function is given by

$$F(x) = \sum_{i=0}^{x} \frac{m!}{i!(m-i)!} p^i q^{m-i} \tag{2.41}$$

where

$F(x)$ is the cumulative distribution function or the probability of x or less failures in m trials.

The mean or the expected value of the distribution is [10]

$$E(x) = m\,p \tag{2.42}$$

2.6.2 Poisson Distribution

The Poisson distribution is named after Simeon Poisson (1781–1840), a French mathematician, and is used in situations where one is interested in the occurrence of a number of events that are of the same type. More specifically, this distribution is used when the number of possible events is large, but the occurrence probability over a specified time period is small. Waiting lines and the occurrence of defects are two examples of such a situation. The distribution probability density function is defined by

$$f(x) = \frac{\lambda^x \mathrm{e}^{-\lambda}}{x!}, \; for \; x = 0, 1, 2, ... \tag{2.43}$$

where

λ is the distribution parameter.

The cumulative Poisson distribution function is

$$F(x) = \sum_{i=0}^{x} \frac{\lambda^i \mathrm{e}^{-\lambda}}{i!} \tag{2.44}$$

The mean or the expected value of the distribution is [10]

$$E(x) = \lambda \tag{2.45}$$

2.6.3 Normal Distribution

Although normal distribution was discovered by De Moivre in 1733, time to time it is also referred to as Gaussian distribution after German mathematician, Carl Friedrich Gauss (1777–1855). Nonetheless, it is one of the most widely used continuous random variable distributions, and its probability density function is defined by

$$f(t)=\frac{1}{\sigma\sqrt{2\Pi}}\exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right], -\infty\langle t\langle+\infty \tag{2.46}$$

where

t is the time variable.

μ and σ are the distribution parameters (*i. e.*, mean and standard deviation, respectively).

By substituting Equation (2.46) into Equation (2.35) we get the following equation for the cumulative distribution function:

$$F(t)=\frac{1}{\sigma\sqrt{2\Pi}}\int_{-\infty}^{t}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]\mathrm{d}x \tag{2.47}$$

Using Equation (2.46) in Equation (2.37) yields the following expression for the distribution mean:

$$E(t)=\mu \tag{2.48}$$

2.6.4 Gamma Distribution

The Gamma Distribution is a two-parameter distribution, and in 1961 it was considered as a possible model in life test problems [15]. The distribution probability density function is defined by

$$f(t)=\frac{\lambda(\lambda t)^{K-1}}{\Gamma(K)}\exp(-\lambda t), \quad t\geq 0, K\rangle 0, \lambda\rangle 0 \tag{2.49}$$

where

t is time.

K is the shape parameter.

$\Gamma(K)$ is the gamma function.

$\lambda=\frac{1}{\theta}, \theta$ is the scale parameter.

Using Equation (2.49) in Equation (2.35) yields the following equation for the cumulative distribution function:

$$F(t) = 1 - \frac{\Gamma(K, \lambda t)}{\Gamma(K)} \tag{2.50}$$

where

$\Gamma(K, \lambda t)$ is the incomplete gamma function.

Substituting Equation (2.49) into Equation (2.37) we get the following equation for the distribution mean:

$$E(t) = \frac{K}{\lambda} \tag{2.51}$$

Three special case distributions of the gamma distribution are the exponential distribution, the chi-square distribution, and the special case Erlangian distribution [16].

2.6.5 Exponential Distribution

This is probably the most widely used statistical distribution in reliability studies because it is easy to handle in performing reliability analysis and many engineering items exhibit constant failure rates during their useful life [17]. Its probability density function is defined by

$$f(t) = \lambda \mathrm{e}^{-\lambda t}, \qquad \lambda \rangle 0, t \geq 0 \tag{2.52}$$

where

t is time.

λ is the distribution parameter. In reliability work, it is called constant failure rate.

Substituting Equation (2.52) into Equation (2.35) we get the following equation for the cumulative distribution function:

$$F(t) = 1 - \mathrm{e}^{-\lambda t} \tag{2.53}$$

Using Equation (2.53) in Equation (2.37) yields the following equation for the distribution mean:

$$E(t) = \frac{1}{\lambda} \tag{2.54}$$

2.6.6 Rayleigh Distribution

The Rayleigh distribution is named after John Rayleigh (1842–1919) and is often used in the theory of sound and in reliability studies. The distribution probability density function is defined by

$$f(t) = \left(\frac{2}{\theta^2}\right) t \, e^{-\left(\frac{t}{\theta}\right)^2}, \qquad \theta \rangle 0, \, t \geq 0 \tag{2.55}$$

where

t is time.

θ is the distribution parameter.

By substituting Equation (2.55) into Equation (2.35) we get the following equation for the cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^2} \tag{2.56}$$

Inserting Equation (2.55) into Equation (2.37) yields the following equation for the distribution mean:

$$E(t) = \theta \Gamma\left(\frac{3}{2}\right) \tag{2.57}$$

where

$\Gamma(.)$ is the gamma function, which is expressed by

$$\Gamma(y) = \int_0^\infty t^{y-1} \, e^{-t} \, dt, \qquad y \rangle 0 \tag{2.58}$$

2.6.7 Weibull Distribution

The Weibull distribution is named after W. Weibull, a Swedish mechanical engineering professor who developed it in the early 1950s [17]. It is often used in reliability studies, and its probability density function is defined by

$$f(t) = \frac{\beta t^{\beta-1}}{\theta^\beta} \, e^{-\left(\frac{t}{\theta}\right)^\beta}, \qquad \theta \rangle 0, \, \beta \rangle 0, \, t \geq 0 \tag{2.59}$$

where

t is time.

θ and β are the distribution scale and shape parameters, respectively.

Using Equation (2.59) in Equation (2.35) yields the following equation for the cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \tag{2.60}$$

By inserting Equation (2.59) into Equation (2.37) we get the following equation for the distribution mean:

$$E(t) = \theta \Gamma\left(1 + \frac{1}{\beta}\right) \tag{2.61}$$

It is to be noted that exponential and Rayleigh distributions are the special cases of this distribution for $\beta = 1$ and $\beta = 2$, respectively.

2.7 Problems

1. What is mean deviation?
2. Obtain the Laplace transform of the following function:

$$f(t) = \lambda e^{-\lambda t} \tag{2.62}$$

where
λ is a constant.
t is time.

3. Find roots of the following equation by using the quadratic formula:

$$x^2 + 15x + 50 = 0 \tag{2.63}$$

Approximate the real roots of the following equation by using the Newton method:

$$x^2 - 37 = 0 \tag{2.64}$$

4. Write down the five most important probability properties.
5. Prove that the total area under a continuous random variable probability density function curve is equal to unity.
6. Define the probability density function of a continuous random variable.
7. What are the special case distributions of the Weibull distribution?
8. Prove that the mean or the expected value of the gamma distribution is given by Equation (2.51).
9. Prove Equation (2.60).

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3

Introduction to Reliability and Quality

3.1 Introduction

Today the reliability of engineering systems has become an important factor during their planning, design, and operation. The factors that are responsible for this include high acquisition cost, increasing number of reliability-related lawsuits, complex and sophisticated systems, competition, public pressures, and the past well-publicized system failures. Needless to say, over the past 60 years, many new advances have been made in the field of reliability that help to produce reliable systems.

The importance of quality in business and industry has increased to a level greater than ever before. Factors such as growing demand from customers for better quality, the global economy, and the complexity and sophistication of products have played an instrumental role in increasing this importance. As per [1, 2], the cost of quality control accounts for roughly 7–10% of the total sales revenue of manufacturers. Today, the industrial sector is faced with many quality-related challenges. Some of these are the rising cost of quality, the Internet economy, an alarming rate of increase in customer quality-related requirements, and the need for improvements in methods and practices associated with quality-related activities. This chapter presents various introductory aspects of both reliability and quality.

3.2 Bathtub Hazard Rate Concept and Reliability Basic Formulas

The bathtub hazard rate concept is widely used to represent failure behavior of many engineering items. The term "bathtub" stems from the fact that the shape of the hazard rate curve resembles a bathtub (Figure 3.1.) As shown in the figure, the curve is divided into three distinct regions: burn-in, useful life, and wear-out. During the burn-in region the item hazard rate decreases with time. Some of the

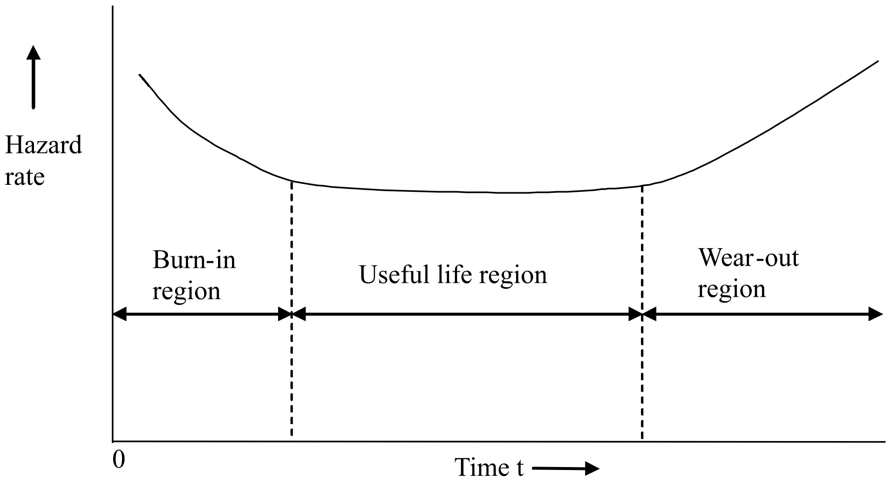

Figure 3.1. Bathtub hazard rate curve

reasons for the occurrence of failures during this region are poor quality control, poor manufacturing methods and procedures, poor debugging, poor workmanship and substandard materials, inadequate processes, and human error.

During the useful life region the item hazard rate remains constant with respect to time. Some of the main reasons for the occurrence of failures during this region are undetectable defects, higher random stress than expected, abuse, low safety factors, and human error.

During the wear-out region the item hazard rate increases with time. Some of the principal reasons for the occurrence of failures during this region are inadequate maintenance, wear due to aging, wear due to friction, short designed-in life of items, wrong overhaul practices, and corrosion and creep.

There are many basic formulas used in reliability work. Four widely used such formulas are as follows [3]:

$$f(t) = -\frac{\mathrm{d}R(t)}{\mathrm{d}t} \tag{3.1}$$

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{\mathrm{d}R(t)}{\mathrm{d}t} \tag{3.2}$$

$$R(t) = \mathrm{e}^{-\int_0^t \lambda(t)\,\mathrm{d}t} \tag{3.3}$$

and

$$MTTF = \int_0^\infty R(t)\,\mathrm{d}t \tag{3.4}$$

where
t is time.
$f(t)$ is the item failure (or probability) density function.
$R(t)$ is the item reliability at time t.
$\lambda(t)$ is the item hazard rate or time dependent failure rate.
MTTF is the item mean time to failure.

Example 3.1
Assume that the failure rate, λ, of an engineering system is 0.0004 failures per hour. Calculate the following:

- System reliability during a 100-hour mission.
- System mean time to failure.

By substituting the specified data values into Equation (3.3), we get

$$R(100) = e^{-\int_0^{100} (0.0004)\,dt}$$
$$= e^{-(0.0004)(100)}$$
$$= 0.9608$$

Similarly, using the given data in Equation (3.4) yields

$$MTTF = \int_0^{\infty} e^{-(0.0004)t}\,dt$$
$$= \frac{1}{0.0004}$$
$$= 2500 \text{ } hours$$

Thus, the system reliability and mean time to failure are 0.9608 and 2500 hours, respectively.

Example 3.2
Assume that the hazard rate of a system is defined by

$$\lambda(t) = \frac{\alpha t^{\alpha-1}}{\theta^{\alpha}} \tag{3.5}$$

where
α is the shape parameter.
θ is the scale parameter.
t is time.

Obtain an expression for the system reliability.

By inserting Equation (3.5) into Equation (3.3), we get

$$
\begin{aligned}
R(t) &= \mathrm{e}^{-\int_0^t \frac{\alpha t^{\alpha-1}}{\theta^\alpha}\mathrm{d}t} \\
&= \mathrm{e}^{-\left(\frac{t}{\theta}\right)^\alpha}
\end{aligned}
\tag{3.6}
$$

Thus, Equation (3.6) is the expression for the system reliability.

3.3 Reliability Evaluation of Standard Configurations

As engineering systems can form various types of configurations in performing reliability analysis, this section presents reliability analysis of some standard networks or configurations.

3.3.1 Series Configuration

In this case, all units must work normally for the system success. A block diagram representing an m-unit series system is shown in Figure 3.2. Each block in the diagram represents a unit.

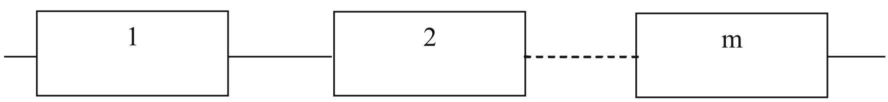

Figure 3.2. Block diagram of an m-unit series system

For independently failing units, the reliability of the series system shown in Figure 3.2 is

$$
R_s = \prod_{i=1}^{m} R_i \tag{3.7}
$$

where

R_s is the series system reliability.

m is the total number of units in series.

R_i is the unit i reliability; for $i = 1, 2, \ldots, m$.

For constant failure rate of unit i (*i. e.*, $\lambda_i(t) = \lambda_i$) from Equation (3.3), we get

$$
\begin{aligned}
R_i(t) &= \mathrm{e}^{-\int_0^t \lambda_i \,\mathrm{d}t} \\
&= \mathrm{e}^{-\lambda_i t}
\end{aligned}
\tag{3.8}
$$

where
$R_i(t)$ is the reliability of unit i at time t.
$\lambda_i(t)$ is the unit i hazard rate.
λ_i is the unit i constant failure rate.

By substituting Equation (3.8) into Equation (3.7), we get

$$\begin{aligned} R_s(t) &= \prod_{i=1}^{m} e^{-\lambda_i t} \\ &= e^{-\sum_{i=1}^{m} \lambda_i t} \end{aligned} \tag{3.9}$$

where
$R_s(t)$ is the series system reliability at time t.

Using Equation (3.9) in Equation (3.4) yields

$$\begin{aligned} MTTF_s &= \int_0^\infty e^{-\sum_{i=1}^{m} \lambda_i t}\, dt \\ &= \frac{1}{\sum_{i=1}^{m} \lambda_i} \end{aligned} \tag{3.10}$$

where
$MTTF_s$ is the series system mean time to failure.

Example 3.3
Assume that an aircraft has four independent and identical engines and all must work normally for the aircraft to fly successfully. Calculate the reliability of the aircraft flying successfully, if each engine's reliability is 0.99.

By substituting the given data values into Equation (3.7), we get

$$\begin{aligned} R_s &= (0.99)^4 \\ &= 0.9606 \end{aligned}$$

Thus, the reliability of the aircraft flying successfully is 0.9606.

3.3.2 Parallel Configuration

In this case, the system is composed of m active units, and at least one such unit must operate normally for the system success. The system block diagram is shown in Figure 3.3. Each block in the diagram represents a unit.

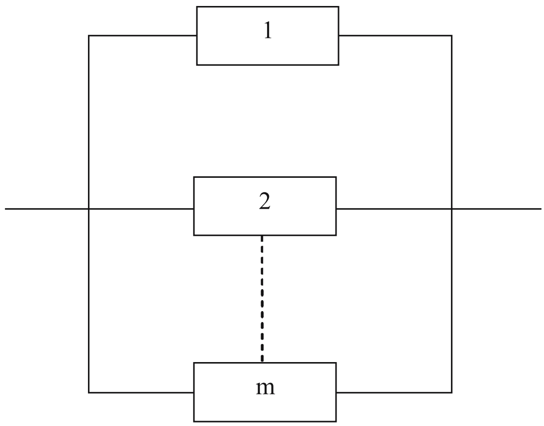

Figure 3.3. A parallel system with *m* units

For independently failing units, the parallel system reliability is given by

$$R_{ps} = 1 - \prod_{i=1}^{m} (1 - R_i) \tag{3.11}$$

where
R_{ps} is the parallel system reliability.
m is the total number of units in parallel.
R_i is the unit i reliability; for $i = 1, 2, \ldots, m$.

For constant failure rate, λ_i, of unit i by substituting Equation (3.8) into Equation (3.11), we get

$$R_{ps}(t) = 1 - \prod_{i=1}^{m} \left(1 - e^{-\lambda_i t}\right) \tag{3.12}$$

where
$R_{ps}(t)$ is the parallel system reliability at time t.

For identical units, inserting Equation (3.12) into Equation (3.4) yields.

$$\begin{aligned} MTTF_{ps} &= \int_0^{\infty} \left[1 - \left(1 - e^{-\lambda t}\right)^m\right] dt \\ &= \frac{1}{\lambda} \sum_{i=1}^{m} \frac{1}{i} \end{aligned} \tag{3.13}$$

where
λ is the unit constant failure rate.
$MTTF_{ps}$ is the parallel system mean time to failure.

Example 3.4
A system is composed of two independent and identical active units and at least one unit must operate normally for the system success. Each unit's constant failure rate is 0.0008 failures per hour. Calculate the system mean time to failure and reliability for a 150-hour mission.

Substituting the given data values into Equation (3.13) yields

$$MTTF_{\text{ps}} = \frac{1}{(0.0008)}\left(1+\frac{1}{2}\right) = 1875 \text{ hours}$$

Using the specified data values in Equation (3.12) yields

$$\begin{aligned} R_{\text{ps}}(150) &= \left[1-\left\{1-\mathrm{e}^{-(0.0008)(150)}\right\}^2\right] \\ &= 0.9872 \end{aligned}$$

Thus, the system mean time to failure and reliability are 1875 hours and 0.9872, respectively.

3.3.3 *K*-out-of-*m* Configuration

In this case, the system is composed of m active units and at least K such units must work normally for the system success. The series and parallel configurations are special cases of this configuration for $K = m$ and $K = 1$, respectively.

For independent and identical units, the K-out-of-m configuration reliability is given by

$$R_{K/m} = \sum_{i=K}^{m} \binom{m}{i} R^i (1-R)^{m-i} \tag{3.14}$$

where

$$\binom{m}{i} = \frac{m!}{(m-i)!i!}$$

$R_{K/m}$ is the K-out-of-m configuration reliability.

R is the unit reliability.

For constant failure rates of units, using Equation (3.8) and (3.14), we get

$$R_{K/m}(t) = \sum_{i=K}^{m} \binom{m}{i} \mathrm{e}^{-i\lambda t} \left(1-\mathrm{e}^{-\lambda t}\right)^{m-i} \tag{3.15}$$

where

$R_{K/m}(t)$ is the K-out-of-m configuration reliability at time t.

λ is the unit constant failure rate.

Substituting Equation (3.15) into Equation (3.4) yields

$$\begin{aligned} MTTF_{K/m} &= \int_0^\infty \left[\sum_{i=K}^{m} \binom{m}{i} e^{-i\lambda t} \left(1 - e^{-\lambda t}\right)^{m-i} \right] dt \\ &= \frac{1}{\lambda} \sum_{i=K}^{m} \frac{1}{i} \end{aligned} \tag{3.16}$$

Example 3.5

Assume that a system is composed of three active, independent, and identical units, and at least two units must work normally for the system success. Calculate the system mean time to failure, if each unit's failure rate is 0.0004 failures per hour.

By substituting the specified data values into Equation (3.16), we get

$$\begin{aligned} MTTF_{K/m} &= \frac{1}{(0.0004)} \sum_{i=2}^{3} \frac{1}{i} \\ &= 2083.3 \text{ hours} \end{aligned}$$

Thus, the system mean time to failure is 2083.3 hours.

3.3.4 Standby System

In the case of the standby system, only one unit operates and m units are kept in their standby mode. As soon as the operating unit fails, the switching mechanism detects the failure and turns on one of the standbys. The system contains a total of $(m+1)$ units and it fails when all the m standby units fail. For perfect switching mechanism and standby units, independent and identical units, and units' constant failure rates, the standby system reliability is given by [4]

$$R_{std}(t) = \sum_{i=0}^{m} \frac{(\lambda t)^i e^{-\lambda t}}{i!} \tag{3.17}$$

where

$R_{std}(t)$ is the standby system reliability at time t.

m is the total number of standby units.

λ is the unit constant failure rate.

Using Equation (3.17) in Equation (3.4) yields

$$\begin{aligned} MTTF_{std} &= \int_0^\infty \left[\sum_{i=0}^{m} \frac{(\lambda t)^i e^{-\lambda t}}{i!} \right] dt \\ &= \frac{m+1}{\lambda} \end{aligned} \tag{3.18}$$

where

$MTTF_{\mathrm{std}}$ is the standby system mean time to failure.

Example 3.6

A system has two independent and identical units. One of these units is operating, and the other is on standby. Calculate the system mean time to failure and reliability for a 200-hour mission by using Equations (3.17) and (3.18), if the unit failure rate is 0.0001 failures per hour.

By substituting the given data values into Equation (3.17), we get

$$R_{\mathrm{std}}(200) = \sum_{i=0}^{1} \frac{\left[(0.0001)(200)\right]^i \mathrm{e}^{-(0.0001)(200)}}{i!}$$
$$= 0.9998$$

Similarly, substituting the given data values into Equation (3.18) yields

$$MTTF_{\mathrm{std}} = \frac{(1+1)}{(0.0001)}$$
$$= 20,000 \text{ hours}$$

Thus, the system reliability and mean time to failure are 0.9998 and 20,000 hours, respectively.

3.3.5 Bridge Configuration

In some engineering systems, particularly communications networks, units may form a bridge configuration (Figure 3.4). Each block in the figure represents a unit, and numerals in blocks denote unit number. For independent units, the reliability of the Figure 3.4 bridge configuration is [5]

$$\begin{aligned} R_{\mathrm{b}} = {} & 2R_1 R_2 R_3 R_4 R_5 + R_2 R_3 R_4 + R_1 R_3 R_5 + R_2 R_5 + R_1 R_4 \\ & - R_2 R_3 R_4 R_5 - R_1 R_2 R_3 R_4 - R_1 R_2 R_3 R_5 \\ & - R_1 R_3 R_4 R_5 - R_1 R_2 R_4 R_5 \end{aligned} \tag{3.19}$$

where

R_i is the unit i reliability; for $i = 1, 2, 3, 4, 5$.

R_{b} is the bridge configuration or system reliability.

For identical units, Equation (3.19) reduces to

$$R_{\mathrm{b}} = 2R^5 - 5R^4 + 2R^3 + 2R^2 \tag{3.20}$$

where

R is the unit reliability.

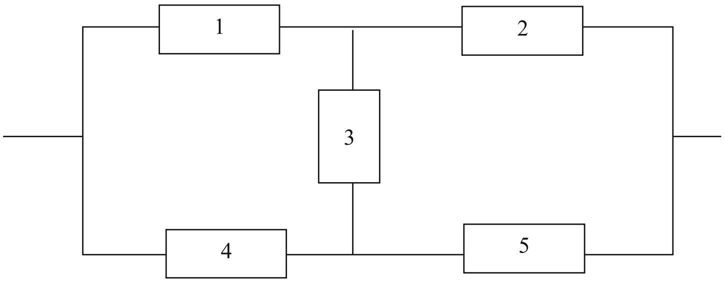

Figure 3.4. A five-unit bridge network

For constant failure rates of units, using Equations (3.8) and (3.20), we get

$$R_b(t) = 2e^{-5\lambda t} - 5e^{-4\lambda t} + 2e^{-3\lambda t} + 2e^{-2\lambda t} \tag{3.21}$$

Inserting Equation (3.21) into Equation (3.4) yields

$$\begin{aligned} MTTF_b &= \int_0^\infty \left[2e^{-5\lambda t} - 5e^{-4\lambda t} + 2e^{-3\lambda t} + 2e^{-2\lambda t}\right] dt \\ &= \frac{49}{60\lambda} \end{aligned} \tag{3.22}$$

where

$MTTF_b$ is the bridge system mean time to failure.

λ is the unit constant failure rate.

Example 3.7

Assume that five independent and identical units form a bridge configuration and each unit's reliability is 0.9. Calculate the bridge configuration reliability.

By substituting the given data value into Equation (3.20), we get

$$\begin{aligned} R_b &= 2(0.9)^5 - 5(0.9)^4 + 2(0.9)^3 + 2(0.9)^2 \\ &= 0.9785 \end{aligned}$$

Thus, the bridge configuration reliability is 0.9785.

3.4 Reliability Analysis Methods

There are many methods that can be used to perform reliability analysis of engineering systems [4, 5]. This section presents three of these commonly used methods.

3.4.1 Failure Modes and Effect Analysis (FMEA)

Failure modes and effect analysis (FMAE) is a widely used method in the industrial sector to perform reliability analysis of engineering systems. It may simply be described as an approach used to conduct analysis of each potential failure mode in the system under consideration to examine the effects of such failure modes on that system [6]. Furthermore, the approach demands listing of all potential failure modes of all parts on paper and their effects on the listed subsystems and the system under consideration. When this approach (*i. e.*, FMEA) is extended to classify each potential failure effect according to its severity, then it is called failure mode, effects, and criticality analysis (FMECA) .

The history of FMEA goes back to the early 1950s, when the U.S. Navy's Bureau of Aeronautics developed a requirement called "Failure Analysis" [7]. In the 1970s, the U.S. Department of Defense developed a military standards entitled "Procedures for Performing a Failure Mode, Effects, and Criticality Analysis" [8]. FMEA is described in detail in [5] and a comprehensive list of publications on FMEA/FMECA is available in [9].

The six main steps followed in performing FMEA are shown in Figure 3.5 [10]. Some of the main characteristics of the FMEA method are as follows:

- It is a routine upward approach that starts from the detailed level.
- By determining all possible failure effects of each part, the entire system is screened completely.
- It identifies weak spots in a system design and highlights areas where further or detailed analyses are required.
- It improves communication among individuals involved in design.

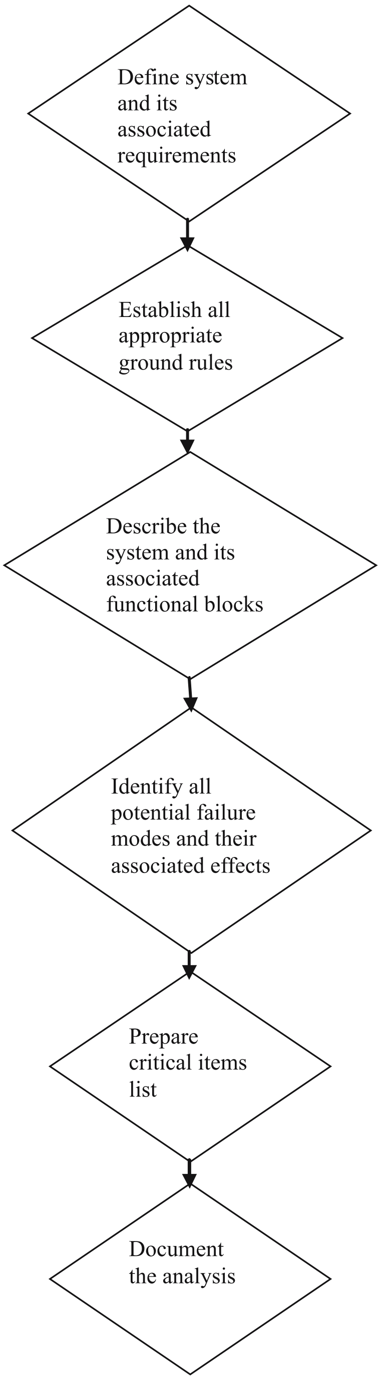

Figure 3.5. Main steps for conducting FMEA

3.4.2 Markov Method

The Markov method is a powerful reliability analysis tool that is named after Russian mathematician Andrei Andreyevich Markov (1856–1922). It can handle both repairable and non-repairable systems. In analyzing large and complex systems, a problem may occur in solving a set of differential equations generated by this method. Nonetheless, the Markov method is based on the following assumptions [4]:

- The transitional probability from one state to the next state in the finite time interval Δt is given by $\lambda\Delta t$, where λ is transition rate (*e. g.*, failure or repair rate) associated with Markov states.
- The probability of more than one transition occurrence in finite time interval Δt from one state to the next is negligible (*e. g.*, $(\lambda\Delta t)(\lambda\Delta t) \rightarrow 0$).
- All occurrences are independent of each other.

The application of this method is demonstrated through the following example.

Example 3.8
Assume that a system can either be in an operating or a failed state and its failure rate, λ_S, is constant. The system state space diagram is shown in Figure 3.6. The numerals in boxes denote the system state. Obtain expressions for system state probabilities (*i. e.*, system operating or failed) by using the Markov method.

Using the Markov method, we write down the following two equations for the diagram in Figure 3.6:

$$P_0(t+\Delta t) = P_0(t)(1-\lambda_s\Delta t) \quad (3.23)$$

$$P_1(t+\Delta t) = P_1(t) + P_0(t)\lambda_s\Delta t \quad (3.24)$$

where

$P_i(t+\Delta t)$ is the probability that the system is in state i at time $(t+\Delta t)$; for $i=0$ (operating normally), $i=1$ (failed).

$P_i(t)$ is the probability that the system is in state i at time t; for $i=0$ (operating normally), $i=1$ (failed).

λ_S is the system constant failure rate.

$\lambda_s\,\Delta t$ is the probability of system failure in finite time interval Δt.

$(1-\lambda_s\,\Delta t)$ is the probability of no failure in time interval Δt when the system is in state 0.

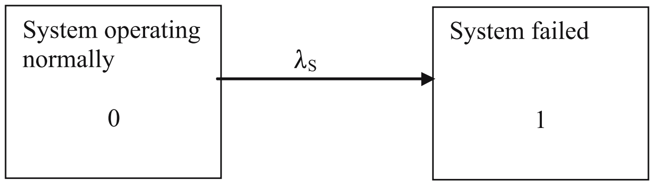

Figure 3.6. System state space diagram

In the limiting case, Equations (3.23) and (3.24) become

$$\lim_{\Delta t \to 0} \frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} = \frac{\mathrm{d}P_0(t)}{\mathrm{d}t} = -\lambda_s P_0(t) \tag{3.25}$$

and

$$\lim_{\Delta t \to 0} \frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = \frac{\mathrm{d}P_1(t)}{\mathrm{d}t} = -\lambda_s P_0(t) \tag{3.26}$$

At time $t=0$, $P_0(0)=1$, and $P_1(0)=0$.

Solving Equations (3.25) and (3.26) by using Laplace transforms, we get

$$P_0(s) = \frac{1}{s+\lambda_s} \tag{3.27}$$

and

$$P_1(s) = \frac{1}{s(s+\lambda_s)} \tag{3.28}$$

where

s is the Laplace transform variable.

$P_i(s)$ is the Laplace transform of the probability that the system is in state i; for $i=0$ (operating normally), $i=1$ (failed).

Taking the inverse Laplace transforms of Equations (3.27) and (3.28), we get

$$P_0(t) = \mathrm{e}^{-\lambda_s t} \tag{3.29}$$

$$P_1(t) = 1 - \mathrm{e}^{-\lambda_s t} \tag{3.30}$$

Example 3.9

Assume that the constant failure rate of a system is 0.002 failures per hour. Calculate the system probability of failure during a 150-hour mission.

By substituting the given data values into Equation (3.30), we get

$$\begin{aligned} P_1(150) &= 1 - \mathrm{e}^{-(0.002)(150)} \\ &= 0.2592 \end{aligned}$$

It means, the system probability of failure is 0.2592.

3.4.3 Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is one of the most widely used methods in the industrial sector to evaluate reliability of engineering systems. The method was developed in the early 1960s at Bell Telephone Laboratories to evaluate the reliability and safety of the minuteman Launch Control System [11]. The method is described in detail in [11].

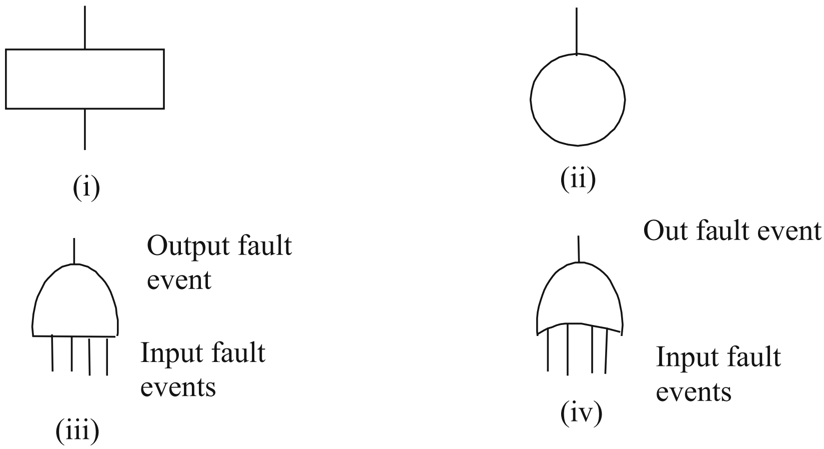

Figure 3.7. Commonly used fault tree symbols: (**i**) rectangle, (**ii**) circle; (**iii**) AND gate; (**iv**) OR gate.

Although many symbols are used in performing FTA, the four commonly used symbols are shown in Figure 3.7. Each of these symbols is described below.

- **AND gate.** This denotes that an output fault event occurs only if all of the input fault events occur.
- **OR gate.** This denotes that an output fault event occurs if one or more of the input fault events occur.
- **Rectangle.** This denotes a fault event that results from the logical combination of fault events through the input of a logic gate.
- **Circle.** This represents a basic fault event or the failure of an elementary component. The event's probability of occurrence, failure, and repair rates are normally obtained from field failure data.

FTA begins by identifying an undesirable event, called a top event, associated with a system. Fault events which could cause the top event are generated and connected by logic gates such as OR and AND. The fault tree construction proceeds by generation of fault events in a successive manner until the events need not be developed any further.

Example 3.10
Assume that a windowless room contains one switch and four light bulbs and the switch can only fail to close. Develop a fault tree for the top event "Dark room" (*i. e.*, no light in the room), if the interruption of electrical power coming into the room can only be caused either by fuse failure or power failure.

By using the Figure 3.7 symbols, a fault tree for the example shown in Figure 3.8 is developed. Each fault event in the figure is labeled as X_0, X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, and X_9.

Probability Evaluation of Fault Trees

For independent fault events, the probability of occurrence of top events of fault trees can easily be evaluated by applying the basic rules of probability to the output fault events of logic gates. For example, in the case of Figure 3.8 fault tree, we have [5]

$$P(X_2) = P(X_6)P(X_7)P(X_8)P(X_9) \tag{3.31}$$

$$P(X_1) = P(X_4) + P(X_5) - P(X_4)P(X_5) \tag{3.32}$$

$$P(X_0) = 1 - [1 - P(X_1)][1 - P(X_2)][1 - P(X_3)] \tag{3.33}$$

where

$P(X_i)$ is the probability of occurrence of fault event X_i; for $i = 1, 2, 3, \ldots, 9$.

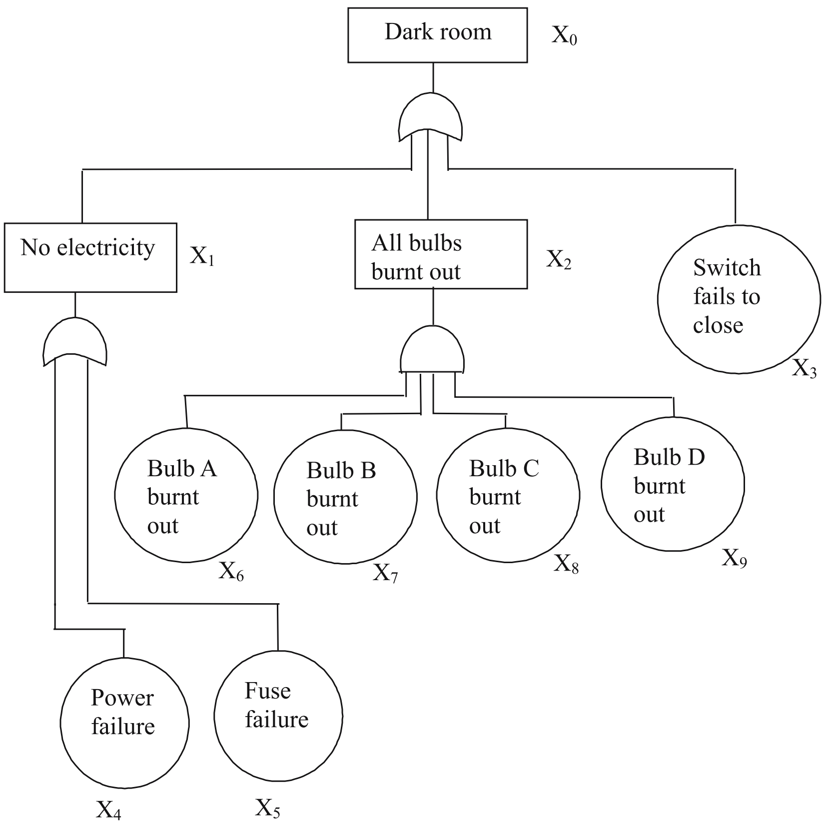

Figure 3.8. A fault tree for Example 3.10

Example 3.11
In Figure 3.8, assume that the probability of occurrence of fault events X_3, X_4, X_5, X_6, X_7, X_8, and X_9 are 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, and 0.07, respectively. Calculate the probability of occurrence of the top event "Dark room" by using Equations (3.31)–(3.33).

Thus, by substituting the given data values into Equations (3.31)–(3.33), we get

$$P(X_2) = (0.04)(0.05)(0.06)(0.07) = 0.0000084$$

$$P(X_1) = 0.02 + 0.03 - (0.02)(0.03) = 0.0494$$

and

$$\begin{aligned} P(X_0) &= 1 - (1 - 0.0494)(1 - 0.0000084)(1 - 0.01) \\ &= 0.9411 \end{aligned}$$

Thus, the probability of occurrence of the top event "Dark room" is 0.9411.

3.5 Quality Goals, Quality Assurance System Elements, and Total Quality Management

Normally, organizations set various types of quality goals. These goals may be divided under the following two distinct categories [12]:

- **Goals for breakthrough.** These are concerned with improving the existing quality of products or services. Three important reasons for establishing such goals are shown in Figure 3.9.
- **Goals for control.** These goals are concerned with maintaining the quality of products or services to the current level for a specified period of time. Some of the important reasons for establishing such goals are as follows:
  - Acceptable competitiveness at current levels of quality
  - Improvements are uneconomical
  - Insignificant number of customers or other complaints about the quality of products or services

The main goal of a quality assurance system is to maintain the specified level of quality, and its important elements are as follows [13]:

- Evaluate, plan, and control product quality.
- Consider the quality and reliability needs during the product design and development.
- Keep track of suppliers' quality assurance programs.
- Develop personnel.
- Determine and control product quality in use environment.
- Conduct special quality studies.

- Provide quality-related information to management.
- Assure accuracy of quality measuring equipment.
- Manage the total quality assurance system.

The term total quality management (TQM) was coined by Nancy Warren, a behavioral scientist [14]. Some of the important elements of TQM are management commitment and leadership, team work, customer service, quality cost, training, statistical approaches, and supplier participation [15]. For the success of the TQM process, goals such as listed below must be satisfied in an effective manner [16].

- Clear understanding of all internal and external customer requirements by all company personnel
- Meeting of all control guidelines, per customer requirements, by all involved systems and processes
- Use of a system to continuously improve processes that better satisfy current and future needs of customers
- Establishment of appropriate incentives and rewards for employees when process control and customer satisfaction results are attained successfully

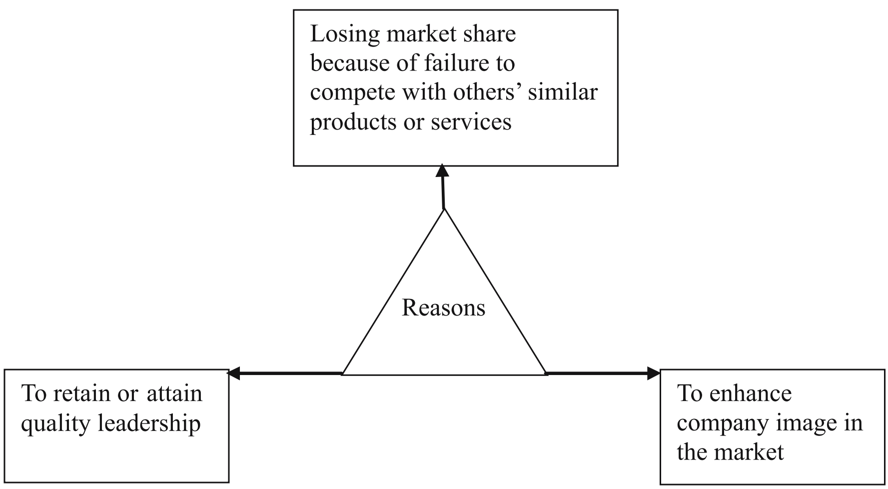

Figure 3.9. Reasons for establishing quality goals for breakthrough

3.6 Quality Analysis Methods

Over the years, many methods and techniques have been developed to conduct various types of quality-related analysis. This section presents some of these methods.

3.6.1 Quality Control Charts

A control chart may simply be described as a graphical method used for determining whether a process is in a "state of statistical control" or out of control [17]. The history of control charts may be traced back to a memorandum written by Walter Shewhart on May 16, 1924, in which he presented the idea of a control chart [18]. Nonetheless, the construction of control charts is based on statistical principles and distributions and a chart is basically composed of three elements: average or standard value of the characteristic under consideration, upper control limit (UCL), and lower control limit (LCL).

There are many types of quality control charts: the P-charts, the C-charts, the R-charts, the $\overline{X}$-charts, etc. [19, 20]. One of these is described below.

The P-charts

P-charts are also known as the control charts for attributes, in which the data population is grouped under two classifications (*e. g.*, pass or fail, good or bad). More specifically, components with defects and components without defects. Thus, attributes control charts use pass-fail information for charting and a p-chart basically is a single chart that tracks the proportion of nonconforming items in each sample taken from representative population.

Upper and lower control limits of p-charts are established by using the binomial distribution; thus are expressed by

$$UCL_{\mathrm{p}} = m_{\mathrm{b}} + 3\sigma_{\mathrm{b}} \tag{3.34}$$

and

$$LCL_{\mathrm{p}} = m_{\mathrm{b}} - 3\sigma_{\mathrm{b}} \tag{3.35}$$

where

m_{b} is the mean of the binomial distribution.
σ_{b} is the standard deviation of the binomial distribution.
UCL_{p} is the upper control limit of the p-chart.
LCL_{p} is the lower control limit of the p-chart.

The mean, m_b, is given by

$$m_b = \frac{K}{n\theta} \tag{3.36}$$

where

n is the sample size.
K is the total number of defectives/failures in classification.
θ is the number of samples.

Similarly, the standard deviation, σ_b, is given by

$$\sigma_b = \left[m_b \left(1 - m_b\right) / n \right]^{1/2} \tag{3.37}$$

Example 3.12
A total of eight samples were taken from the production line of a firm manufacturing mechanical components for use in a nuclear power plant. Each sample contained 60 components. The inspection process revealed that samples 1, 2, 3, 4, 5, 6, 7, and 8 contain 5,2, 12, 4, 8, 10, 15, and 6 defective components, respectively. Construct the p-chart for mechanical components.

Using the given data values in Equation (3.36) yields

$$\begin{aligned} m_b &= \frac{\left(5+2+12+4+8+10+15+6\right)}{\left(60\right)\left(8\right)} \\ &= 0.1292 \end{aligned}$$

By substituting the above calculated value and the other given data value into Equation (3.37), we get

$$\begin{aligned} \sigma_b &= \left[0.1292\left(1-0.1292\right)/60\right]^{1/2} \\ &= 0.0433 \end{aligned}$$

The fraction of defectives, p, in sample 1 is given by

$$p = \frac{5}{60} = 0.083$$

Similarly, the fractions of defective components in samples 2, 3, 4, 5, 6, 7, and 8 are 0.033, 0.2, 0.066, 0.133, 0.166, 0.25, and 0.1, respectively.

Substituting the above-calculated values for m_b and σ_b into Equations (3.34) and (3.35) yield

$$\begin{aligned} UCL_p &= 0.1292 + 3\left(0.0433\right) \\ &= 0.2591 \end{aligned}$$

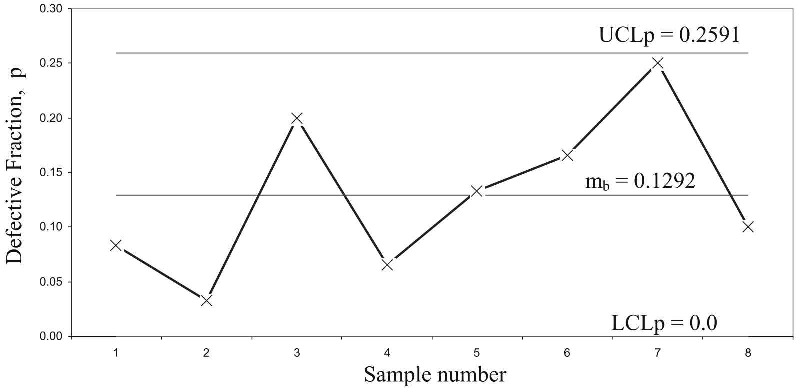

Figure 3.10. p-chart for mechanical components

and

$$\begin{aligned} LCL_{\mathrm{p}} &= 0.1292 - 3(0.0433) \\ &= -0.0007 \\ &\cong 0.0 \end{aligned}$$

A p-chart for the above calculated values is shown in Figure 3.10. The crosses in the figure represent the fraction of defective components in each sample.

As all these crosses are within the upper and lower control limits, it means that there is no abnormality in the ongoing production process.

3.6.2 Cause-and-Effect Diagram

A Cause-and-effect diagram is basically a picture made up of lines and symbols designed to represent a meaningful relationship between an effect and its associated causes [21]. Other names used for this diagram or method are Ishikawa diagram (*i. e.*, after its originator, Kaoru Ishikawa) and "fishbone" diagram because of its resemblance to the skeleton of a fish. Nonetheless, the cause-and-effect diagram is a useful tool to determine the root causes of a given problem and generate relevant ideas.

From the quality perspective, the effect or problem could be a quality characteristic that needs improvement and the causes work methods, equipment, materials, people, environment, etc. Usually, the five steps shown in Figure 3.11 are followed to develop a cause-and-effect diagram.

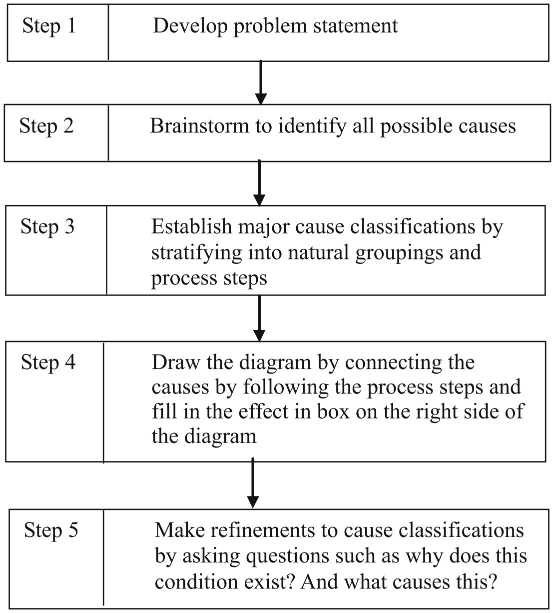

Figure 3.11. Steps for developing a cause-and-effect diagram

3.6.3 Quality Function Deployment (QFD)

The quality function deployment approach was developed in the 1960s in Japan and is used for optimizing the process of developing and manufacturing new products as per customer requirements [22–23]. Thus, QFD may simply be described as a formal process employed for translating customer needs into a set of technical requirements. The approach makes use of a set of matrices for relating customer requirements to counterpart characteristics that are expressed as process control requirements and technical specifications.

A QFD matrix is often referred to as the "House of Quality" because of its resemblance to the structure of a house. The main steps used to build the house of quality are as follows [22–24]:

- Highlight customer needs or requirements.
- Identify lay process/product characteristics that will meet customer requirements.
- Establish all necessary relationships between the customer needs and the counterpart characteristics.
- Analyse competing products.
- Establish all competing products' counterpart characteristics and develop appropriate goals.
- Identify counterpart characteristics to be utilized in the remaining process.

Additional information on this method is available in [24].

3.6.4 Pareto Diagram

The Pareto diagram is named after Wilfredo Pareto (1848–1923), an Italian economist and sociologist, and it may simply be described as a bar chart that ranks related problems/measures in decreasing occurrence frequency. In the quality area, the Pareto diagram or principle was first introduced by J.M. Juran, who believed that there are always a few types of defects in the hardware manufacture that loom large in the frequency of occurrence and severity [25, 26]. In other words, about 20% of the problems cause around 80% of the scrap. Usually, the steps followed to construct a Pareto diagram are shown in Figure 3.12 [21].

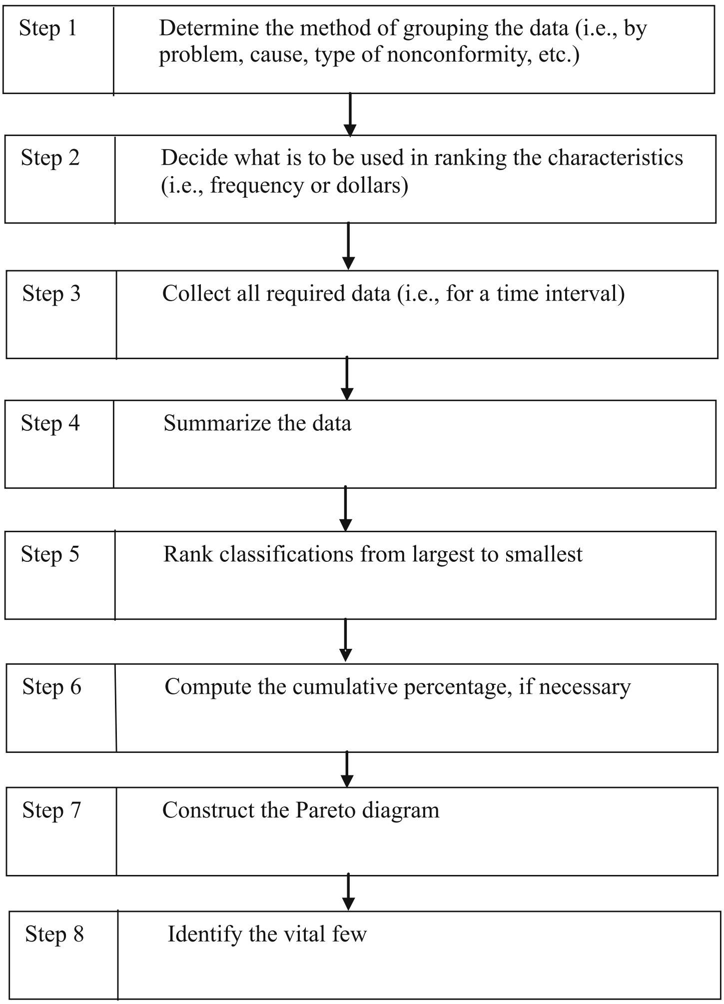

Figure 3.12. Steps for constructing the Pareto diagram

3.7 Quality Costs and Indices

Quality costs are a significant element of the sales income in many manufacturing organizations. They may be classified under five distinct categories as shown in Figure 3.13 [27–28]. These are administrative costs, appraisal and detection costs, prevention costs, internal failure costs, and external failure costs.

The administrative costs are concerned with administrative-related activities such as performing data analysis, reviewing contracts, preparing budgets, preparing proposals, and forecasting. The appraisal and detection costs are associated with appraisal and detection activities, and three main elements of these costs are cost of auditing, cost of inspection (*i. e.*, receiving, shipping, source, in-process, etc.), and cost of testing. The prevention costs are concerned with activities performed to prevent the production of defective products, parts, and materials. Some of these activities are reviewing designs, training personnel, evaluating suppliers, calibrating and certifying inspection and test devices and instruments, implementing and maintaining sampling plans, and coordinating plans and programs.

The internal failure costs occur prior to the delivery of the product to the buyer. They are associated with items such as in-house components and materials failures, redesign, scrap, failure analysis, and re-inspection and retest. The external failure costs occur after the delivery of the product to the buyers and are associated with items such as warranty charges, replacement of defective parts, liability, investigation of customer complaints, failure analysis, and repair.

Often, manufacturing organizations use various types of quality cost indices to monitor their performance. The values of such indices are plotted periodically and their trends are monitored. Three of these indices are as follows [29, 30].

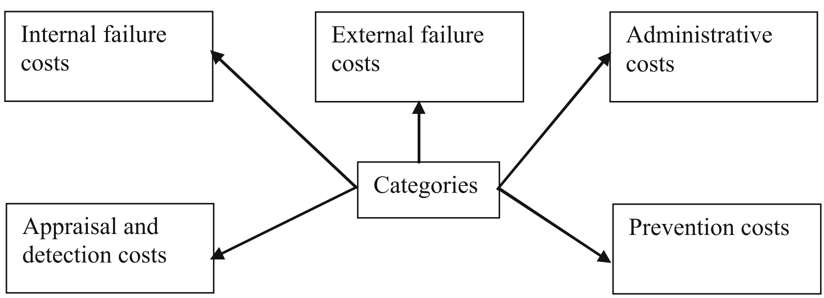

Figure 3.13. Quality cost categories

3.7.1 Index I

Index I is expressed by

$$\theta_1 = \left[\frac{QC_t(100)}{V}\right] + 100 \tag{3.38}$$

where
θ_1 is the quality cost index.
V is the value of output
QC_t is the total quality cost.

The common interpretations of three θ_1 values in the industrial sector are presented in Table 3.1 [30].

Table 3.1. Interpretations of three θ_1 values

θ_1 value	Interpretation
100	There is no defective output.
105	It can readily be achieved in a real-life environment.
110–130	Quality costs are ignored.

3.7.2 Index II

Index II is expressed by

$$\theta_2 = \frac{QC_t(100)}{LC_d} \tag{3.39}$$

where
θ_2 is the quality cost index expressed as a percentage.
LC_d is the direct labor cost.

Although this index does not provide management with much useful information for problem diagnosis and decision making, it is often used to eliminate the effects of inflation [30].

3.7.3 Index III

Index III is expressed by [30]

$$\theta_3 = \frac{QC_t(100)}{S_t} \tag{3.40}$$

where
θ_3 is the quality cost index expressed as a percentage.
S_t is the total sales.

3.8 Problems

1. Discuss the bathtub hazard rate curve.
2. Obtain a hazard rate expression for a series system by using Equations (3.2) and (3.9). Comment on the end result.
3. Prove the resulting Equation (3.13).
4. Assume that a system is composed of four active, independent, and identical units and at least two units must work normally for the system success. Calculate the system mean time to failure, if each unit's failure rate is 0.0005 failures per hour.
5. Compare standby system with the *k*-out-of-*m* configuration.
6. Compare FMEA with FTA.
7. Discuss at least eight important elements of a quality assurance system.
8. Describe the following two quality analysis methods:
   - Pareto diagram
   - Cause-and-effect diagram
9. What are the five categories of quality costs?
10. Who coined the term total quality management?

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4

Robot Reliability

4.1 Introduction

Robots are increasingly being used to perform various types of tasks including spot welding, materials handling, routing, and arc welding. A robot may simply be described as a mechanism guided by automatic controls. The word "robot" is derived from the Czechoslovakian language, in which it means "worker" [1]. In 1954, George Devol designed and applied for a patent for a programmable device that could be considered the first industrial robot. Nonetheless, in 1959, the Planet Corporation manufactured the first commercial robot [2]. Currently, the worldwide industrial robot population is estimated to be around one million [3].

As robots use mechanical, electrical, electronics, hydraulic, and pneumatic components, their reliability-related problems are quite challenging because of many different sources of failures. Although there is no clear-cut definitive point in the beginning of robot reliability and maintainability field, a publication by J.F. Engelberger, in 1974, could be regarded as its starting point [4]. In 1987, an article presented a comprehensive list of publications on robot reliability [5], and in 1991, a book entitled "Robot Reliability and Safety" covered the topic of robot reliability in a significant depth [6]. A comprehensive list of publications on robot reliability up to 2002 is available in Ref. [7], and some of the important recent publications on robot reliability and associated areas are listed at the end of this book. This chapter presents various important aspects of robot reliability.

4.2 Terms and Definitions

There are many robot reliability-related terms and definitions. Some of the important ones are as follows [1, 6, 8–12]:

- **Robot reliability.** This is the probability that a robot will perform its specified mission according to stated conditions for a given time period.
- **Robot availability.** This is the probability that a robot is available for service at the moment of need.
- **Graceful failure.** The performance of the manipulator degraded at a slow pace, in response to overloads, instead of failing catastrophically.
- **Erratic robot.** A robot moved appreciably off its specified path.
- **Robot mean time to failure.** This is the average time that a robot will operate before failure.
- **Robot mean time to repair.** This is the average time that a robot is expected to be out of operation after failure.
- **Fail-safe.** This is the failure of a robot/robot part without endangering people or damage to equipment or plant facilities.
- **Fault in teach pendant.** This is the part failure in the teach pendant of a robot.
- **Robot out of synchronization.** This is when the position of the robot's arm is not in line with the robot's memory of where it is supposed to be.
- **Error recovery.** This is the capability of intelligent robotic systems to reveal errors and, through programming, to initiate appropriate correction actions to overcome the impending problem and complete the specified process.
- **Robot repair.** This is to restore robots and their associated parts or systems to an operational condition after experiencing failure, damage, or wear.

4.3 Robot Failure Causes and Classifications

There are many causes of robot failures. Some of the most common ones are as follows [6]:

- Oil pressure valve problems
- Printed circuit board problems
- Human errors
- Encoder-related problems
- Servo valve problems
- Noise

As per Refs [13, 14], robot problems or troubles followed the following order:

- Control system problems
- Incompatibility of jigs and other tools
- Robot body-related problems
- Programming and operation errors
- Welding gun troubles and difficulties with other tooling parts

- Deterioration, precision deficiency
- Runaway
- Miscellaneous

There are basically four types of failures (Figure 4.1), that affect robot reliability and its safe operation [15, 16]. These are random component failures, systematic hardware faults, human errors, and software failures.

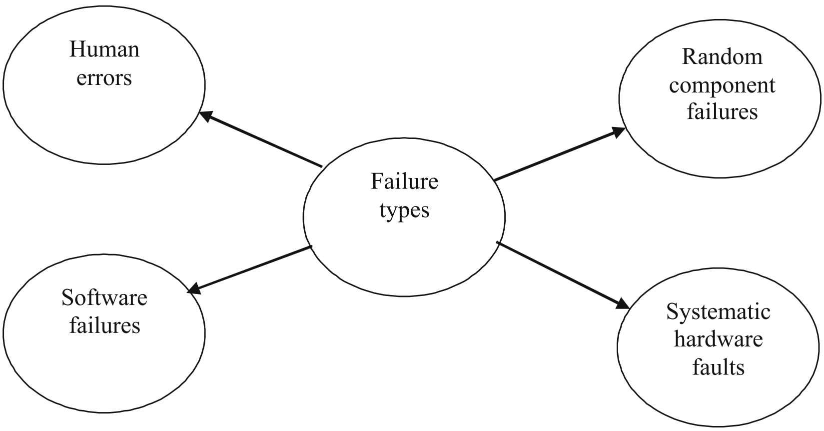

Figure 4.1. Types of failures that affect robot reliability

Failures that occur during the useful life of a robot are called random component failures because they occur unpredictably. Some of the reasons for the occurrence of such failures are undetectable defects, low safety factors, unexplainable causes, and unavoidable failures. Systematic hardware faults are those failures that occur because of the existence of unrevealed mechanisms in the robot design. Reasons such as peculiar wrist orientations and unusual joint-to-straight-line mode transition can lead the robot not to perform a specific task or to execute certain portions of a program.

Human errors are caused by people who design, manufacture, test, operate, and maintain robots. Various studies reveal that the human error is a significant element of total equipment failures [6, 17]. Some of the important reasons for the occurrence of human errors are poor equipment design, poorly trained operation and maintenance personnel, task complexity, inadequate lighting in the work areas, improper tools used by maintenance personnel, and poorly written maintenance and operating procedures [17]. Software failures are an important element in the malfunctioning of robots, and they occur in robots due to reasons such as embedded software or the controlling software and application software. Some of the methods that can be useful to reduce the occurrence of software faults in robots are failure mode and effects analysis (FMEA), fault tree analysis (FTA), and testing.

4.4 Robot Reliability Measures

There are various types of reliability-related measures associated with robots. Some of these are presented below.

4.4.1 Mean Time to Robot Failure

Mean time to robot failure can be obtained by using either of the following three formulas:

$$MTRF = \int_0^\infty R_{rb}(t)\mathrm{d}t \tag{4.1}$$

$$MTRF = \lim_{s \to 0} R_{rb}(s) \tag{4.2}$$

$$MTRF = \frac{RPH - DDTRF}{TNRF} \tag{4.3}$$

where

MTRF	is the mean time to robot failure.
$R_{rb}(t)$	is the robot reliability at time t.
s	is the Laplace transform variable.
$R_{rb}(s)$	is the Laplace transform of the robot reliability function.
TNRF	is the total number of robot failures.
RPH	is the robot production hours.
DDTRF	is the downtime due to robot failure expressed in hours.

Example 4.1
The annual total robot production hours and total downtime due to robot failures in an organization are 60,000 hours and 500 hours, respectively. During the period a total of 20 robot failures has occurred. Calculate the mean time to robot failure.

By substituting the given data values into Equation (4.3), we get

$$MTRF = \frac{60,000 - 500}{20} = 2,975 \text{ hours}$$

Thus, the mean time to robot failure is 2,975 hours.

Example 4.2
Assume that the failure rate, λ_{rb}, of a robot is 0.0005 failures per hour and its reliability is expressed by

$$\begin{aligned} R_{rb}(t) &= \mathrm{e}^{-\lambda_{rb} t} \\ &= \mathrm{e}^{-(0.0005)t} \end{aligned} \tag{4.4}$$

where
$R_{rb}(t)$ is the robot reliability at time t.

Calculate mean time to robot failure by using Equations (4.1) and (4.2). Comment on the end result.

By substituting Equation (4.4) into Equation (4.1), we obtain

$$MTRF = \int_0^\infty e^{-(0.0005)t}\,dt$$
$$= \frac{1}{0.0005} = 2{,}000 \text{ hours}$$

By taking the Laplace transform of Equation (4.4), we get

$$R_{rb}(s) = \frac{1}{(s+0.0005)} \tag{4.5}$$

where
$R_{rb}(s)$ is the Laplace transform of the reliability function.

Using Equation (4.5) in Equation (4.2) yields

$$MTRF = \lim_{s\to 0} \frac{1}{(s+0.0005)}$$
$$= \frac{1}{0.0005}$$
$$= 2{,}000 \text{ hours}$$

In both cases, the end result (*i. e.*, MTRF = 2,000 hours) is exactly the same.

4.4.2 Mean Time to Robot-related Problems

Mean time to robot-related problems is the average productive robot time prior to the occurrence of a robot-related problem and is defined by

$$MTRP = \frac{RPH - DDTRP}{TNRP} \tag{4.5}$$

where
$MTRP$ is the mean time to robot-related problems.
$DDTRP$ is the downtime due to robot-related problems expressed in hours.
$TNRP$ is the total number of robot-related problems.

Example 4.3
Assume that the annual total robot production hours and total downtime due to robot-related problems, at an industrial installation, are 80,000 hours and

1,000 hours, respectively. During the period a total of 30 robot-related problems has occurred. Calculate the mean time to robot-related problems.

By inserting the specified data values into Equation (4.5) yields

$$\begin{aligned} MTRP &= \frac{80{,}000 - 1{,}000}{30} \\ &= 2633.3 \text{ hours} \end{aligned}$$

Thus, the mean time to robot-related problems is 2633.3 hours.

4.4.3 Robot Reliability

This is defined by [6]

$$R_{\mathrm{rb}}(t) = \exp\left[-\int_0^t \lambda_{rb}(t)\,\mathrm{d}t\right] \tag{4.6}$$

where

$\lambda_{\mathrm{rb}}(t)$ is the robot hazard rate or time-dependent failure rate.

Equation (4.6) is the general expression for obtaining robot reliability. More specifically, it can be used to obtain a robot's reliability when robot times to failure follow any statistical distribution (*e.g.*, Weibull, normal, gamma, or exponential).

Example 4.4

A robot's hazard rate is defined by the following function:

$$\lambda_{\mathrm{rb}}(t) \equiv \frac{\theta t^{\theta-1}}{\alpha\alpha^{\theta-1}} \tag{4.7}$$

where

$\lambda_{\mathrm{rb}}(t)$ is the robot's hazard rate when its times to failure follow Weibull distribution.

t is time.

θ is the shape parameter.

α is the scale parameter.

Obtain an expression for the robot reliability and then use the expression to calculate reliability when $t = 500$ hours, $\theta = 1$, and $\alpha = 1{,}000$ hours.

Using Equation (4.7) in Equation (4.6) yields

$$
\begin{aligned}
R_{\mathrm{rb}}(t) &= \exp\left[-\int_0^t \frac{\theta t^{\theta-1}}{\alpha\alpha^{\theta-1}}\,\mathrm{d}t\right] \\
&= \mathrm{e}^{-\left(\frac{t}{\alpha}\right)^{\theta}}
\end{aligned}
\tag{4.8}
$$

By substituting the given data values into Equation (4.8), we get

$$
\begin{aligned}
R_{\mathrm{rb}}(500) &= \mathrm{e}^{-\left(\frac{500}{1000}\right)} \\
&= 0.6065
\end{aligned}
$$

Thus, the robot reliability for the specified mission period of 500 hours is 0.6065.

4.4.4 Robot Hazard Rate

This is defined by [6]:

$$
\lambda_{\mathrm{rb}}(t) = -\frac{1}{R_{\mathrm{rb}}(t)}\cdot\frac{\mathrm{d}R_{\mathrm{rb}}(t)}{\mathrm{d}t}
\tag{4.9}
$$

where

$\lambda_{\mathrm{rb}}(t)$ is the robot hazard rate.

$R_{\mathrm{rb}}(t)$ is the robot reliability at time t.

Equation (4.9) can be used to obtain robot hazard rate when robot times to failure follow any time-continuous distribution (*e. g.*, exponential, Rayleigh, Weibull, etc.).

Example 4.5

By using Equations (4.8) and (4.9), prove that the robot hazard rate is given by Equation (4.7).

Using Equation (4.8) in Equation (4.9) yields

$$
\begin{aligned}
\lambda_{\mathrm{rb}}(t) &= -\frac{1}{\mathrm{e}^{-\left(\frac{t}{\theta}\right)^{\theta}}}\left[-\frac{\theta}{\alpha}\left(\frac{t}{\alpha}\right)^{\theta-1}\right]\mathrm{e}^{-\left(\frac{t}{\alpha}\right)^{\theta}} \\
&= \frac{\theta}{\alpha}\frac{t^{\theta-1}}{\alpha^{\theta-1}}
\end{aligned}
\tag{4.10}
$$

Both Equations (4.7) and (4.10) are identical. It proves that Equation (4.7) is an expression for robot hazard rate.

4.5 Robot Reliability Analysis Methods

There are many methods used to perform various types of reliability analysis in the field of reliability engineering. Some of them can be used quite effectively to conduct robot reliability-related studies. Four of these methods are shown in Figure 4.2. These are parts count method, failure modes and effect analysis (FMEA) , fault tree analysis, and Markov method.

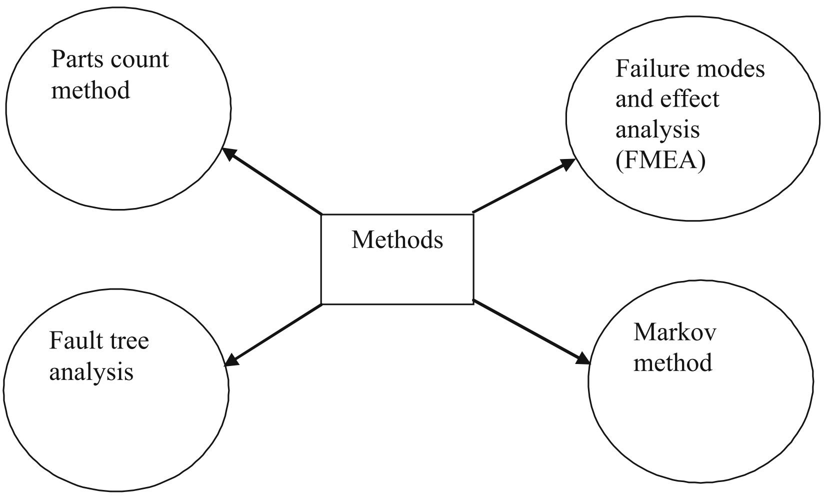

Figure 4.2. Methods for performing robot reliability-related studies

The parts count method is used during bid proposal and early design phases for estimating equipment failure rate. The method requires information on items such as equipment/product use environment, generic part types and quantities, and part quality levels [18].

Additional information on parts count method is available in Refs. [18, 19].

Failure modes and effect analysis (FMEA) is an effective tool to conduct analysis of each failure mode in the system/equipment to determine the effects of such failure modes on the total system/equipment [20]. This method was developed by the United States Department of Defense in the early 1950s and comprises of the following six steps [19–22]:

- Define system/equipment and its associated requirements.
- Develop appropriate ground rules.
- Describe the system/equipment and all its related functional blocks.
- Highlight all possible failure modes and their effects.
- Develop critical items list.
- Document the analysis.

FMEA is described in detail in Chapter 3 and in [19, 23].

Fault tree analysis is a widely used method to evaluate reliability of engineering systems during their design and development phase. A fault tree may be described as a logical representation of the relationship of basic or primary events that result in a specified undesirable event called the “top event”. This method was developed in the early 1960s at Bell Telephone Laboratories and is described in detail in Chapter 3 and in [19, 24].

The Markov method can be used in more cases than any other reliability evaluation method and is used to model systems with constant failure and repair rates. The method is described in detail in Chapter 3 and in [19, 25]. Its application to robot-related problems is demonstrated by two of the mathematical models presented in Section 4.6.

4.6 Models for Performing Robot Reliability and Maintenance Studies

There are many mathematical models that can be used to perform various types of robot reliability and maintenance studies. Four of these models are presented below.

4.6.1 Model I

This model represents a robot system that can fail either due to a human error or other failures (*e. g.*, hardware and software). The failed robot system is repaired to its operating state. The robot system state diagram is shown in Figure 4.3. The numerals in the rectangle, circle, and diamond denote system states. The following assumptions are associated with this robot system model [6]:

- Human error and other failures are statistically independent.
- Human error and other failure rates are constant.
- The failed robot system repair rates are constant.
- The repaired robot system is as good as new.

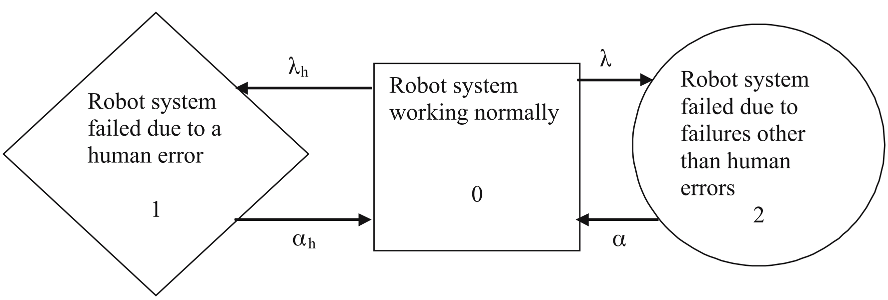

Figure 4.3. Robot system state space diagram

The following symbols are associated with the diagram in Figure 4.2 and its associated equations:

P_i (t) is the probability that the robot system is in state i at time t; for $i=0$ (working normally), $i=1$ (failed due to a human error), $i=2$ (failed due to failures other than human errors).
λ_h is the robot system human error rate.
α_h is the robot system repair rate from failed state 1.
λ is the robot system non-human error failure rate.
α is the robot system repair rate from failed state 2.

Using the Markov method, we write down the following equations for the Figure 4.2 diagram [6]:

$$\frac{dP_0(t)}{dt} + (\lambda + \lambda_h) P_0(t) = \alpha_h P_1(t) + \alpha P_2(t) \tag{4.11}$$

$$\frac{dP_1(t)}{dt} + \alpha_h P_1(t) = \lambda_h P_0(t) \tag{4.12}$$

$$\frac{dP_2(t)}{dt} + \alpha P_2(t) = \lambda P_0(t) \tag{4.13}$$

At time $t=0$, $P_0(0)=1$, $P_1(0)=0$, and $P_2(0)=0$.

Solving Equations (4.11)–(4.13) using Laplace transforms, we get

$$P_0(t) = \frac{\alpha\alpha_h}{m_1 m_2} + \left[\frac{(m_1+\alpha)(m_1+\alpha_h)}{m_1(m_1-m_2)}\right] e^{m_1 t} - \left[\frac{(m_2+\alpha)(m_2+\alpha_h)}{m_2(m_1-m_2)}\right] e^{m_2 t} \tag{4.14}$$

where

$$m_1, m_2 = \frac{-b \pm \left[b^2 - 4(\alpha\alpha_h + \lambda_h\alpha + \lambda\alpha_h)\right]^{1/2}}{2} \tag{4.15}$$

$$b = \lambda + \lambda_h + \alpha + \alpha_h \tag{4.16}$$

$$m_1 m_2 = \alpha\alpha_h + \lambda_h\alpha + \lambda\alpha_h \tag{4.17}$$

$$m_1 + m_2 = (\lambda + \lambda_h + \alpha + \alpha_h) \tag{4.18}$$

$$P_1(t) = \frac{\alpha\lambda_h}{m_1 m_2} + \left[\frac{\lambda_h m_1 + \lambda_h\alpha}{m_1(m_1-m_2)}\right] e^{m_1 t} - \left[\frac{(\alpha+m_2)\lambda_h}{m_2(m_1-m_2)}\right] e^{m_2 t} \tag{4.19}$$

$$P_2(t) = \frac{\lambda\alpha_h}{m_1 m_2} + \left[\frac{\lambda m_1 + \lambda\alpha_h}{m_1(m_1-m_2)}\right] e^{m_1 t} - \left[\frac{(\alpha_h+m_2)\lambda}{m_2(m_1-m_2)}\right] e^{m_2 t} \tag{4.20}$$

The robot system availability, $AV_r(t)$, is given by

$$AV_{rb}(t) = P_0(t) \tag{4.21}$$

As time t becomes large in Equations (4.19)–(4.21), we get the following steady state probability expressions:

$$AV_{rb} = \frac{\alpha\alpha_h}{m_1 m_2} \tag{4.22}$$

$$P_1 = \frac{\alpha\lambda_h}{m_1 m_2} \tag{4.23}$$

$$P_2 = \frac{\lambda\alpha_h}{m_1 m_2} \tag{4.24}$$

where
AV_{rb} is the robot system steady state availability.
P_1 is the steady state probability of the robot system being in state 1.
P_2 is the steady state probability of the robot system being in state 2.

For $\alpha = \alpha_h = 0$, from Equations (4.14), (4.19), and (4.20) we get

$$P_0(t) = e^{-(\lambda+\lambda_h)t} \tag{4.25}$$

$$P_1(t) = \frac{\lambda_h}{(\lambda+\lambda_h)}\left[1 - e^{-(\lambda+\lambda_h)t}\right] \tag{4.26}$$

$$P_2(t) = \frac{\lambda}{(\lambda+\lambda_h)}\left[1 - e^{-(\lambda+\lambda_h)t}\right] \tag{4.27}$$

The robot system reliability at time t from Equation (4.25) is

$$R_{rb}(t) = e^{-(\lambda+\lambda_h)t} \tag{4.28}$$

where
$R_{rb}(t)$ is the robot system reliability at time t.

By substituting Equation (4.28) into Equation (4.1), we get the following expression for mean time to robot failure:

$$\begin{aligned} MTRF &= \int_0^{\infty} e^{-(\lambda+\lambda_h)t}\,dt \\ &= \frac{1}{\lambda+\lambda_h} \end{aligned} \tag{4.29}$$

Using Equation (4.28) in Equation (4.9) yields the following expression for the robot system hazard rate:

$$\lambda_{rb}(t) = -\frac{1}{e^{-(\lambda+\lambda_h)t}} \cdot \frac{d\left[e^{-(\lambda+\lambda_h)t}\right]}{dt} \tag{4.30}$$
$$= \lambda + \lambda_h$$

The right-hand side of Equation (4.30) is independent of time, which means that the robot system failure rate is constant.

Example 4.6

A robot system can fail either due to human error or other failures, and its constant human error and other failure rates are 0.0004 errors per hour and 0.0008 failures per hour, respectively. The robot system constant repair rate from both the failure modes is 0.009 repairs per hour. Calculate the robot system steady state availability by using Equations (4.23) and (4.24).

By substituting the specified data values into Equations (4.23) and (4.24), we get

$$P_1 = \frac{(0.009)(0.0004)}{(0.009)(0.009)+(0.0004)(0.009)+(0.0008)(0.009)}$$
$$= 0.0392$$

and

$$P_2 = \frac{(0.0008)(0.009)}{(0.009)(0.009)+(0.0004)(0.009)+(0.0008)(0.009)}$$
$$= 0.0784$$

Thus, the robot system steady state unavailability, UAV_{rb}, is

$$UAV_{rb} = P_1 + P_2 = 0.0392 + 0.0784$$
$$= 0.1176$$

The robot system steady state availability, AV_{rb}, by using the above-calculated value is

$$AV_{rb} = 1 - UAV_{rb}$$
$$= 1 - 0.1176$$
$$= 0.8824$$

4.6.2 Model II

This model is concerned with determining the economic life of a robot, more specifically, the time limit beyond which it is not economical to carry out repairs. Thus, the economic life, T_e, of the robot is expressed as [26–28]:

$$T_e = \left[\frac{2(C_{ir} - SV_r)}{C_{rin}} \right]^{1/2} \tag{4.31}$$

where
C_{rin} is the annual increase in robot repair cost.
SV_r is the robot scrap value.
C_{ir} is the robot initial cost (installed).

Example 4.7
Assume that a robot costs \$90,000 (installed) and its estimated scrap value is \$2,000. The estimated annual increase in repair cost is \$500. Calculate the time limit beyond which the robot repairs will not be beneficial.

Inserting the given data values into Equation (4.31) yields

$$T_e = \left[\frac{2(90,000 - 2,000)}{500} \right]^{1/2}$$
$$= 18.76 \text{ years}$$

Thus, the time limit beyond which the robot repairs will not be economical or beneficial is 18.76 years.

4.6.3 Model III

This model can be used to calculate the optimum number of inspections per robot facility per unit time [28]. This information is useful to decision makers because inspections are often disruptive; however, such inspections usually reduce the robot downtime because they lead to fewer breakdowns. In this model, the total robot downtime is minimized to get the optimum number of inspections.

The total robot downtime, *TRDT*, per unit time is defined as [29]

$$TRDT = nT_{dp} + \frac{kT_{db}}{n} \tag{4.32}$$

where
n is the number of inspections per robot facility per unit time.
T_{dp} is the downtime per inspection for a robot facility.
T_{db} is the downtime per breakdown for a robot facility.
k is a constant for a specific robot facility.

By differentiating Equation (4.32) with respect to n and then equating it to zero, we get

$$n^* = \left[\frac{kT_{\mathrm{db}}}{T_{\mathrm{dp}}}\right]^{1/2} \tag{4.33}$$

where

n^* is the optimum number of inspections per robot facility per unit time.

By substituting Equation (4.33) into Equation (4.32), we get

$$TRDT^* = 2\left[T_{\mathrm{dp}} \cdot kT_{\mathrm{db}}\right]^{1/2} \tag{4.34}$$

where

$TRDT^*$ is the minimum total robot downtime.

Example 4.8

Assume that for a certain robot facility, the following data are specified:

- $T_{\mathrm{dp}} = 0.04$ months
- $T_{\mathrm{db}} = 0.12$ months
- $k = 3$

Compute the optimum number of robot inspections per month and the minimum total robot downtime.

By substituting the above given values into Equations (4.33) and (4.34), we get

$$n^* = \left[\frac{3(0.12)}{0.04}\right]^{1/2} = 3 \text{ inspections per month}$$

and

$$\begin{aligned} TRDT^* &= 2\left[(0.04)(3)(0.12)\right]^{1/2} \\ &= 0.24 \text{ months} \end{aligned}$$

4.6.4 Model IV

This model represents a robot system composed of a robot and a safety unit. In the industrial sector, the inclusion of safety units or systems with robots is often practiced because of robot accidents involving humans. In this model, it is assumed that after the failure of the safety unit, the robot may fail safely or with an incident. The failed safety unit is repaired. The robot system state space diagram is shown in Figure 4.4. The numerals in boxes and circles denote system states.

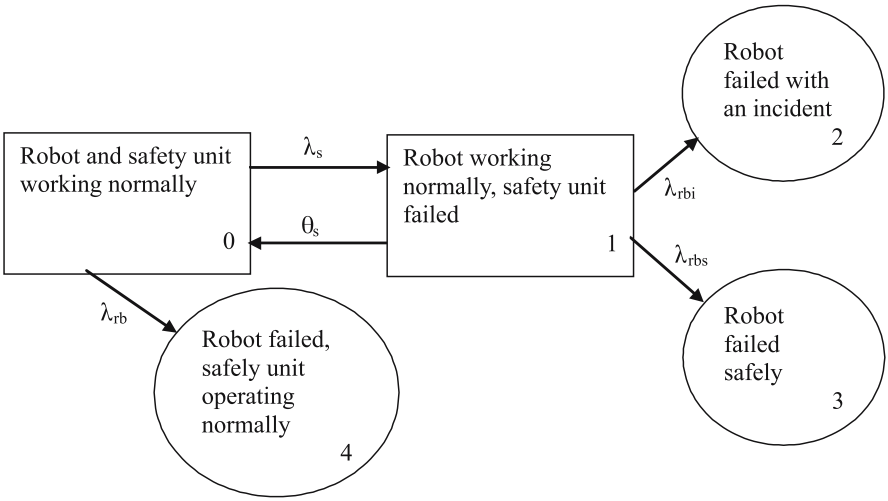

Figure 4.4. Robot system state space diagram

The following assumptions are associated with this model:

- All failures are statistically independent.
- All failure and repair rates are constant.
- The robot system fails when the robot fails.
- The repaired safety unit is as good as new.

The following symbols are associated with the diagram in Figure 4.4 and its associated equations:

$P_i(t)$ is the probability that the robot system is in state i at time t; for $i=0$ (robot and safety unit working normally), $i=1$ (robot working normally, safety unit failed), $i=2$ (robot failed with an incident), $i=3$ (robot failed safely), $i=4$ (robot failed, safety unit operating normally).
λ_{rb} is the robot failure rate.
λ_{s} is the safety unit failure rate.
λ_{rbi} is the rate of the robot failing with an incident.
λ_{rbs} is the rate of the robot failing safely.
θ_{s} is the safety unit repair rate.

Using the Markov method, we write down the following equations for the diagram in Figure 4.3 [30]:

$$\frac{dP_0(t)}{dt} + (\lambda_{rb} + \lambda_s) P_0(t) = \theta_s P_1(t) \tag{4.35}$$

$$\frac{dP_1(t)}{dt} + (\lambda_{rbi} + \lambda_{rbs} + \theta_s) P_1(t) = \lambda_s P_0(t) \tag{4.36}$$

$$\frac{dP_2(t)}{dt} = \lambda_{rbi} P_1(t) \tag{4.37}$$

$$\frac{dP_3(t)}{dt} = \lambda_{rbs} P_1(t) \tag{4.38}$$

$$\frac{dP_4(t)}{dt} = \lambda_{rb} P_0(t) \tag{4.39}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, $P_3(0) = 0$, and $P_4(0) = 0$.

Solving Equations (4.35)–(4.39) using Laplace transforms, we get

$$P_0(t) = e^{-At} + \lambda_s \theta_s \left[\frac{e^{-At}}{(c_1 + A)(c_2 + A)} + \frac{e^{c_1 t}}{(c_1 + A)(c_2 - c_2)} + \frac{e^{c_2 t}}{(c_2 + A)(c_2 - c_1)} \right] \tag{4.40}$$

where

$$A = \lambda_s + \lambda_{rb} \tag{4.41}$$

$$c_1, c_2 = \frac{-B \pm \left(B^2 - 4F\right)^{1/2}}{2} \tag{4.42}$$

$$B = A + \theta_s + \lambda_{rbi} + \lambda_{rbs} \tag{4.43}$$

$$F = \lambda_{rbi}\lambda_s + \lambda_{rbs}\lambda_s + \lambda_{rbi}\lambda_{rb} + \lambda_{rbs}\lambda_{rb} + \theta_s\lambda_{rb} \tag{4.44}$$

$$P_1(t) = \lambda_s\left[\left(e^{c_1 t} - e^{c_2 t}\right) / \left(c_1 - c_2\right)\right] \tag{4.45}$$

$$P_2(t) = \frac{\lambda_{rbi}\lambda_s}{c_1 c_2}\left[1 + \left(c_1 e^{c_2 t} - c_2 e^{c_1 t}\right) / \left(c_2 - c_1\right)\right] \tag{4.46}$$

$$P_3(t) = \frac{\lambda_{rbs}\lambda_s}{c_1 c_2}\left[1 + \left(c_1 e^{c_2 t} - c_2 e^{c_1 t}\right) / \left(c_2 - c_1\right)\right] \tag{4.47}$$

$$P_4(t) = \frac{\lambda_{rb}}{A}\left(1 - e^{-At}\right) + \lambda_s\lambda_{rb}\theta_s \left[\frac{1}{c_1 c_2 A} - \frac{e^{-At}}{A(c_1 + A)(c_2 + A)} + \frac{e^{c_1 t}}{c_1 (c_1 + A)(c_1 - c_2)} + \frac{e^{c_2 t}}{c_2 (c_2 + A)(c_2 - c_1)} \right] \tag{4.48}$$

The robot system reliability (*i. e.*, when both robot and safety unit work normally) with safety unit repair facility is given by

$$R_{rbr}(t) = P_0(t) \tag{4.49}$$

By substituting Equation (4.49) into Equation (4.1), we get the following expression for robot system mean time to failure:

$$MTTF_{rbr} = \frac{1}{A}\left[1 + \frac{\lambda_s \theta_s}{F}\right] \tag{4.50}$$

where

$MTTF_{rbr}$ is the robot system mean time to failure (*i. e.*, when both robot and safety unit are working) with safety unit repair facility.

Example 4.9

Assume that a robot system is composed of a robot and a safety unit. The operating robot with failed safety unit can either fail with an incident or safely and the failed safety unit is repaired.

Calculate the robot system mean time to failure by using Equation (4.50) for the following given data values:

- $\lambda_{rb} = 0.0005$ failures per hour
- $\lambda_s = 0.0003$ failures per hour
- $\lambda_{rbi} = 0.0002$ failures per hour
- $\lambda_{rbs} = 0.0003$ failures per hour
- $\theta_s = 0.008$ repairs per hour

Using the above data values in Equation (4.50) yields

$$MTTF = \frac{1}{A}\left[1 + \frac{(0.0003)(0.008)}{F}\right]$$

where

$A = 0.0003 + 0.0005 = 0.0008$

$$\begin{aligned} F &= (0.0002)(0.0003) + (0.0003)^2 + (0.0002)(0.0005) \\ &\quad + (0.0003)(0.0005) + (0.008)(0.0005) \\ &= 0.0000044 \end{aligned}$$

$$\begin{aligned} MTTF &= \frac{1}{(0.0008)}\left[1 + \frac{(0.0003)(0.008)}{(0.0000044)}\right] \\ &= 1931.8 \text{ hours} \end{aligned}$$

Thus, the robot system mean time to failure is 1931.8 hours.

4.7 Problems

1. Write an essay on historical developments in robot reliability.
2. Define the following terms:
   - Robot reliability
   - Graceful failure
   - Fail-safe
3. List at least six common causes of robot failures.
4. Write down three formulas that can be used to calculate mean time to robot failure.
5. Assume that the reliability of a robot is defined by the following equation:

$$R_{rb}(t) = e^{-0.002t} \tag{4.51}$$

   where
   $R_{rb}(t)$ is the robot reliability at time t.
6. Prove Equation (4.7) by using Equation (4.8).
7. Discuss the parts count method.
8. Discuss at least three methods that can be used to perform robot reliability analysis.
9. Prove Equations (4.22)–(4.25).
10. A robot costs \$100,000 (installed) and its estimated scrap value is \$4,000. The estimated annual increase in repair cost is \$600. Calculate the time limit beyond which the robot repairs will not be beneficial.

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5

Medical Equipment Reliability

5.1 Introduction

The history of the earliest use of medical devices may be traced back to the ancient Egyptians and Etruscans using various types of dental devices [1]. Today medical devices and equipment are widely used throughout the world. In fact, in 1988 the world medical equipment production was estimated to be around $36 billion [1], and in 1997, the world market for medical devices was valued at around $120 billion [2].

The beginning of the medical equipment or device reliability field may be traced back to the latter part of the 1960s, when a number of publications on the subject appeared [3–7]. These publications covered topics such as “Instrument induced errors in the electrocardiogram”, “Reliability of ECG instrumentation”, “Safety and reliability in medical electronics”, and “The effect of medical test instrument reliability on patient risks” [3–6]. In 1980, an article presented a comprehensive list of publications on medical equipment reliability [8], and in 1983 a text on reliability engineering devoted one entire chapter to medical/equipment reliability [9]. In 2000, a book entitled *Medical Device Reliability and Associated Areas* provided a comprehensive list of publications on the subject [10]. More recent publications on medical device/equipment reliability are listed at the end of this book. This chapter presents various important aspects of medical equipment reliability.

5.2 Medical Equipment Reliability-related Facts and Figures

Some of the facts and figures directly or indirectly related to medical equipment/device reliability are as follows:

- In 1997, there were a total of 10,420 registered medical device manufacturers in the United States [11].
- Due to faulty medical instrumentation around 1,200 deaths per year occur in the United States [12, 13].
- In 1969, the United States Department of Health, Education, and Welfare special committee reported that over a 10 year period, around 10,000 injuries were associated with medical devices/equipment and 731 resulted in deaths [14, 15].
- A study reported that over 50% of all technical medical equipment problems were due to operator errors [16].
- A study reported that around 100,000 Americans die each year due to human errors, and their financial impact on the United States economy was estimated to be between $17 billion and $29 billion [17].
- The Emergency Care Research Institute (ECRI) tested a sample of 15,000 products used in hospitals and found that around 4% to 6% of these products were sufficiently dangerous to warrant immediate correction [16].
- In 1990, a study performed by the US Food and Drug Administration (FDA) revealed that around 44% of the quality-related problems that resulted in the voluntary recall of medical devices for the period October 1983 to September 1989 were the result of deficiencies/errors that could have been prevented through effective design controls [18].

5.3 Medical Devices and Classification of Medical Devices/Equipment

Today, there are over 5,000 different types of medical devices being used in a modern hospital. They range from a simple tongue depressor to a complex pacemaker [1, 10]. Thus, the criticality of their reliability varies from one device to another. Nonetheless, past experiences indicate that the failure of medical devices has been very costly in terms of fatalities, injuries, dollar and cents, etc. Needless to say, modern medical devices and equipment have become very complex and sophisticated and are expected to operate under stringent environments.

Electronic equipment used in the health care system may be classified under the following three categories [7]:

- **Category I.** This category includes those medical equipment/devices that are directly and immediately responsible for the patient's life or may become so under emergency conditions. When such equipment fails, there is seldom sufficient time for the repair action. Thus, this type of equipment must always operate successfully at the moment of need. Some examples of such equipment/devices are as follows:
  - Respirators
  - Cardiac pacemakers
  - Electrocardiographic monitors
  - Cardiac defibrillators

- **Category II.** This category includes those medical equipment/devices that are used for routine or semi-emergency diagnostic or therapeutic purposes. Failure of such equipment or devices is not as critical as those fall under Category I, because there is time for repair. Some examples of such equipment/devices are as follows:
  - Spectrophotometers
  - Gas analyzers
  - Electrocardiograph and electroencephalograph recorders and monitors
  - Diathermy equipment
  - Ultrasound equipment
  - Colorimeters
- **Category III.** This category includes those equipment/devices that are not critical to a patient's life or welfare but serve as convenience equipment or devices. Three examples of such equipment or devices are as follows:
  - Electric beds
  - Wheel chairs
  - Bedside television sets

All in all, there could be some overlap between the above three categories of equipment, particularly between categories I and II. An electrocardiograph recorder or monitor is a typical example of such equipment.

5.4 Medical Equipment Reliability Improvement Procedures and Methods

There are many procedures and methods used to improve medical equipment reliability. Some of these are presented below.

5.4.1 General Approach

The general approach is a 13-step approach developed by Bio-Optronics to produce safe and reliable medical devices [19]. The approach steps are shown in Figure 5.1.

5.4.2 Parts Count Method

The parts count method is used to predict equipment or system failure during the bid proposal and early design stages [20]. The method requires information on areas shown in Figure 5.2.

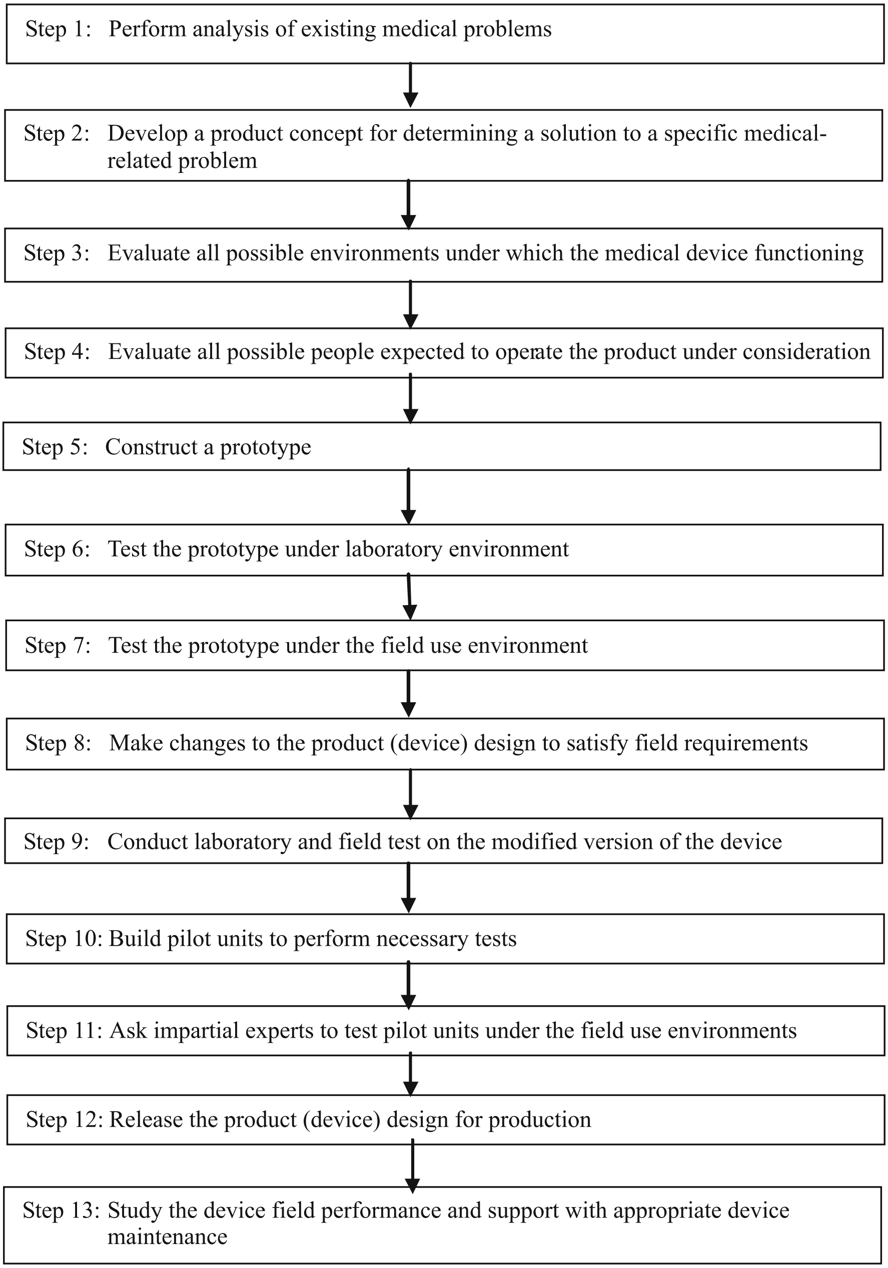

Figure 5.1. An approach for producing safe and reliable medical devices

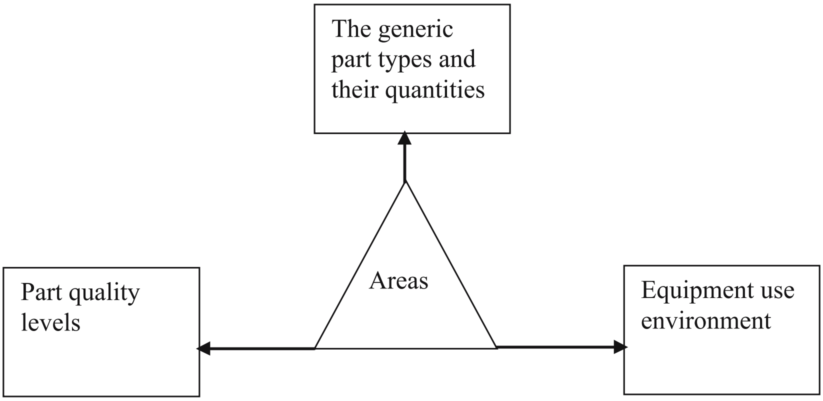

Figure 5.2. Areas of information required by the parts count method

The method calculates the system or equipment failure rate under the single-use environment by using the following equation [20]:

$$\lambda_S = \sum_{i=1}^{n} \theta_i \left(\lambda_g Q_g\right)_i \tag{5.1}$$

where

λ_S is the system failure rate expressed in failures/10^6 hours.
n is the number of different generic component classifications.
Q_g is the generic component quality factor.
λ_g is the generic part failure rate expressed in failures/10^6 hours.
θ_i the generic part quantity for classification *i*.

The values of Q_g and λ_g are tabulated in Ref. [20], and additional information on the method is available in Refs. [20, 21].

5.4.3 Markov Method

The markov method is a very general approach and can generally handle more cases than any other method or technique. It can be used in situations when the components or parts are independent as well as for equipment/systems involving dependent failure and repair modes.

The method proceeds by the enumeration of system states. The state probabilities are then computed, and the steady-state reliability measures can be calculated by applying the frequency balancing method [22]. Additional information on this method is available in Chapter 3 and in Refs. [23, 24].

5.4.4 Failure Mode and Effect Analysis (FMEA)

Failure mode and effect analysis (FMEA) is a widely used tool to evaluate design at the early stage from the reliability aspect. This criterion is extremely useful to identify the need for and the effects of design change. FMEA requires the listing of all possible failure modes of each component on paper and their effects on the listed subsystems, etc. The method is known as failure modes, effects, and criticality analysis (FMECA) when criticalities or priorities are assigned to failure mode effects.

Some of the important characteristics of FMEA are as follows [25]:

- It is an upward approach that starts at the detailed level.
- By examining failure effects of all components, the entire system is screened completely.
- It is an effective tool to identify weak spots in system design and indicate areas where further or detailed analysis is desirable.

Additional information on FMEA is available in Chapter 3 and in Refs. [25–26].

5.4.5 Fault Tree Analysis

Fault tree analysis (FTA) begins by identifying an undesirable event, called the top event, associated with a system under consideration [27]. Fault events which could cause the occurrence of the top event are generated and connected by logic operators such as AND and OR. The AND gate provides a TRUE (failed) output when all its inputs are TRUE (failures). In contrast, the OR gate provides a TRUE (failure) output when only one OR more of its inputs are true (failures). All in all, the fault tree construction proceeds by generation of events in a successive manner until the events need not be developed any further.

Additional information on FTA is available in Chapter 3 and in Refs. [27, 28].

5.5 Human Error in Medical Equipment

Human errors are universal and are committed each day. Past experiences indicate that although most are trivial, some can be quite serious or fatal. In the area of health care, one study revealed that in a typical year around 100,000 Americans die due to human errors [17]. Nonetheless, some of the medical equipment/device-related, directly or indirectly, human error facts and figures are as follows:

- The Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration reported that human errors account for 60% of all device-related deaths or injuries in the United States [29].
- Over 50% of all technical medical equipment problems are due to operator errors [16].
- Human error is responsible for up to 90% of accidents both generally and in medical devices [30–31].

- A fatal radiation overdose accident involving the Therac radiation therapy device was the result of a human error [32].
- A patient was seriously injured by over-infusion because the attending nurse incorrectly read the number 7 as 1 [33].

5.5.1 Medical Devices with High Incidence of Human Error

As per Ref. [34], each day human errors in using medical devices cause at least three deaths or serious injuries. Over the years, many studies have been conducted to identify medical devices with a high occurrence of human error. Consequently, the most error-prone medical devices were identified. These devices, in the order of most error-prone to least error-prone, are as follows [34]:

- Glucose meter
- Balloon catheter
- Orthodontic bracket aligner
- Administration kit for peritoneal dialysis
- Permanent pacemaker electrode
- Implantable spinal cord simulator
- Intra-vascular catheter
- Infusion pump
- Urological catheter
- Electrosurgical cutting and coagulation device
- Non-powered suction apparatus
- Mechanical/hydraulic impotence device
- Implantable pacemaker
- Peritoneal dialysate delivery system
- Catheter introducer
- Catheter guide wire
- Trans-luminal coronary angioplasty catheter
- External low-energy defibrillator
- Continuous ventilator (respirator)
- Contact lens cleaning and disinfecting solutions

5.5.2 Important Medical Device/Equipment Operator Errors

There are many types of operator-related errors that occur during medical device/equipment operation or maintenance. Some of the important ones are as follows [35]:

- Incorrect interpretation of or failure to recognize critical device outputs
- Mistakes in setting device parameters

- Incorrect decision-making and actions in critical moments
- Misassembly
- Departure from following specified instructions and procedures
- Inadvertent or untimely activation of controls
- Over-reliance on automatic features of devices/equipment
- Wrong selection of devices in regard to the clinical objectives and requirements

5.6 Useful Guidelines for Reliability and Other Professionals to Improve Medical Equipment Reliability

There is a large number of professionals involved in the manufacture and use of various types of medical devices. Reliability analysts and engineers are one of them. Nonetheless, some of the useful guidelines for reliability and other professionals to improve medical equipment reliability are as follows [24, 36]:

- Reliability professionals
  - Use methods such as FMEA, qualitative FTA, design review, and parts review to obtain immediate results.
  - Focus on critical failures as not all device failures are equally important.
  - Aim to use simple reliability methods as much as possible instead of some sophisticated approaches used in the aerospace industry.
  - Keep in mind that manufacturers are responsible for reliability during the device design and manufacturing phase, and during its operational phase it is basically the responsibility of users.
  - Focus on cost effectiveness and always keep in mind that some reliability improvement decisions require very little or no additional expenditure.
- Other professionals
  - Recognize that failures are the cause of poor medical device reliability, and positive thinking and measures can be quite useful to improve device reliability.
  - For the total success with respect to device reliability, both manufacturers and users must accept their share of related responsibilities.
  - Compare human body and medical device failures. Both of them require appropriate measures from reliability professionals and doctors to enhance device reliability and extend human life, respectively.
  - Remember that the cost of failures is probably the largest single expense in a business organization. Such failures could be associated with equipment, people, business systems, etc., and a reduction in these failures can decrease the cost of business quite significantly.
  - Keep in mind that the application of reliability principles have successfully improved the reliability of systems used in the aerospace area, and their applications to medical devices can generate similar dividends.

5.7 Medical Equipment Maintenance and Maintainability

Medical equipment maintenance may simply be described as all actions necessary for retaining medical equipment in, or restoring to, a specified condition. Similarly, medical equipment maintainability is the probability that a failed piece of medical equipment will be restored to its acceptable operating state. Both these items (*i. e.*, medical equipment maintenance and maintainability) are discussed below, separately [37, 38].

5.7.1 Medical Equipment Maintenance

For the purpose of repair and maintenance, medical equipment may be classified under six classifications: patient diagnostic equipment (*e. g.*, Spiro meters, endoscopes, and physiologic monitors), life support and therapeutic equipment (*e. g.*, ventilators, lasers, and anaesthesia machines), imaging and radiation therapy equipment (*e. g.*, linear accelerators, X-ray machines, and ultrasound devices), laboratory apparatus (*e. g.*, lab analyzers, lab refrigeration equipment, and centrifuges), patient environmental and transport equipment (*e. g.*, patient beds, wheelchairs, and patient-room furniture), and miscellaneous equipment (*e. g.*, all other items that are not included in the other five classifications, for example, sterilizers) [39].

Indices

Just like in the case of the general maintenance activity, there are many indices that can be used to measure the effectiveness of the medical equipment maintenance activity.

Three of these indices are presented below [39].

- Index I

  Index I is a cost ratio and is expressed by

$$\theta_C = \frac{C_s}{C_a} \tag{5.2}$$

where

θ_C is the cost ratio.
C_a is the medical equipment acquisition cost.
C_s is the medical equipment service cost. It includes all labour, parts, and material costs for scheduled and unscheduled service, including in-house, vendor, prepaid contracts, and maintenance insurance.

A range of values for this index, for various classifications of medical equipment, are given in Ref. [10].

- Index II

Index II measures how much time elapses from a customer request until the failed medical equipment is repaired and put back in service. The index is expressed by

$$\theta_{\mathrm{at}} = \frac{T_{\mathrm{t}}}{N} \tag{5.3}$$

where
θ_{at} is the average turnaround time per repair.
N is the total number of work orders or repairs.
T_{t} is the total turnaround time.

As per one study, the turnaround time per medical equipment repair ranged from 35.4 to 135 hours [10].

- Index III

Index III measures how frequently the customer has to request for service per medical equipment. The index is expressed by

$$\theta_{\mathrm{C}} = \frac{R_{\mathrm{r}}}{M} \tag{5.4}$$

where
θ_{C} is the number of repair requests completed per medical equipment.
R_{r} is the total number of repair requests.
M is the number of pieces of medical equipment.

As per one study, the value of θ_{C} ranged from 0.3 to 2 [10].

Mathematical Models

Over the years, a large number of mathematical models concerning engineering equipment maintenance have been developed. Some of these models can equally be used in the area of medical equipment maintenance. One of these models is presented below.

- Model

This model can be used to determine the optimum time interval between item replacements. The model assumes that the item/equipment average annual cost is made up of average investment, operating, and maintenance costs. Thus, the average annual total cost of a piece of equipment is expressed by

$$C_{\mathrm{t}} = C_{\mathrm{o}} + C_{\mathrm{m}} + \frac{C_{\mathrm{i}}}{t} + \frac{(t-1)}{2}[i+j] \tag{5.5}$$

where

C_t is the average annual total cost of a piece of equipment.
i is the amount by which maintenance cost increases annually.
j is the amount by which operational cost increases annually.
C_o is the item/equipment operational cost for the first year.
C_m is the item/equipment maintenance cost for the first year.
C_i is the investment cost.
t is the item/equipment life expressed in years.

Differentiating Equation (5.5) with respect to t and then equating it to zero, yields

$$t^* = \left[\frac{2C_i}{i+j}\right]^{1/2} \tag{5.6}$$

where

t^* is the optimum time between item/equipment replacements.

Example 5.1
Assume that we have following data for a medical equipment:

$i = \$1{,}000$
$j = \$4{,}000$
$C_i = \$400{,}000$

Determine the optimum replacement period for the equipment under consideration.

By inserting the above given data values into Equation (5.6), we get

$$\begin{aligned} t^* &= \left[\frac{2(400{,}000)}{1000+4000}\right]^{1/2} \\ &= 12.7 \text{ years} \end{aligned}$$

Thus, the optimum replacement period for the medical equipment under consideration is 12.7 years.

5.7.2 Medical Equipment Maintainability

Past experiences indicate that the application of maintainability principles during designing engineering equipment has helped to produce effectively maintainable end products. Their application in the design of medical equipment can also be helpful to produce effectively maintainable end medical items. This section presents three aspects of maintainability considered useful to produce effectively maintainable medical equipment.

Reasons for the Application of Maintainability Principles

Some of the main reasons for applying maintainability principles are as follows [40]:

- To reduce projected maintenance time
- To reduce projected maintenance cost through design modifications
- To determine the number of labour hours and related resources needed to carry out the projected maintenance
- To determine the amount of downtime due to maintenance

Maintainability Design Factors

There are many maintainability design factors. Some of the most frequently addressed factors are shown in Figure 5.3 [41]. Each of these factors is described in detail in Refs. [10, 41].

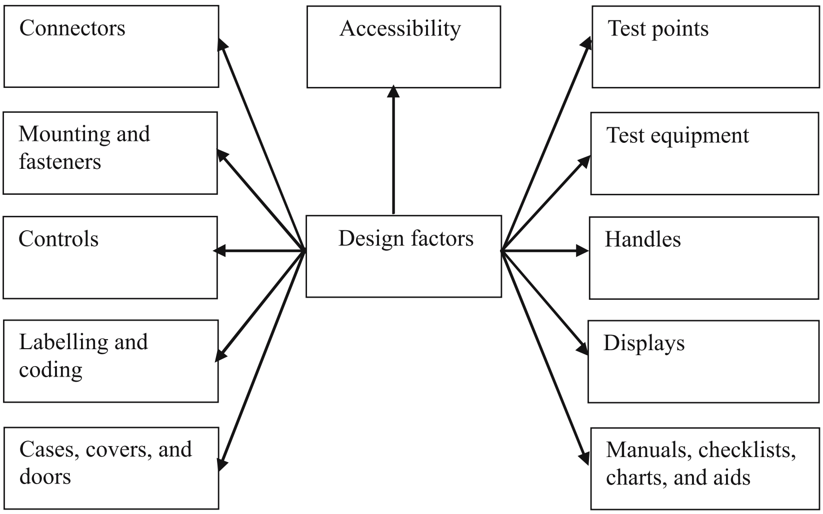

Figure 5.3. Frequently addressed maintainability design factors

Maintainability Measures

There are various types of maintainability measures used in performing maintainability analysis of engineering equipment. Two of these measures are presented below [40–42].

- Mean Time to Repair is defined by

$$MTTR = \frac{\sum_{j=1}^{m} T_{rj}\,\lambda_j}{\sum_{j=1}^{m} \lambda_j} \tag{5.7}$$

where

$MTTR$ is the mean time to repair
m is the number of units.
λ_j is the constant failure rate of unit j; for $j = 1, 2, 3, \ldots, m$.
T_{rj} is the repair time required to repair unit j; for $j = 1, 2, 3, \ldots, m$.

- Maintainability Function

This measure is used to predict the probability that the repair will be completed in a time t, when it starts on an equipment/item at time $t = 0$.

Thus, the maintainability function, $M(t)$, is defined as follows:

$$M(t) = \int_0^t f(t)\,\mathrm{d}t \tag{5.8}$$

where

t is time.
$f(t)$ is the probability density function of the repair time.

Equation (5.8) is used to obtain maintainability functions for various probability distributions (*e.g.*, exponential, normal, and Weibull) representing failed equipment/item repair times. Maintainability functions for such distributions are available in Refs. [41–43].

Example 5.2
Assume that the repair times of a medical equipment are exponentially distributed with a mean value (*i.e.*, *MTTR*) of 4 hours. Thus, the probability density function of repair times is defined by

$$\begin{aligned} f(t) &= \frac{1}{MTTR}\exp\left(-\frac{t}{MTTR}\right) \\ &= \frac{1}{4}\exp\left(-\frac{t}{4}\right) \end{aligned} \tag{5.9}$$

where

$MTTR$ is the medical equipment mean time to repair.
t is time.

Calculate the probability that a repair will be completed in ten hours.

By substituting Equation (5.9) and the given data values into Equation (5.8), we get

$$M(10) = 1 - \exp\left(-\frac{10}{4}\right)$$
$$= 0.9179$$

Thus, the probability of accomplishing a repair within ten hours is 0.9179.

5.8 Organizations and Sources for Obtaining Medical Equipment Failure-related Data

There are many organizations from which failure data directly or indirectly concerned with medical equipment can be obtained. Six of these organizations are as follows:

- Center for Devices and Radiological Health (CDRH)

  Food and Drug Administration (FDA)
  1390 Piccard Drive
  Rockville, MD 20850
  USA

- Emergency Care Research Institute (ECRI)

  5200 Butler Parkway
  Plymouth Meeting, PA 19462
  USA

- Government Industry Data Exchange Program (GIDEP)

  GIDEP Operations Center
  Fleet Missile Systems, Analysis, and Evaluation Group
  Department of Navy
  Corona, CA 91720
  USA

- Parts Reliability Information Center (PRINCE)

  Reliability Office
  George C. Marshall Space Flight Center
  National Aeronautics and Space Administration (NASA)
  Huntsville, AL 35812
  USA

- Reliability Analysis Center (RAC)

  Rome Air Development Center (RADC)
  Griffiss Air Force Base
  Department of Defense
  Rome, NY 13441
  USA

- National Technical Information Service

  5285 Port Royal Road
  Springfield, VA 22161
  USA

Some of the data banks and documents for obtaining failure data concerning medical equipment are as follows:

- **Hospital Equipment Control System (HECS).** This system was developed by Emergency Care Research Institute (ECRI) in 1985 [44].
- **Medical Device Reporting System (MDRS).** This system was developed by Center for Devices and Radiological Health [45].
- **Universal Medical Device Registration and Regulatory Management System (UMDRMS)**. This system was also developed by ECRI [44].
- **MIL-HDBK-217.** Reliability Prediction of Electronic Equipment, Department of Defense, Washington, D.C., USA.
- **NUREG/CR-1278.** Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, U.S. Nuclear Regulatory Commission, Washington, D.C., USA.

5.9 Problems

1. What are the main categories of medical equipment/devices?
2. Discuss the steps of the approach developed by Bio-Optronics to produce safe and reliable medical devices.
3. Compare FMEA with FTA with respect to medical equipment.
4. List at least five facts and figures concerned, directly or indirectly, with human error in medical equipment/devices.
5. List at least 12 medical devices with a high incidence of human error.
6. Discuss important operator-related errors that occur during medical equipment/device operation or maintenance.
7. Discuss useful guidelines for reliability and other professionals to improve medical equipment reliability.
8. Define and compare the following two terms:
   - Medical equipment maintainability
   - Medical equipment maintenance

9. Discuss at least ten maintainability design factors with respect to medical equipment.
10. List at least five good sources for obtaining medical equipment reliability-related data.

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6

Power System Reliability

6.1 Introduction

The three main areas of an electric power system are generation, transmission, and distribution [1]. The basic function of a modern electric power system is to supply its customers cost-effective electrical energy with a high degree of reliability. During planning, design, control, operation, and maintenance of an electric power system, consideration of the two important aspects of quality and continuity of supply, along with other important factors, is normally referred to as reliability assessment. In the context of an electric power system, reliability may simply be defined as concern regarding the system's ability to provide a satisfactory amount of electrical power [2].

The history of power system reliability goes back to the early 1930s when probability concepts were applied to electric power system-related problems [3−5]. The first book on the subject in English appeared in 1970 [6]. Over the years, a large number of publications on the subject have appeared. Most of the publications on power system reliability up to 1977 are listed in Refs. [7−8]. An extensive list of recent publications on power system reliability is presented at the end of this book. This chapter presents various important aspects of power system reliability.

6.2 Terms and Definitions

There are many terms and definitions used in power system reliability. Some of the common ones are as follow: [9−12]:

- **Power system reliability.** This is the degree to which the performance of the elements in a bulk system results in electrical energy being delivered to customers within the framework of specified standards and in the amount required.
- **Forced outage.** This is when a piece of equipment or a unit has to be taken out of service because of damage or a component failure.

- **Forced derating.** This is when a piece of equipment or a unit is operated at a forced derated or lowered capacity because of damage or a component failure.
- **Scheduled outage.** This is the shutdown of a generating unit, transmission line, or other facility, for maintenance or inspection, as per an advance schedule.
- **Service hours.** These are the total number of operation hours of a piece of equipment or a unit.
- **Forced outage hours.** These are the total number of hours a piece of equipment or a unit spends in the forced outage condition.
- **Mean time to forced outage.** This is analogous to mean time to failure (MTTF) and is given by the total of service hours over the total number of forced outages.
- **Mean forced outage duration.** This is analogous to mean time to repair (MTTR) and is given by the total number of forced outage hours over the total number of forced outages.
- **Forced outage rate.** This is (for an equipment) given by the total number of forced outage hours times 100 over the total number of service hours plus the total number of forced outage hours.

6.3 Service Performance Indices

In the electric power system area, usually various service performance indices are calculated for the total system, a specific region or voltage level, designated feeders or different groups of customers, etc. [2]. Some of the most widely used indices are presented below [2, 13].

6.3.1 Index I

The Index I is known as average service availability index (ASAI) and is expressed by

$$ASAI = \frac{CHAS}{CHD} \tag{6.1}$$

where

CHAS is the customer hours of available service.

CHD is customer hours demanded. These hours are given by the 12-month average number of customers serviced times 8,760 hours.

6.3.2 Index II

The Index II is known as system average interruption frequency index (SAIFI) and is defined by

$$SAIFI = \frac{TNCI}{TNC} \tag{6.2}$$

where
TNC is the total number of customers.
TNCI is the total number of customer interruptions per year.

6.3.3 Index III

The Index III is known as system average interruption duration index (SAIDI) and is expressed by

$$SAIDI = \frac{SCID}{TNC} \tag{6.3}$$

where
SCID is the sum of customer interruption durations per year.

6.3.4 Index IV

The Index IV is known as customer average interruption frequency index (CAIFI) and is defined by

$$CAIFI = \frac{TNCI}{TNCA} \tag{6.4}$$

where
TNCA is the total number of customers affected. It is be noted that the customers affected should only be counted once, irrespective of the number of interruptions during the year they may have experienced.

6.3.5 Index V

The Index V is known as customer average interruption duration index (CAIDI) and is expressed by

$$\begin{aligned} CAIDI &= \frac{SAIDI}{DAIFI} \\ &= \frac{SCID}{TNCI} \end{aligned} \tag{6.5}$$

6.4 Loss of Load Probability

Over the years, loss-of-load probability (LOLP) has been used as the single most important metric for estimating overall power system reliability. LOLP may simply be described as a projected value of how much time, in the long run, the load on a given power system is expected to be more than the capacity of the generating resources [9]. Various probabilistic techniques are used to calculate LOLP.

In the setting up of an LOLP criterion, it is assumed that an electric power system strong enough to have a low LOLP can probably withstand most of the foreseeable peak loads, outages, and contingencies. Thus, an utility is expected to arrange for resources (*i. e.*, generation, purchases, load management, and so on) in such a way so that the resulting system LOLP will be at or less than an acceptable level.

Usually, the common practice is to plan to power system for achieving an LOLP of 0.1 days per year or less. All in all, some of the difficulties with this use of LOLP are as follows [9]:

- Different LOLP estimation methods can lead to different indices for exactly the same electric power system.
- LOLP itself does not specify the magnitude or duration of the shortage of electricity.
- Major loss-of-load incidents normally occur because of contingencies not modeled properly by the traditional LOLP calculation.
- LOLP does not take into consideration the factor of additional emergency support that one region or control area may receive from another, or other emergency actions/measures that control area operators can exercise to maintain system reliability.

6.5 Models for Performing Availability Analysis of a Single Generator Unit

There are a number of mathematical models that can be used to perform availability analysis of a single generator unit. This section presents three Markov models that can also be used to perform availability analysis of equipment other than a generator unit [12]. Two examples of such equipment are a transformer and a pulverizer.

6.5.1 Model I

Model I represents a generator unit that can either be in operating state or in failed state. The failed generator unit is repaired. The generator unit state space diagram is shown in Figure 6.1. The numerals in the rectangle and circle denote the system state. The following assumptions are associated with the model:

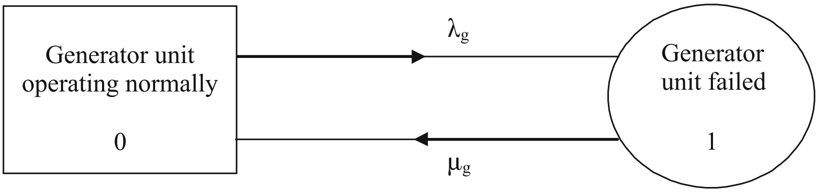

Figure 6.1. Generator unit state space diagram

- The generator unit failures are statistically independent.
- The generator unit failure and repair rates are constant.
- The repaired generator unit is as good as new.

The following symbols are associated with the diagram in Figure 6.1 and its associated equations:

$P_i(t)$ is the probability that the generator unit is in state i at time t; for $i=0$ (operating normally), $i=1$ (failed).
λ_g is the generator unit failure rate.
μ_g is the generator unit repair rate.

Using the Markov method, we write down the following equations for the diagram in Figure 6.1 diagram [1, 12]:

$$\frac{dP_0(t)}{dt} + \lambda_g P_0(t) - \mu_g P_1(t) = 0 \tag{6.6}$$

$$\frac{dP_1(t)}{dt} + \mu_g P_1(t) - \lambda_g P_0(t) = 0 \tag{6.7}$$

At time $t=0$, $P_0(0)=1$ and $P_1(0)=0$

Solving Equations (6.6)–(6.7) by using Laplace transforms we get

$$P_0(t) = \frac{\mu_g}{\lambda_g + \mu_g} + \frac{\lambda_g}{\lambda_g + \mu_g} e^{-(\lambda_g + \mu_g)t} \tag{6.8}$$

$$P_1(t) = \frac{\lambda_g}{\lambda_g + \mu_g} - \frac{\mu_g}{\lambda_g + \mu_g} e^{-(\lambda_g + \mu_g)t} \tag{6.9}$$

The generator unit availability and unavailability are given by

$$AV_g(t) = P_0(t) = \frac{\mu_g}{\lambda_g + \mu_g} + \frac{\lambda_g}{\lambda_g + \mu_g} e^{-(\lambda_g + \mu_g)t} \tag{6.10}$$

and

$$UA_g(t) = P_1(t) = \frac{\lambda_g}{\lambda_g + \mu_g} - \frac{\mu_g}{\lambda_g + \mu_g} e^{-(\lambda_g + \mu_g)t} \tag{6.11}$$

where
$AV_g(t)$ is the generator unit availability at time t.
$UA_g(t)$ is the generator unit unavailability at time t.

For large t, Equations (6.10)–(6.11) reduce to

$$AV_g = \frac{\mu_g}{\lambda_g + \mu_g} \tag{6.12}$$

and

$$UA_g = \frac{\lambda_g}{\lambda_g + \mu_g} \tag{6.13}$$

where
AV_g is the generator unit steady state availability.
UA_g is the generator unit steady state unavailability.

Since $\lambda_g = \frac{1}{MTTF_g}$ and $\mu_g = \frac{1}{MTTR_g}$, Equations (6.12)–(6.13) become

$$AV_g = \frac{MTTF_g}{MTTR_g + MTTF_g} = \frac{\text{Generator unit uptime}}{\text{Generator unit downtime} + \text{Generator unit uptime}} \tag{6.14}$$

and

$$UA_g = \frac{MTTR_g}{MTTR_g + MTTF_g} = \frac{\text{Generator unit downtime}}{\text{Generator unit downtime} + \text{Generator unit uptime}} \tag{6.15}$$

where
$MTTF_g$ is the generator unit mean time to failure.
$MTTR_g$ is the generator unit mean time to repair.

Example 6.1
Assume that a generator unit's constant failure and repair rates are as follows:

$$\lambda_g = 0.0004 \text{ failures / hour}$$

and

$$\mu_g = 0.0009 \text{ repairs / hour}$$

Calculate the generator unit's steady state availability. By substituting the given data values into Equation (6.12) we get

$$AV_g = \frac{0.0009}{0.0004 + 0.0009} = 0.6923$$

Thus, the generator unit's steady state availability is 0.6923.

6.5.2 Model II

Model II represents a generator unit that can either be in operating state or failed state or down for preventive maintenance. This is depicted by the state space diagram shown in Figure 6.2. The numerals in the rectangle, diamond, and circle denote the system state.

The following assumptions are associated with the model:

- The generator unit failures are statistically independent.
- The generator unit failure, repair, preventive maintenance down, and preventive maintenance performance rates are constant.
- After repair and preventive maintenance the generator unit is as good as new.

The following symbols are associated with the diagram in Figure 6.2 and its associated equations:

$P_i(t)$ is the probability that the generator unit is in state i at time t; for $i = 0$ (operating normally), $i = 1$ (down for preventive maintenance), $i = 2$ (failed).
λ is the generator unit failure rate.
μ is the generator unit repair rate.
λ_p is the generator unit (down for) preventive maintenance rate.
μ_p is the generator unit preventive maintenance performance (repair) rate.

As for Model I, using the Markov method, we write down the following equations for the Figure 6.2 diagram [1, 12]:

$$\frac{dP_0(t)}{dt} + (\lambda_p + \lambda) P_0(t) - \mu P_2(t) - \lambda_p P_1(t) = 0 \tag{6.16}$$

$$\frac{dP_1(t)}{dt} + \mu_p P_1(t) - \lambda_p P_0(t) = 0 \tag{6.17}$$

$$\frac{dP_2(t)}{dt} + \mu P_2(t) - \lambda P_0(t) = 0 \tag{6.18}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

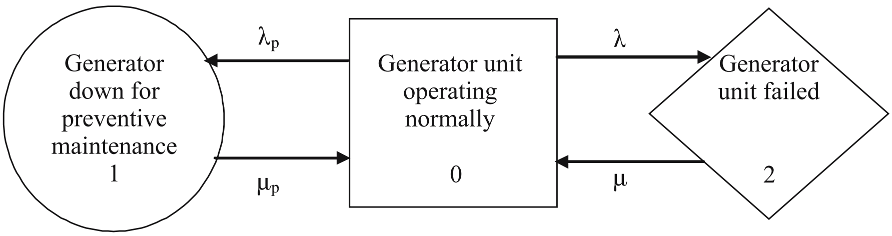

Figure 6.2. Generator unit state space diagram

Solving Equations (6.16)–(6.18) by using Laplace transforms, we get

$$P_0(t) = \frac{\mu_p \mu}{c_1 c_2} + \left[\frac{(c_1 + \mu_p)(c_1 + \mu)}{c_1 (c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(c_2 + \mu_p)(c_2 + \mu)}{c_2 (c_1 - c_2)}\right] e^{c_2 t} \tag{6.19}$$

$$P_1(t) = \frac{\lambda_p \mu}{c_1 c_2} + \left[\frac{(\lambda_p c_1 + \lambda_p \mu)}{c_1 (c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu + c_2)\lambda_p}{c_2 (c_1 - c_2)}\right] e^{c_2 t} \tag{6.20}$$

$$P_2(t) = \frac{\lambda \mu_p}{c_1 c_2} + \left[\frac{(\lambda c_1 + \lambda \mu_p)}{c_1 (c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu_p + c_2)\lambda}{c_2 (c_1 - c_2)}\right] e^{c_2 t} \tag{6.21}$$

where

$$c_1 c_2 = \mu_p \mu + \lambda_p \mu + \lambda \mu_p \tag{6.22}$$

$$c_1 + c_2 = -(\mu_p + \mu + + \lambda_p + \lambda) \tag{6.23}$$

The generator unit availability, $AV_g(t)$, is given by

$$AV_g(t) = P_0(t) = \frac{\mu_p \mu}{c_1 c_2} + \left[\frac{(c_1 + \mu_p)(c_1 + \mu)}{c_1 (c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(c_2 + \mu_p)(c_2 + \mu)}{c_2 (c_1 - c_2)}\right] e^{c_2 t} \tag{6.24}$$

The above availability expression is valid if and only if c_1 and c_2 are negative. Thus, for large t, Equation (6.24) reduces to

$$AV_g = \lim_{t \to \infty} AV_g(t) = \frac{\mu_p \mu}{c_1 c_2} \tag{6.25}$$

where

AV_g is the generator unit steady state availability.

Example 6.2

Assume that for a generator unit we have the following data values:

$\lambda = 0.0002$ failures / hour
$\lambda_p = 0.0005$ / hour
$\mu = 0.0006$ repairs / hour
and $\mu_p = 0.0009$ / hour

Calculate the generator unit's steady state availability. By substituting the specified data values into Equation (6.25), we get

$$AV_g = \frac{(0.0009)(0.0006)}{(0.0009)(0.0006) + (0.0005)(0.0006) + (0.0002)(0.0009)}$$
$$= 0.5294$$

Thus, the generator unit's steady state availability is 0.5294.

6.5.3 Model III

Model III represents a power generator unit that can be either operating normally (*i. e.*, producing electricity at its full capacity), derated (*i. e.*, producing electricity at a derated capacity, for example, say 250 megawatts instead of 500 megawatts at full capacity), or failed. This is depicted by the state space diagram in Figure 6.3. The numerals in the rectangle, circle, and diagram denote system state.

The following assumptions are associated with the model:

- The generator unit failures are statistically independent.
- The repaired generator unit is as good as new.
- All generator unit failure and repair rates are constant.

The following symbols are associated with the diagram in Figure 6.3 and its associated equations:

$P_i(t)$ is the probability that the generator unit is in state i at time t; for $i = 0$ (operating normally), $i = 1$ (derated), $i = 2$ (failed).
λ is the generator unit failure rate from state 0 to state 2.
λ_d is the generator unit failure rate from state 0 to state 1.
λ_1 is the generator unit failure rate from state 1 to state 2.
μ is the generator unit repair rate from state 2 to state 0.
μ_d is the generator unit repair rate from state 1 to state 0.
μ_1 is the generator unit repair rate from state 2 to state 1.

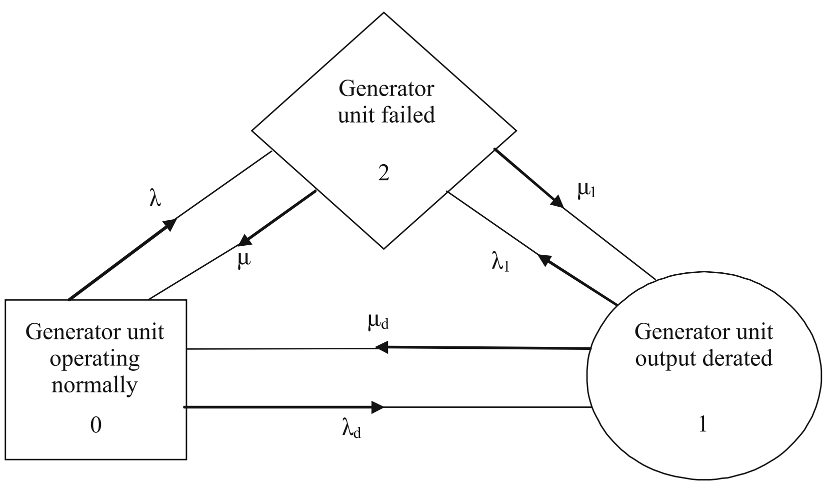

Figure 6.3. Generator unit state space diagram

As for Models I and II, using the Markov method, we write down the following equations for Figure 6.3 diagram [1, 12]:

$$\frac{dP_0(t)}{dt} + (\lambda_d + \lambda) P_0(t) - \mu_d P_1(t) - \mu P_2(t) = 0 \tag{6.26}$$

$$\frac{dP_1(t)}{dt} + (\mu_d + \lambda_1) P_1(t) - \mu_1 P_2(t) - \lambda_d P_0(t) = 0 \tag{6.27}$$

$$\frac{dP_2(t)}{dt} + (\mu + \mu_1) P_2(t) - \lambda_1 P_1(t) - \lambda P_0(t) = 0 \tag{6.28}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

Solving Equations (6.26)–(6.28) by using Laplace transforms, we get

$$P_0(t) = \frac{A_1}{k_1 k_2} + \frac{A_2}{k_1 (k_1 - k_2)} e^{k_1 t} + \left[1 - \frac{A_1}{k_1 k_2} - \frac{A_2}{k_1 (k_1 - k_2)}\right] e^{k_2 t} \tag{6.29}$$

where

$$A_1 = \mu \mu_d + \lambda_1 \mu + \mu_d \mu_1 \tag{6.30}$$

$$A_2 = \mu_d k_1 + \mu k_1 + \mu_1 k_1 + k_1 \lambda_1 + k_1^2 + \mu_d \mu + \lambda_1 \mu + \mu_d \mu_1 \tag{6.31}$$

$$k_1, k_2 = \frac{-A_3 \pm \left[A_3^2 - 4 A_4\right]^{1/2}}{2} \tag{6.32}$$

$$A_3 = \mu + \mu_1 + \mu_d + \lambda + \lambda_1 + \lambda_d \tag{6.33}$$

$$A_4 = \mu_d \mu + \lambda_1 \mu + \mu_d \mu_1 + \mu \lambda_d + \lambda_1 \lambda_d + \mu_d \lambda + \lambda \mu_1 + \lambda \lambda_1 + \lambda_d \mu_1 \tag{6.34}$$

$$P_1(t) = \frac{A_5}{k_1 k_2} + \frac{A_6}{k_1 (k_1 - k_2)} e^{k_1 t} - \left[\frac{A_5}{k_1 k_2} + \frac{A_6}{k_1 (k_1 - k_2)}\right] e^{k_2 t} \tag{6.35}$$

where

$$A_5 = \lambda_d \mu + \lambda_d \mu_1 + \lambda \mu_1 \tag{6.36}$$

$$A_6 = k_1 \lambda_d + A_5 \tag{6.37}$$

$$P_2(t) = \frac{A_7}{k_1 k_2} + \frac{A_8}{k_1 (k_1 - k_2)} e^{k_1 t} - \left[\frac{A_7}{k_1 k_2} + \frac{A_8}{k_1 (k_1 - k_2)}\right] e^{k_2 t} \tag{6.38}$$

where

$$A_7 = \lambda_d \lambda_1 + \mu_d \lambda + \lambda \lambda_1 \tag{6.39}$$

$$A_8 = k_1 \lambda + A_7 \tag{6.40}$$

The generator unit operational availability is given by

$$AV_{go}(t) = P_0(t) + P_1(t) \tag{6.41}$$

For large t, Equation (6.41) reduces to

$$AV_{go} = \lim_{t \to \infty} \left[P_0(t) + P_1(t) \right] = \frac{A_1 + A_5}{k_1 k_2} \tag{6.42}$$

where

AV_{go} is the generator unit operational steady state availability.

6.6 Models for Performing Availability Analysis of Transmission and Associated Systems

In the power system area various types of equipment and systems are used to transmit electrical energy from one end to another. Two examples of such systems are transmission lines and transformers. This section presents three Markov models for performing availability analysis of transmission lines and transformers [6, 11, 12].

6.6.1 Model I

Model I represents transmission lines and other equipment operating in fluctuating outdoor environments (*i. e.*, normal and stormy). The system can fail under both these conditions. The system state space diagram is shown in Figure 6.4. The numerals in rectangles and circles denote system states. The following assumptions are associated with the model:

- All failures are statistically independent.
- All failures, repair, and weather fluctuation rates are constant.
- The repaired system is as good as new.

The following symbols are associated with the diagram in Figure 6.4 and its associated equations:

$P_i(t)$ is the probability that the system is in state i at time t; for $i = 0$ (operating normally in normal weather), $i = 1$ (failed in normal weather), $i = 2$ (operating normally in stormy weather), $i = 3$ (failed in stormy weather).
α is the constant transition rate from normal weather to stormy weather.
β is the constant transition rate from stormy weather to normal weather.
λ_n is the system constant failure rate in normal weather.
λ_s is the system constant failure rate in stormy weather.
μ_n is the system constant failure rate in stormy weather.
μ_s is the system constant repair rate in stormy weather.

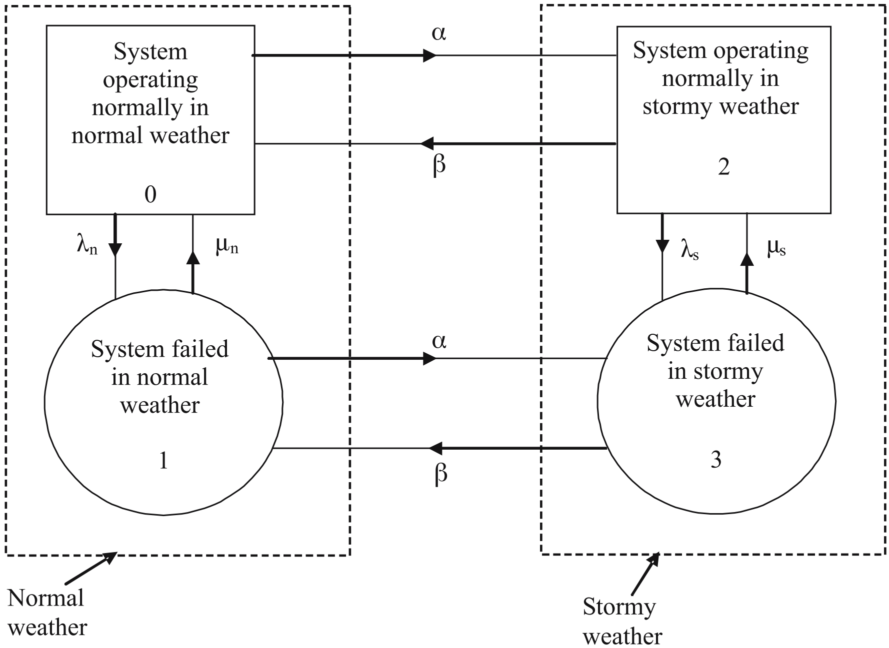

Figure 6.4. State space diagram of a system operating under fluctuating environments

Using the Markov method, we write down the following equations for Figure 6.4 diagram [1, 12]:

$$\frac{dP_0(t)}{dt} + (\lambda_n + \alpha) P_0(t) - \beta P_2(t) - \mu_n P_1(t) = 0 \tag{6.43}$$

$$\frac{dP_1(t)}{dt} + (\mu_n + \alpha) P_1(t) - \beta P_3(t) - \lambda_n P_0(t) = 0 \tag{6.44}$$

$$\frac{dP_2(t)}{dt} + (\lambda_s + \beta) P_2(t) - \mu_s P_3(t) - \alpha P_0(t) = 0 \tag{6.45}$$

$$\frac{dP_3(t)}{dt} + (\beta + \mu_s) P_3(t) - \lambda_s P_2(t) - \alpha P_1(t) = 0 \tag{6.46}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = (0)$, and $P_3(0) = 0$.

The following steady-state equations are obtained from Equations (6.43)–(6.46) by setting the derivatives with respect to time t equal to zero and using the relationship $\sum_{i=0}^{3} P_i = 1$:

$$P_o = \frac{\beta B_1}{\alpha(B_2 + B_3) + \beta(B_4 + B_1)} \tag{6.47}$$

where

$$B_1 = \mu_s \alpha + \mu_n B_5 \tag{6.48}$$

$$B_2 = \mu_n \beta + \mu_s B_6 \tag{6.49}$$

$$B_3 = \lambda_n \beta + \lambda_s B_6 \tag{6.50}$$

$$B_4 = \lambda_s \alpha + \lambda_n B_5 \tag{6.51}$$

$$B_5 = \lambda_s + \beta + \mu_s \tag{6.52}$$

$$B_6 = \lambda_n + \alpha + \mu_n \tag{6.53}$$

$$P_1 = B_4 P_0 / B_1 \tag{6.54}$$

$$P_2 = \alpha P_0 B_2 / \beta B_1 \tag{6.55}$$

$$P_3 = \alpha P_0 B_3 / \beta B_1 \tag{6.56}$$

P_0, P_1, P_2, and P_3 are the steady state probabilities of the system being in states 0, 1, 2, and 3, respectively.

The system steady state availability, AV_{ss}, is given by

$$AV_{ss} = P_0 + P_2 \tag{6.57}$$

6.6.2 Model II

Model II represents a system composed of two non-identical and redundant transmission lines subject to common-cause failures. A common-cause failure may simply be described as any instance where multiple units fail due to a single cause [14, 15]. In transmission lines a common-cause failure may occur due to factors such as poor weather, tornado, and aircraft crash. The system state space diagram is shown in Figure 6.5. The numerals in the boxes and the circle denote system states.

The following assumptions are associated with the model:

- All failures are statistically independent.
- A repaired transmission line is as good as new.
- All failures and repair rates are constant.

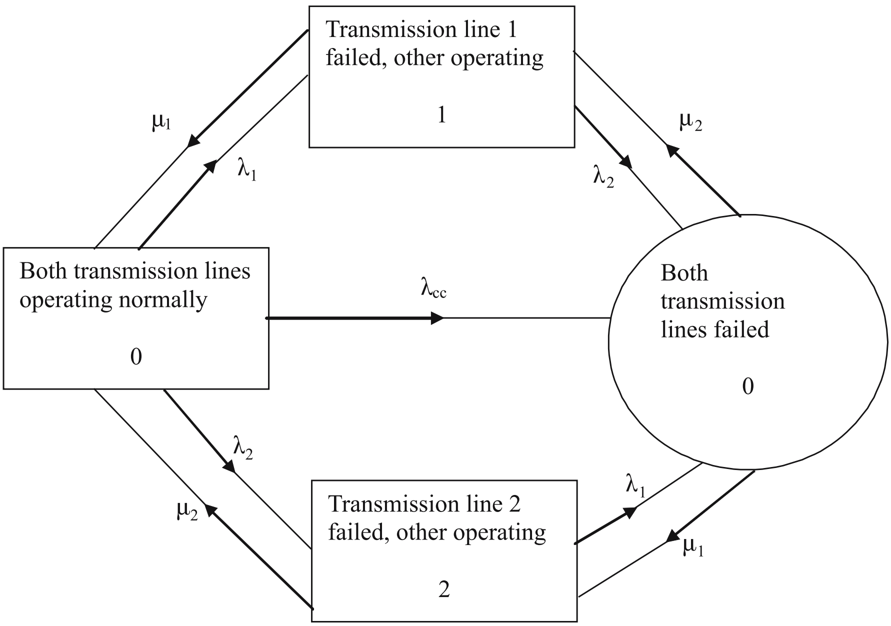

Figure 6.5. State space diagram for two non-identical transmission lines

The following symbols are associated with Figure 6.5 diagram and its associated equations:

- $P_i(t)$ is the probability that the system is in state i at time t; for $i=0$ (both transmission lines operating normally), $i=1$ (transmission line 1 failed, other operating), $i=2$ (transmission line 2 failed, other operating), $i=3$ (both transmission lines failed).
- λ_1 is the transmission line 1 failure rate.
- λ_2 is the transmission line 2 failure rate.
- λ_{cc} is the system common-cause failure rate.
- μ_1 is the transmission line 1 repair rate.
- μ_2 is the transmission line 2 repair rate.

As for Model I, using the Markov method, we write down the following equations for Figure 6.5 diagram [1, 12, 15]:

$$\frac{dP_0(t)}{dt}+(\lambda_1+\lambda_2+\lambda_{cc})P_0(t)-\mu_1 P_1(t)-\mu_2 P_2(t)=0 \tag{6.58}$$

$$\frac{dP_1(t)}{dt}+(\lambda_2+\mu_1)P_1(t)-\mu_2 P_3(t)-\lambda_1 P_0(t)=0 \tag{6.59}$$

$$\frac{dP_2(t)}{dt}+(\lambda_1+\mu_2)P_2(t)-\mu_1 P_3(t)-\lambda_2 P_0(t)=0 \tag{6.60}$$

$$\frac{dP_3(t)}{dt} + (\mu_1 + \mu_2)P_3(t) - \lambda_1 P_2(t) - \lambda_2 P_1(t) - \lambda_{cc} P_0(t) = 0 \tag{6.61}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

The following steady-state equations are obtained from Equations (6.58)–(6.61) by setting the derivatives with respect to time t equal to zero and using the relationship $\sum_{i=0}^{3} P_i = 1$:

$$P_o = \mu_1 \mu_2 C / C_3 \tag{6.62}$$

where

$$C = C_1 + C_2 \tag{6.63}$$

$$C_1 = (\lambda_1 + \mu_1) \tag{6.64}$$

$$C_2 = (\lambda_2 + \mu_2) \tag{6.65}$$

$$C_3 = CC_1 C_2 + \lambda_{CC} \left[C_1 (C_2 + \mu_1) + \mu_2 C_2 \right] \tag{6.66}$$

$$P_1 = [C_1 \lambda_1 + C_4 \lambda_{cc}] \mu_2 / C_3 \tag{6.67}$$

where

$$C_4 = (\lambda_1 + \mu_2) \tag{6.68}$$

$$P_2 = [C\ \lambda_2 + C_5 \lambda_{cc}] \mu_1 / C_3 \tag{6.69}$$

where

$$C_5 = (\lambda_2 + \mu_1) \tag{6.70}$$

$$P_3 = C \lambda_1 \lambda_2 + C_4 C_5 \lambda_{cc} / C_3 \tag{6.71}$$

P_0, P_1, P_2, and P_3 are the steady state probabilities of the system being in states 0, 1, 2, and 3, respectively.

The system steady state availability, AV_{ss}, is given by

$$AV_{ss} = P_0 + P_1 + P_2 \tag{6.72}$$

6.6.3 Model III

Model III represents a system composed of three active and identical single-phase transformers with one standby transformer (*i. e.*, unit) [11]. The system state space diagram is shown in Figure 6.6. The numerals in boxes denote system states.

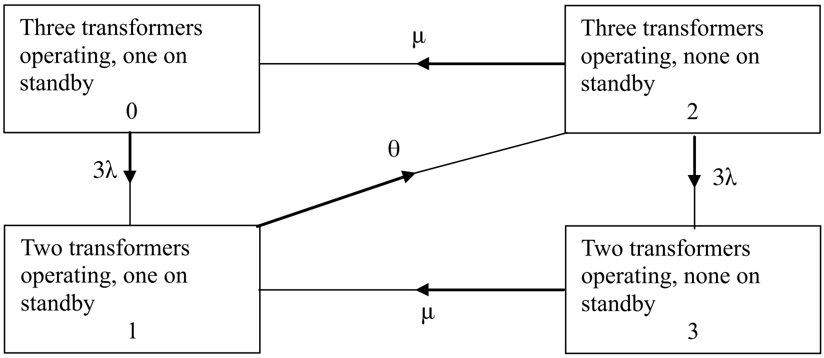

Figure 6.6. State space diagram of three single-phase transformers with one standby

The model is subject to the following assumptions [11, 12]:

- Transformer failure, repair, and replacement (*i. e.*, installation) rates are constant.
- All failures are statistically independent.
- The standby transformer or unit cannot fail in its standby mode.
- The whole transformer bank is considered failed when more than one transformer fails. In addition, it is assumed that no more transformer failures occur.
- Repaired transformers are as good as new.

The following symbols are associated with the diagram in Figure 6.6 and its associated equations:

$P_i(t)$ is the probability that the system is in state i at time t; for $i=0$ (three transformers operating, one on standby), $i=1$ (two transformers operating, one on standby), $i=2$ (three transformers operating, none on standby), $i=3$ (two transformers operating, none on standby).
λ is the transformer failure rate.
μ is the transformer repair rate.
θ is the standby transformer or unit installation rate.

As for Models I and II, using the Markov method, we write down the following equations for Figure 6.6 diagram [1, 11, 12]:

$$\frac{dP_0(t)}{dt} + 3\lambda P_0(t) - \mu P_2(t) = 0 \tag{6.73}$$

$$\frac{dP_1(t)}{dt} + \theta P_1(t) - 3\lambda P_0(t) - \mu P_3(t) = 0 \tag{6.74}$$

$$\frac{dP_2(t)}{dt} + (3\lambda + \mu) P_2(t) - \theta P_1(t) = 0 \tag{6.75}$$

$$\frac{dP_3(t)}{dt} + \mu P_3(t) - 3\lambda P_2(t) = 0 \tag{6.76}$$

At time $t = 0$, $P_0\,(0) = 1$, $P_1\,(0) = 0$, $P_2\,(0) = 0$, and $P_3\,(0) = 0$.

The following steady-state equations are obtained from Equations (6.73)–(6.76) by setting the derivatives with respect to time t equal to zero and using the relationship $\sum_{i=0}^{3} P_i = 1$:

$$P_0 = \left[1 + D_1\left(1 + D_2 + D_1\right)\right]^{-1} \tag{6.77}$$

where

$$D_1 = 3\lambda / \mu \tag{6.78}$$

$$D_2 = \left(3\lambda + \mu\right) / \theta \tag{6.79}$$

$$P_1 = D_1 D_2 P_0 \tag{6.80}$$

$$P_2 = D_1 P_0 \tag{6.81}$$

$$P_3 = D_1^2 P_0 \tag{6.82}$$

P_0, P_1, P_2, and P_3 are the steady state probabilities of the system being in states 0, 1, 2, and 3, respectively.

6.7 Problems

1. Write an essay on power system reliability.
2. Define the following terms:
   - Power system reliability
   - Forced outage rate
   - Forced derating
3. Define the following indices:
   - SAIFI
   - CAIDI
   - CAIFI
4. What is loss of load probability (LOLP) ?
5. What are the problems associated with the use of LOLP?
6. A generator unit's constant failure and repair rates are as follows:
   - $\lambda = 0.003$ failure/hour
   - $\mu = 0.008$ repairs/hour

   Calculate the generator unit's steady state availability.

7. Using the data from problem 6, calculate the generator unit's steady state unavailability.
8. Prove Equation (6.42).
9. Prove that the sum of Equations (6.47), (6.54)−(6.56) is equal to unity.
10. Prove Equations (6.62), (6.67), (6.69), and (6.71).

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7

Computer and Internet Reliability

7.1 Introduction

Today, billions of dollars are being spent annually to produce computers for various types of applications ranging from personal use to control space and other systems. As the computers are composed of both the hardware and software components, the reliability of both these components is equally important for their successful operation. The history of computer hardware reliability may be traced back to the works of Shannon [1], Hamming [2], Von Neumann [3] and Moore and Shannon [4] that appeared in 1948, 1950, 1956, and 1956, respectively. For example, in 1956 Von Neumann proposed the well-known triple modular redundancy (TMR) scheme to improve hardware reliability.

It appears that the first serious effort on software reliability started at Bell Laboratories in 1964 [5]. Nonetheless, some of the important works that appeared in the 1960s were by Haugk, Tsiang, and Zimmerman [6], Floyd [7], Hudson [8], Barlow and Scheuer [9], London [10], and Sauter [11]. Computer hardware and software reliability history is discussed in detail in Ref. [12].

The history of the Internet goes back to 1969 with the development of Advanced Research Projects Agency Network (ARPANET). It has grown from 4 hosts in 1969 to over 147 million hosts and 38 million sites in 2002. In 2000, the Internet economy generated around $830 billion in revenues in the United States alone. In 2001, there were 52,658 Internet-related incidents and failures. Needless to say, today a reliable and stable Internet is extremely important to the global economy and other areas, because Internet failures can easily generate millions of dollars in losses and interrupt the daily routine of hundreds of thousands of end users [13]. An extensive list of references directly or indirectly related to Internet reliability are listed at the end of this book. This chapter presents various important aspects of computer hardware, software, and Internet reliability.

7.2 Computer System Failure Causes and Reliability Measures

Although there are many causes for computer system failures, the important ones are as follows [12, 14, 15]:

- Human errors
- Processor and memory failures
- Peripheral device failures
- Environmental and power failures
- Communication network failures
- Saturation
- Gradual erosion of the data base
- Mysterious failures

Some of the above causes or sources of computer system failure are described below.

Human errors, in general, occur due to operator mistakes and oversights, and often occur during starting up, running, and shutting down the system. Processor and memory failures are associated with processor and memory party errors. Although processor errors occur quite rarely, they are generally catastrophic. However, there are occasions when the central processor fails to execute instructions properly due to a "dropped bit". Nowadays, the memory parity errors occur very rarely because of improvements in hardware reliability and also they are not necessarily fatal.

Peripheral device failures are quite important to consider because they too can cause serious problems but they seldom lead to a system shutdown. The frequently occurring errors in peripheral devices are transient or intermittent, and the electromechanical nature of the devices is the usual reason for their occurrence.

Environmental failures occur due to factors such as failure of air conditioning equipment, fires, earthquakes, and electromagnetic interference, whereas power failures due to factors such as transient fluctuations in frequency or voltage and total power loss from the local utility company. Communication network failures are mostly of a transient nature and are associated with inter-module communication. The use of "vertical parity" logic can help to cut down around 70% of errors in communication lines.

In real-life systems, the failures that cannot be categorized properly are known as mysterious failures. An example of such failures is the sudden stop functioning of a normally operating system without indication of any problem (*i. e.*, software, hardware, etc.).

There are many measures used in performing computer system reliability analysis. They may be grouped under two broad categories: Category I and Category II. Category I includes measures such as system reliability, system availability, mean time to failure, and mission time. These measures are suitable for configurations such as standby, hybrid, and massive redundant systems [3, 12, 16–18]. Category II includes measures such as computation reliability (*i. e.*, the failure-free probability that the system will without an error execute a task of length x initiated at time t), computation availability (*i. e.*, the expected computation capacity of the system at given time t), mean computation before failure (*i. e.*, the expected amount of computation available on the system before failure), capacity threshold (*i. e.*, that time at which a certain value of computation availability is reached), and computation threshold (*i. e.*, the time at which a certain value of computation reliability is reached for a task whose length is x) to handle gracefully degrading systems [12, 19].

7.3 Comparisons Between Hardware and Software Reliability

As it is important to have a clear understanding of the differences between computer hardware and software reliability, Table 7.1 presents comparisons of the some important areas [20–22].

Table 7.1. Hardware and software reliability comparisons

Hardware reliability	Software reliability
Wears out.	Does not wear out.
A hardware failure is usually caused by physical effects.	A software failure is caused by programming error.
Normally redundancy is quite effective.	Redundancy may not be effective at all.
Failure of many hardware components is governed by the "bathtub" hazard rate curve.	Software failures are not governed by the "bathtub" hazard rate curve.
Obtaining good quality failure data is a problem.	Obtaining good quality failure data is a problem.
Interfaces are visual.	Interfaces are conceptual.
The failed system is repaired back to its operating state by performing corrective maintenance.	Corrective maintenance is really redesign.
Mean time to repair has certain significance.	Mean time to repair has no significance.
Preventive maintenance is carried out to inhibit failures.	Preventive maintenance has no meaning whatsoever in software.
Hardware can be repaired by using spare modules.	Software failures cannot be repaired by using spare modules.

7.4 Fault Masking

This is the term used in fault-tolerant computing to state that a system having redundancy can tolerate a number of failures prior to its failure. More specifically, the implication of the term simply is that a problem has appeared somewhere within the digital system framework, but because of the nature of the design, the problem does not effect the overall operation of the system. The best known fault masking method is probably modular redundancy presented below [23].

7.4.1 Triple Modular Redundancy (TMR)

The triple modular redundancy (TMR) scheme was first proposed by Von Neumann [3] in 1956, in which three identical modules or units perform the same task simultaneously and the voter compares their outputs (*i. e.*, the modules') and sides with the majority. More specifically, the TMR system fails only when more than one module/unit fails or the voter fails. In other words, the TMR system can tolerate failure of a single unit or module. An important example of the TMR scheme application was the SATURN V launch vehicle computer, which used TMR with voters in the central processor and duplication in the main memory [24]. The block diagram of the TMR scheme is shown in Figure 7.1. Blocks in the diagram represent modules/units and the voter. In addition, the TMR system without the voter is inside the dotted rectangle. This system is basically a 2-out-of-3 identical unit system.

For independently failing units and the voter, the reliability of the system in Figure 7.1 is [23]

$$R_{\text{tv}} = \left(3R^2 - 2R^3\right) R_{\text{V}} \tag{7.1}$$

where

R_{tv} is the reliability of the TMR system with voter.
R is the unit or module reliability.
R_{V} is the voter reliability.

For the 100% reliable voter (*i. e.*, $R_{\text{V}} = 1$), Equation (7.1) becomes

$$R_{\text{tv}} = 3R^2 - 2R^3 \tag{7.2}$$

where

R_{tv} is the reliability of the TMR system with the perfect voter.

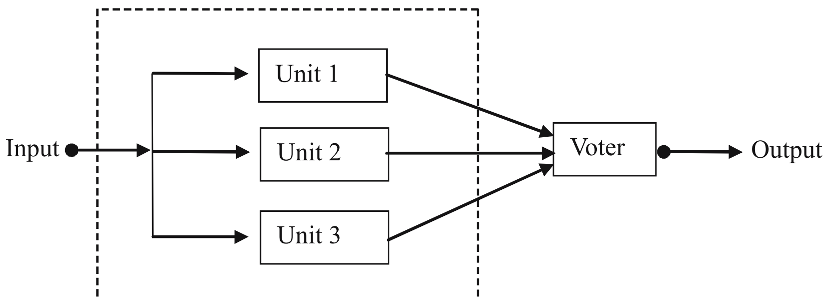

Figure 7.1. Block diagram representing the TMR scheme with voter

The voter reliability and the single unit's reliability determine the improvement in reliability of the TMR system over a single unit system. For the perfect voter (*i. e.*, $R_V = 1$), the TMR system reliability given by Equation (7.2) is only better than the single unit system when the reliability of the single unit is higher than 0.5.

At $R_V = 0.8$, the reliability of the TMR system is always less than the reliability of the single unit. Furthermore, when $R_V = 0.9$ the TMR system reliability is only marginally better than the single unit or module reliability when the single unit reliability is approximately between 0.667 and 0.833 [25].

- TMR System Maximum Reliability with Perfect Voter

For the perfect voter, the TMR system reliability is given by Equation (7.2). For this case, the ratio of R_{tv} to a single unit reliability, R, is given by [26]

$$\theta = \frac{R_{tv}}{R} = \frac{3R^2 - 2R^3}{R} = 3R - 2R^2 \tag{7.3}$$

Differetiating Equation (7.3) with respect to R and equating it to zero yields

$$\frac{\mathrm{d}\theta}{\mathrm{d}R} = 3 - 4R = 0 \tag{7.4}$$

By solving Equation (7.4), we get

$$R = 0.75$$

This simply means that the maximum reliability of the TMR system will occur at $R = 0.75$. Thus, inserting this value for R into Equation (7.2) yields

$$\begin{aligned} R_{tv} &= 3(0.75)^2 - 2(0.75)^3 \\ &= 0.8438 \end{aligned}$$

Thus, the maximum value of the TMR system reliability with the perfect voter is 0.8438.

Example 7.1

For a TMR system with a perfect voter, determine the points where the single unit and the TMR system reliabilities are equal.

In order to determine the points, we equate the single unit's reliability R with Equation (7.2) to get

$$R = R_{tv} = 3R^2 - 2R^3 \tag{7.5}$$

By rearranging Equation (7.5) we get

$$2R^2 - 3R + 1 = 0 \tag{7.6}$$

Obviously, Equation (7.6) is a quadratic equation and its roots are

$$R = \frac{3 + \left[9 - (4)(2)(1)\right]^{1/2}}{(2)(2)} = 1$$

and

$$R = \frac{3 - \left[9 - (4)(2)(1)\right]^{1/2}}{(2)(2)} = \frac{1}{2}$$

It means that the reliabilities of the TMR system and single unit are equal at $R = 1$, ½. The reliability of the TMR system will only be higher than the single unit reliability when the value of R is greater that 0.5.

- Mean Time to Failure of the TMR System

For constant failure rates of the TMR units and the voter, the TMR system with voter reliability using Equation (7.1) is given by [33]

$$\begin{aligned} R_{\mathrm{tv}}(t) &= \left[3\mathrm{e}^{-2\lambda t} - 2\mathrm{e}^{-3\lambda t}\right]\mathrm{e}^{-\lambda_{\mathrm{v}} t} \\ &= 3\mathrm{e}^{-(2\lambda+\lambda_{\mathrm{v}})t} - 2\mathrm{e}^{-(3\lambda+\lambda_{\mathrm{v}})t} \end{aligned} \tag{7.7}$$

where

$R_{\mathrm{tv}}(t)$ is the TMR system with voter reliability.
λ is the unit constant failure rate.
λ_{v} is the voter constant failure rate.

By integrating Equation (7.7) over the time interval from 0 to ∞, we obtain the following expression for the TMR system with voter mean time to failure [12]:

$$\begin{aligned} MTTF_{\mathrm{tv}} &= \int_0^{\infty} \left[3\mathrm{e}^{-(2\lambda+\lambda_{\mathrm{v}})t} - 2\mathrm{e}^{-(3\lambda+\lambda_{\mathrm{v}})t}\right]\mathrm{d}t \\ &= \frac{3}{(2\lambda+\lambda_{\mathrm{v}})} - \frac{2}{(3\lambda+\lambda_{\mathrm{v}})} \end{aligned} \tag{7.8}$$

where

$MTTF_{\mathrm{tv}}$ is the mean time to failure of the TMR system with voter.

For $\lambda_{\mathrm{v}} = 0$ or perfect voter, Equation (7.8) reduces to

$$\begin{aligned} MTTF_{\mathrm{t}} &= \frac{3}{2\lambda} - \frac{2}{3\lambda} \\ &= \frac{5}{6\lambda} \end{aligned} \tag{7.9}$$

where

$MTTF_{\mathrm{t}}$ is the TMR system with perfect voter mean time to failure.

Example 7.2
The constant failure rate of a unit belonging to a TMR system with voter is $\lambda = 0.0004$ failures per hour. Calculate the system reliability for a 500 hour mission if the voter constant failure rate is $\lambda_v = 0.00005$ failures per hour. In addition, calculate the system mean time to failure.

By using the specified data values in Equation (7.7), we get

$$\begin{aligned} R_{tv}(500) &= 3e^{-[(2)(0.0004)+0.00005](500)} - 2e^{-[(3)(0.0004)+0.00005](500)} \\ &= 0.8908 \end{aligned}$$

Similarly, inserting the given data values into Equation (7.8) yields

$$\begin{aligned} &= \frac{3}{[(2)(0.0004)+0.00005]} - \frac{2}{[(3)(0.0004)+0.00005]} \\ &= 1929.4 \text{ hours} \end{aligned}$$

Thus, the TMR system reliability and mean time to failure are 0.8908 and 1929.4 hours, respectively.

7.4.2 *N*-Modular Redundancy (NMR)

This is the general form of the TMR (*i. e.*, it contains N identical units instead of only three). The number N is any odd number, and the NMR system can tolerate a maximum of m unit/modular failures if the value of N is equal to $(2m+1)$.

For independently failing units and the voter, the reliability of the NMR system with voter is given by [12]:

$$R_{NV} = R_V \left[\sum_{j=0}^{m} \binom{N}{j} R^{N-j} (1-R)^j \right] \tag{7.10}$$

where

$$\binom{N}{j} \equiv \frac{N!}{(N-j)!\,j!}$$

R_{NV} is the NMR system with voter reliability.
R is the unit/module reliability.
R_V is the voter reliability.

There are many other redundancy schemes used in computers. Some of these are described in Ref. [12].

7.5 Computer System Life Cycle Costing

The life cycle costing concept is often used in the industrial sector, especially in the procurement of expensive items [27]. In regard to computers, the life cycle cost of a computer may simply be defined as the total of all costs to buyers (*i. e.*, the costs associated with procurement and ownership of the computer) over its entire life span. Some of the uses of the life cycle costing concept with regard to computer systems can be as follows [12]:

- To choose a manufacturer of a computer system out of many competing manufacturers
- To make effective decisions for computer system replacement
- To compare the costs of alternative approaches to meet a requirement

This section presents three mathematical models: one to estimate computer system life cycle cost, and the other two to estimate computer system ownership-related costs only.

Model I

Model I is concerned with estimating the computer system life cycle cost. The life cycle cost of a computer system is expressed by

$$LCC_{\mathrm{CS}} = CSPC + CSOC \tag{7.11}$$

where

LCC_{CS}	is the life cycle cost of a computer system.
$CSPC$	is the computer system procurement cost.
$CSOC$	is the computer system ownership cost.

Model II

Model II is concerned with estimating annual labour cost associated with servicing a computer system. Thus, the annual labour cost is expressed by

$$ASCC = (AH)(HLC)(\theta_1 + \theta_2) \tag{7.12}$$

where

$$\theta_1 = \frac{(MTTR + TT)}{MTBF} \tag{7.13}$$

$$\theta_2 = \frac{(ATPPM + TT_{\mathrm{pm}})}{ATBPM} \tag{7.14}$$

The symbols used in Equations (7.12)–(7.14) are defined below.

$ASCC$	is the annual labour cost associated with servicing a computer system.
AH	is the number of hours in one year (*i. e.*, 8,760 hours).
HLC	is the hourly labour cost.
$MTTR$	is the mean time to repair of the computer system.
TT	is the travel time associated with a repair call.
$MTBF$	is the mean time between failures of the computer system.
$ATPPM$	is the average time to perform preventive maintenance.
TT_{pm}	is the travel time associated with a preventive maintenance call.
$ATBPM$	is the average time between preventive maintenance.

Model III

Model III is concerned with estimating the monthly maintenance cost of computer system hardware. Thus, the computer system hardware monthly maintenance cost is expressed by [28]:

$$CSHMC = PMC + CMC + IC \tag{7.15}$$

where

CSHMC is the computer system hardware maintenance cost per month.
PMC is the preventive maintenance cost per month.
IC is the cost of inventory per month.
CMC is the corrective maintenance cost per month.

The costs *PMC*, *CMC*, and *IC* are defined as follows:

$$PMC = \frac{(OH)(HR)\left[CETPM + TTCEPM\right]}{SPMI} \tag{7.16}$$

$$CMC = \frac{(OH)(HR)\left[MTTR + TTCECM\right]}{MTBF} \tag{7.17}$$

$$IC = (ICR)(MSPOMC) \tag{7.18}$$

where

OH is the equipment operating hours per month.
HR is the hourly rate of the customer engineer.
CETPM is the customer engineer's scheduled time for performing preventive maintenance.
TTCEPM is the travel time of the customer engineer for performing preventive maintenance.
SPMI is the scheduled preventive maintenance interval.
MTTR is the mean time to repair.
TTCECM is the customer engineer's travel time for corrective maintenance.
MTBF is the mean time between failures.
ICR is the monthly inventory cost rate (This includes monthly handling costs and spares' depreciative charges).
MSPOMC is the maintenance spare parts original manufacturing cost (*i. e.*, inventory value).

The customer engineer's hourly rate is given by

$$HR = PHC + \left[CEHP\left(1+i\right)\right]/\alpha \tag{7.19}$$

where

PHC is the parts' hourly cost.
i is the overhead rate.
CEHP is the customer engineer's hourly pay.
α is the fraction of the total time customer engineer spends for the maintenance purpose.

7.6 Software Reliability Evaluation Models

Over the years many mathematical models to evaluate software reliability have been developed [5, 29, 30]. This section presents two such models.

7.6.1 Mills Model

This model was developed by H.D. Mills in 1972 by arguing that the faults remaining in a given software program can be estimated through a seeding process that makes an assumption of a homogeneous distribution of a representative class of faults [31]. Thus, both seeded and unseeded faults are identified during reviews or testing and the discovery of seeded and unseeded faults permits an assessment of remaining faults for the fault type in question.

The maximum likelihood of the unseeded faults is defined by [25]

$$M_{\mathrm{u}} = [M_{\mathrm{s}} n_{\mathrm{u}}]/n_{\mathrm{s}} \tag{7.20}$$

where

M_{u} is the maximum likelihood of the unseeded faults.
M_{s} is the total number of seeded faults.
n_{u} is the total number of unseeded faults uncovered.
n_{s} is the total number of seeded faults found.

Thus, the number of unseeded faults still remaining in a program under consideration is

$$M = M_{\mathrm{u}} - n_{\mathrm{u}} \tag{7.21}$$

Example 7.3
A software program was seeded with a total of 20 faults and, during testing, 45 faults of the same kind were discovered. Fifteen of these faults were the seeded faults and the remaining thirty unseeded faults.

Estimate the number of unseeded faults still remaining in the program.

By substituting the specified data values into Equation (7.20), we get

$$M_{\mathrm{u}} = \frac{(20)(30)}{15} = 40 \text{ faults}$$

Using the above calculated value and the other given data value in Equation (7.21) yields

$$M = 40 - 30 = 10 \text{ faults}$$

It means ten unseeded faults still remain in the program.

7.6.2 Musa Model

This model is based on the premise that reliability assessments in the time domain can only be based upon actual or real execution time, as opposed to elapsed or calendar time, because only during execution a software program really becomes exposed to failure-provoking stress. Some of the important assumptions pertaining to this model are as follows [12, 23, 32]:

- Failure intervals follow a Poisson distribution and are statistically independent.
- Failure rate is proportional to the remaining defects.
- Execution times between failures are piecewise exponentially distributed.

A comprehensive list of assumptions is available in Ref. [12]. The net number of corrected faults is expressed by [23, 32]:

$$n = N\left[1 - \exp\left(-\alpha t / N T_{\mathrm{m}}\right)\right] \tag{7.22}$$

where

n is the net number of corrected software faults.
t is time.
α is the testing compression factor and is defined as the average ratio of detection rate of failures during test to the rate during normal application of the software program.
T_{m} is the mean time to failure at the start of the test.
N is the number of initial faults.

Mean time to failure, T, increases exponentially with execution time and is defined by

$$T = T_{\mathrm{m}} \exp\left(\alpha t / N T_{\mathrm{m}}\right) \tag{7.23}$$

Thus, the reliability at operational time t is expressed by

$$R(t) = \exp\left(-t / T\right) \tag{7.24}$$

From the above relationships, the number of failures that must occur to increase mean time to failure from, say, T_{a} to T_{b} [33]:

$$\Delta n = N T_{\mathrm{m}} \left[\frac{1}{T_{\mathrm{a}}} - \frac{1}{T_{\mathrm{b}}}\right] \tag{7.25}$$

The additional execution time needed to experience Δn is expressed by

$$\Delta n = \left[\frac{N T_{\mathrm{m}}}{\alpha}\right] \ln\left(\frac{T_{\mathrm{b}}}{T_{\mathrm{a}}}\right) \tag{7.26}$$

Example 7.4

Assume that a software program is estimated to have around 500 errors, and at the start of the testing process the recorded mean time to failure is 5 hours.

Estimate the test time required to reduce the remaining errors to 20, if the value of the testing compression factor is 6. Calculate reliability over a 50-hour operational period.

Using the given data values in Equation (7.25) yields

$$(500-20) = (500)(5)\left[\frac{1}{5} - \frac{1}{T_b}\right] \tag{7.27}$$

By rearranging Equation (7.27) we get

$$T_b = 125 \text{ hours}$$

By substituting the above calculated value and the other given data values into Equation (7.26), we get

$$\Delta t = \left[\frac{(500)(5)}{6}\right]\ln\left(\frac{125}{5}\right)$$
$$= 1{,}341.2 \text{ hours}$$

Similarly, using the calculated and given data values in Equation (7.24) yields

$$R(50) = \exp\left(-\frac{50}{125}\right)$$
$$= 0.6703$$

Thus, the test time required to reduce errors to 20 is 1,341.2 hours and the software reliability for the given operational period is 0.6703.

7.7 Internet Reliability, Failure Examples, Outage Categories, and Related Observations

The demand for Internet reliability continues to escalate as the Internet evolves to support various applications including telephony and banking [34]. However, various studies conducted over the past decade indicate that the reliability of Internet paths falls far short of the 99.999% availability expected in the public-switched telephone network (PSTN) [35]. Furthermore, small-scale studies conducted in 1994 and 2000 revealed that the probability of encountering a major routing pathology along a path is approximately 1.5% to 3.3% [34, 36]. Over the years various means have been used to improve Internet reliability, including server replication, multi-homing, and overlay networks [34].

Some examples of the Internet failures are as follows [37]:

- On August 14, 1998, a misconfigured important Internet database server mistakenly referred all queries for Internet machines with names ending in ".net" to the incorrect secondary database server. As the result of this problem, most of connections to ".net" Internet Web servers and other end stations failed for many hours [38].
- On April 25, 1997, a misconfigured router of a Virginia service provider injected a wrong map into the global Internet. In turn, the Internet providers that accepted this incorrect map automatically diverted their concerned traffic to the Virginia provider. This resulted in network congestion, instability, and overload of Internet router table memory that ultimately shut down most of the major Internet backbones for up to two hours [39].
- On November 8, 1998, a malformed routing control message caused by a software fault triggered an interoperability problem between various core Internet backbone routers produced by different vendors. This resulted in a wide-spread loss of network connectivity (*i. e.*, experienced by the Internet end-users) as well as increment in packet loss and latency. All in all, it took several hours for majority of backbone providers to resolve this outage effectively [40].

A case study conducted over a period of one year (*i. e.*, November 1997 to November 1998) concerning Internet outages classified the outages into many categories (along with their occurrence percentages in parentheses) as follows [37]:

- Maintenance (16.2%)
- Power outage (16%)
- Fiber cut/circuit/carrier problem (15.3%)
- Unreachable (12.6%)
- Hardware problem (9%)
- Interface down (6.2%)
- Routing problem (6.1%)
- Miscellaneous (5.9%)
- Unknown/undetermined/no problem (5.6%)
- Congestion/sluggish (4.6%)
- Malicious attacks (1.5%)
- Software problem (1.3%)

As per the findings of one study, some of the Internet reliability-related observations are as follows [37]:

- Availability and mean time to failure of the Internet backbone infrastructure are significantly less than the Public Switched Telephone Network (PSTN).
- There is only a small fraction of network paths in the Internet infrastructure that contribute disproportionately to the number of long-term outages and backbone unavailability.

- The most of Internet backbone paths exhibit a mean time to failure of about 25 days or les and a mean time to repair of around twenty minutes or less.
- It appears that most inter-provider path failures result from congestion collapse.

7.8 An Approach for Automating Fault Detection in Internet Services

As most Internet services (*e. g.*, search engines and e-commerce) suffer faults, a quick detection of these faults could be an important factor in improving the availability of the system. This approach known as the pinpoint method combines the easy deploy-ability of low-level monitors with the higher-level monitors' ability for detecting application-level faults [41]. This method is based upon the following assumptions with respect to the system under observation and its workload [41]:

- The software is made up of various interconnected components (modules) with well-defined narrow interfaces. These could be software subsystems, objects, or simply physical mode boundaries.
- There is a high volume of basically independent requests (*i. e.*, from different users).
- An interaction with the system is relatively short-lived, whose processing can be broken down as a path. More specifically, a tree of the names of elements or components that take part in the servicing of that request.

The pinpoint approach to detecting and localizing anomalies is basically a three stage process [41]:

- **Observing the system.** This is concerned with capturing the runtime path of each request served by the system and then from these paths extracting two specific low-level behaviours likely to reflect high-level functionality: path shapes and interactions of components.
- **Learning the patterns in system behaviour.** This is concerned with constructing a reference model representing the normal behaviour of an application in regard to path shapes and component interactions, by assuming that most of the system functions correctly most of the time.
- **Detecting anomalies in system behaviours.** This is concerned with analyzing the system's current behaviour and detecting anomalies with respect to the reference model.

The pinpoint approach is described in detail in Ref. [41].

7.9 Internet Reliability Models

There are many mathematical models that can be used to perform reliability-related analysis in various areas of Internet [42–45]. This section presents two of these models.

7.9.1 Model I

Model I is concerned with evaluating the reliability and availability of a server system. The model assumes that the Internet server system can either be in an operating or a failed state and its failure/outage and restoration/repair rates are constant. The server system state space diagram is shown in Figure 7.2. The numerals in boxes denote the system state.

Using the Markov method, we write down the following two differential equations for Figure 7.2 state space diagram [23]:

$$\frac{dP_0(t)}{dt} + \lambda_s P_0(t) = \mu_s P_1(t) \tag{7.28}$$

$$\frac{dP_1(t)}{dt} + \mu_s P_1(t) = \lambda_s P_0(t) \tag{7.29}$$

At time $t=0$, $P_0(0)=1$ and $P_1(0)=0$.

The symbols used in Equations (7.28) and (7.29) are defined below.

$P_i(t)$ is the probability that the server system is in state i at time t, for $i=0, 1$.
λ_s is the server system constant failure/outage rate.
μ_s is the server system constant repair/restoration rate.

Solving Equations (7.28) and (7.29), we get [23]

$$P_0(t) = A_s(t) = \frac{\mu_s}{(\lambda_s + \mu_s)} + \frac{\lambda_s}{(\lambda_s + \mu_s)} e^{-(\lambda_s+\mu_s)t} \tag{7.30}$$

$$P_1(t) = UA_s(t) = \frac{\lambda_s}{(\lambda_s + \mu_s)} - \frac{\lambda_s}{(\lambda_s + \mu_s)} e^{-(\lambda_s+\mu_s)t} \tag{7.31}$$

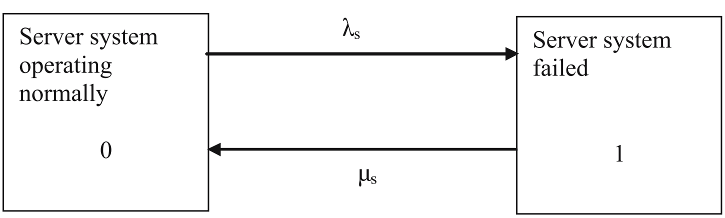

Figure 7.2. Server system transition diagram

where

$A_s(t)$ is the server system availability at time t.

$UA_s(t)$ is the server system unavailability at time t.

As time t becomes very large, Equations (7.30) and (7.31) reduce to

$$A_s = \frac{\mu_s}{\lambda_s + \mu_s} \tag{7.32}$$

and

$$UA_s = \frac{\lambda_s}{\lambda_s + \mu_s} \tag{7.33}$$

where

A_s is the server system steady state availability.

UA_s is the server system steady state unavailability.

For $\mu_s = 0$, Equation (7.30) reduces to

$$R_s(t) = e^{-\lambda_s t} \tag{7.34}$$

where

$R_s(t)$ is the server system reliability at time t.

Thus, the server system mean time to failure ($MTTF_s$) is given by [23]

$$\begin{aligned} MTTF_s &= \int_0^\infty R_s(t)\,dt \\ &= \int_0^\infty e^{-\lambda_s t}\,dt \\ &= \frac{1}{\lambda_s} \end{aligned} \tag{7.35}$$

Example 7.5

Assume that the constant outage and restoration rates of an Internet server system are 0.0045 outages/hour and 0.05 restorations/hour, respectively. Calculate the server system steady state availability.

By substituting the given data values into Equation (7.32) we get

$$\begin{aligned} A_s &= \frac{0.05}{0.0045 + 0.05} \\ &= 0.9174 \end{aligned}$$

Thus, the steady state availability of the server system is 0.9174.

7.9.2 Model II

Model II is concerned with evaluating the availability of an Internetworking (router) system composed of two independent and identical switches. The model assumes that the system fails when both the switches fails and the switches form a standby-type configuration. In addition, the switch failure and restoration rates are constant. The system state space diagram is shown in Figure 7.3. The numerals in circles denote the system state.

Using the Markov method, we write down the following differential equations for Figure 7.3 diagram [23, 46]:

$$\frac{dP_0(t)}{dt} + \left[p\lambda_{sw} + (1-p)\lambda_{sw} \right] P_0(t) = \mu_{sw} P_1(t) + \mu_{sw1} P_2(t) \tag{7.36}$$

$$\frac{dP_1(t)}{dt} + \left(\lambda_{sw} + \mu_{sw} \right) P_1(t) = p\lambda_{sw} P_0(t) \tag{7.37}$$

$$\frac{dP_2(t)}{dt} + \mu_{sw1} P_2(t) = \lambda_{sw} P_1(t) + (1-p)\lambda_{sw} P_0(t) \tag{7.38}$$

At time $t = 0$, $P_0(0) = 1$ and $P_1(0) = P_2(0) = 0$.

The symbols used in Equations (7.36)–(7.38) are defined below.

$P_i(t)$ is the probability that the Internetworking (router) system is in state i at time t, for $i = 0, 1, 2$.

λ_{sw} is the switch constant failure rate.

p is the failure detection and successful switchover probability from switch failure.

μ_{sw} is the switch constant repair/restoration rate.

μ_{sw1} is the constant restoration/repair rate from system state 2 to state 0.

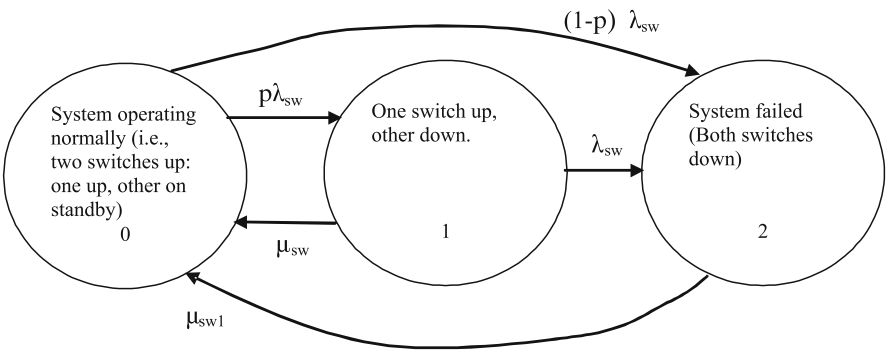

Figure 7.3. System transition diagram

The following steady-state probability solutions are obtained by setting derivatives equal to zero in Equations (7.36)–(7.38) and using the relationship $\sum_{i=0}^{2} P_i = 1$.

$$P_0 = \frac{\mu_{\mathrm{sw1}}(\mu_{\mathrm{sw}} + \lambda_{\mathrm{sw}})}{A} \tag{7.39}$$

$$P_1 = \frac{p\lambda_{\mathrm{sw}}\,\mu_{\mathrm{sw1}}}{A} \tag{7.40}$$

$$P_2 = \frac{p\lambda_{\mathrm{sw}}^2 + (1-p)\lambda_{\mathrm{sw}}(\mu_{\mathrm{sw}} + \lambda_{\mathrm{sw}})}{A} \tag{7.41}$$

where

$$A \equiv \mu_{\mathrm{sw1}}\left(\mu_{\mathrm{sw}} + p\lambda_{\mathrm{sw}} + \lambda_{\mathrm{sw}}\right) + (1-p)\lambda_{\mathrm{sw}}\left(\mu_{\mathrm{sw}} + \lambda_{\mathrm{sw}}\right) + p\lambda_{\mathrm{sw}}^2 \tag{7.42}$$

P_i is the steady state probability that the Internetworking (Router) system is in state i, for $i = 0, 1, 2$.

The system steady state availability is given by

$$\begin{aligned} A_{\mathrm{s}} &= P_0 + P_1 \\ &= \frac{\mu_{\mathrm{sw1}}\left(\mu_{\mathrm{sw}} + \lambda_{\mathrm{sw}} + p\lambda_{\mathrm{sw}}\right)}{A} \end{aligned} \tag{7.43}$$

7.10 Problems

1. Write an essay on developments in computer hardware and software reliability.
2. What are the main causes for computer system failures?
3. Make a comparison between hardware and software reliability.
4. What is fault masking?
5. Assume that the constant failure rate of a unit belonging to a TMR system with voter is $\lambda = 0.0005$ failures per hour. Calculate the system reliability for a 400 hour mission if the voter constant failure rate is $\lambda_V = 0.00001$ failures per hour. In addition, calculate the system mean time to failure.
6. A software program was seeded with 25 faults and, during testing, 50 faults of the same type were found. Twenty of these faults were the seeded faults and the remaining thirty unseeded faults. Calculate the number of unseeded faults still remaining in the program.
7. Compare the Musa model with the Mills model.
8. Discuss Internet failures and their consequences.
9. Describe a method for automating fault detection in Internet services.
10. Prove Equations (7.39)–(7.41).

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8

Quality in Health Care

8.1 Introduction

Each year billions of dollars are being spent on health care worldwide. For example, in 1992 the United States spent $840 billion on health care, or 14% of its gross domestic product (GDP) [1]. Furthermore, since 1960 the health care spending in the United States has increased from 5.3% of the gross national product (GNP) to 13% in 1991 [2].

The history of quality in health care may be traced back to the 1860s, when Florence Nightingale (1820–1910), a British nurse, helped to lay the foundation for the health care quality assurance programs, by advocating the need for a uniform system for the collection and evaluation of hospital-related statistics [1]. Her analysis of the data collected showed that mortality rates varied quite significantly from one hospital to another.

In 1914, in the Untied States E.A. Codman (1869–1940) studied the results of health care with respect to quality, and emphasized the issues, when examining the quality of care, such as the accreditation of institutions, the importance of licensure or certification of providers, the need for taking into consideration the severity or stage of the disease, the economic barriers to receiving care, and the health and illness behaviours of the patients [1, 3].

Over the years, many other people have contributed to the field of quality in health care. An extensive list of publications on the topic is presented at the end of this book. This chapter presents various important aspects of quality in health care.

8.2 Health Care Quality Terms and Definitions and Reasons for the Rising Health Care Cost

Some of the commonly used terms and definitions in health care quality are as follows [4, 5]:

- **Health care.** This is services provided to individuals or communities for promoting, maintaining, monitoring, or restoring health.
- **Quality.** This is the extent to which the properties of a product or service generate/produce a desired outcome.
- **Quality assurance.** This is the measurement of the degree of care given (assessment) and, when appropriate, mechanisms for improving it.
- **Total quality management.** This is a philosophy of pursuing continuous improvement in each and every process through the integrated efforts of all concerned individuals associated with the organization.
- **Quality of care.** This is the level to which delivered health services satisfy established professional standards and judgements of value to consumers.
- **Quality improvement.** This is the total of all the appropriate activities that create a desired change in quality.
- **Clinical audit.** This is the process of reviewing the delivery of care against established standards to identify and remedy all deficiencies through a process of continuous quality improvement.
- **Cost of quality.** This is the expense of not doing effectively all the right things right the first time.
- **Quality assessment.** This is the measurement of the degree of quality at some point in time, without any effort for improving or changing the degree of care.
- **Dimensions of quality.** These are the measures of health system performance, including measures of effectiveness, appropriateness, efficiency, safety, continuity, accessibility, capability, sustainability, and responsiveness.
- **Adverse event.** This is an incident in which unintended harm resulted to an individual receiving health care.

There are many reasons for the rising health care cost. Some of these are shown in Figure 8.1 [6]. Each of these reasons is discussed in detail in Refs. [2, 6].

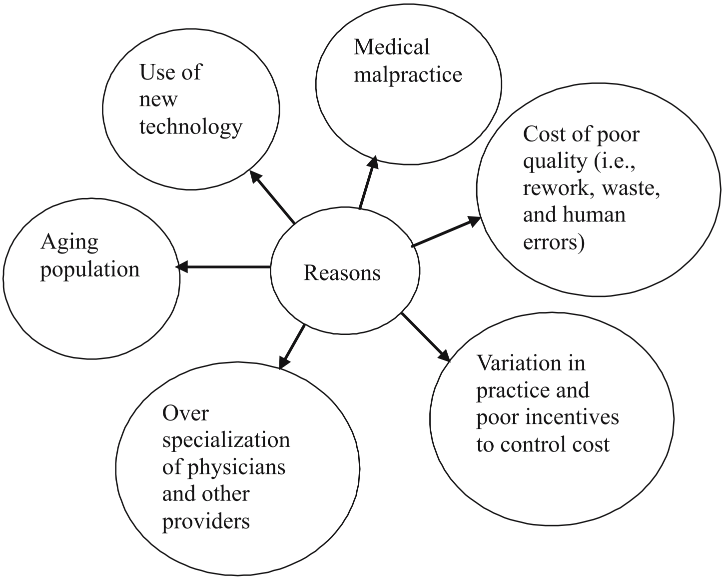

Figure 8.1. Some of the main reasons for the escalating health care cost

8.3 Comparisons of Traditional Quality Assurance and Total Quality Management with Respect to Health Care and Quality Assurance Versus Quality Improvement in Health Care Institutions

A comparison of traditional quality assurance and total quality management, directly or indirectly, with respect to many different areas of health care is presented in Table 8.1 [2].

Over years various authors have discussed the differences between quality assurance and quality improvement in health care institutions [7−11]. A clear understanding of these differences is important, as they contribute to differing information needs. Most of these differences are presented in Table 8.2 [7−11].

Table 8.1. Comprisons of traditional quality assurance and total quality management with respect to health care

No.	Area (characteristic)	Traditional quality assurance	Total quality management
1	Purpose	Enhance quality of patient care for patients	Enhance all products and services quality for patients and other customers
2	Aim	Problem solving	Continuous improvement, even when no deficiency/ problem is identified
3	Leadership	Physician and clinical leaders (*i. e.*, clinical staff chief and quality assurance committee)	All leaders (*i. e.*, clinical and non-clinical)
4	Customer	Customers are review organizations and professionals with focus on patients	Customers are review organizations, patients, professionals, and others
5	Scope	Clinical processes and outcomes	All processes and systems (*i. e.*, clinical and non-clinical)
6	Focus	Peer review vertically focused by clinical process or department (*i. e.*, each department looks after its own quality assurance)	Horizontally focused peer review for improving all processes and individuals that affect outcomes
7	People involved	Appointed committees and quality assurance program	Each and every person involved with process
8	Methods	Includes hypothesis testing, chart audits, indicator monitoring, and nominal group techniques	Includes checklist, force field analysis, Pareto chart, indicator monitoring and data use, Hoshin planning, brainstorming, flowcharts, nominal group techniques, quality function deployment, control chart, fishbone diagram, etc.
9	Outcomes	Includes measurement and monitoring	Includes also measurement and monitoring

Table 8.2. Comparisons of quality assurance and quality improvement in health care institutions

No.	Area (characteristic)	Quality improvement	Quality assurance
1	Goal	Satisfy customer requirements	Regulatory compliance
2	Participants	Every associated person	Peers
3	Viewpoint	Proactive	Reactive
4	Focus	All involved processes	Physician
5	Review technique	Analysis	Summary
6	Customers	Patients, caregivers, payers, technicians, enrollees, support staff, managers, etc.	Regulators
7	Performance measure	Need/capability	External standards
8	Direction	Decentralized through the management line of authority	Committee or central coordinator
9	Functions involved	Many (clinician and support system)	Few (mainly doctors)
10	Action taken	Implement appropriate improvements	Recommend appropriate improvements
11	Defects studied	Special and common causes	Outliers special causes

8.4 Assumptions Guiding the Development of Quality Strategies in Health Care, Health Care-related Quality Goals and Strategies, Steps for Quality Improvement, and Physician Reactions to Total Quality

A clear understanding of the assumptions guiding the development of quality strategies in health care is necessary for the ultimate success of these strategies. Some of these assumptions are [1]:

- Total quality management is an important unifying leadership philosophy that encompasses all functions of a health care organization, not just the quality assurance function and clinical care.
- The measurement of quality care must include items such as the determination of patient outcomes, patient feedback and involvement, cost effectiveness, assurance of appropriateness of care, review of key internal processes, and proper coordination of care across a continuum of services and providers.
- Total quality management (TQM) is a good means of furthering the organizational culture and mission. More specifically, this basically means that quality results from continuously improving care and work processes, patients and others served are the highest priority and should have a rather strong voice in the

design and delivery of care, quality must flow from leadership and permeate all levels of the organization, decisions should be based on facts, but reflect compassion and caring, and processes are improved by teamwork and involvement.

- The system will be increasingly responsible for delivering the quality of care to all enrolled people on a regional basis.
- Quality improvement definitely needs timely access to reliable clinical data and an effective capability for analyzing and interpreting clinical pathways.

Four important health care-related quality goals are shown in Figure 8.2 [1]. Three useful strategies associated with Goal I are as follows [1]:

- Aim to maximize patients' and families' involvement in the care experience by using shared decision making and improving patient involvement in care choices.
- Ensure, in an effective manner, the assessment of employee, patient, and medical staff satisfaction periodically by incorporating survey standards and benchmarking.
- Implement recommendations concerning compassionate care of dying and carefully address the spiritual needs of patients and families through pastoral care.

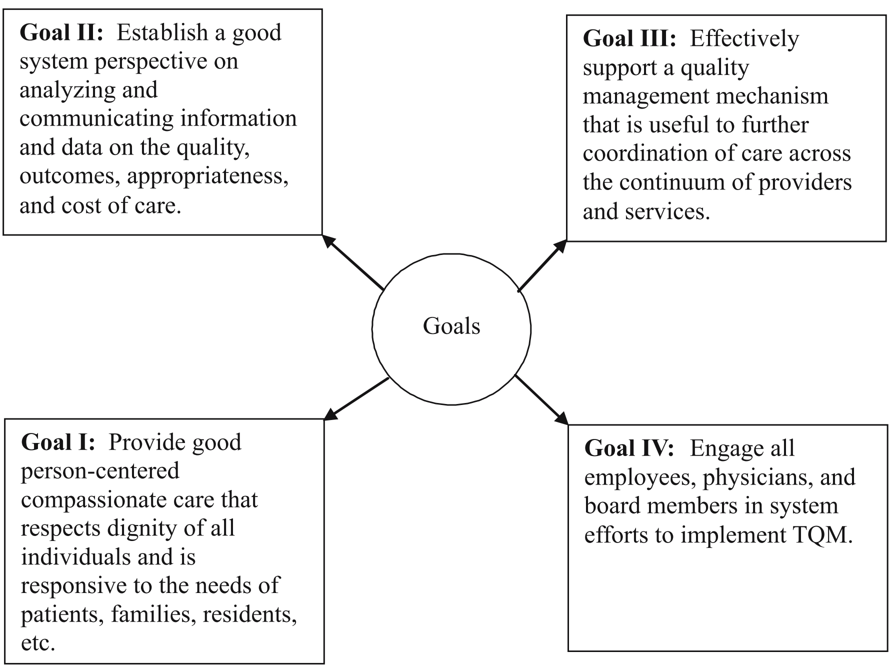

Figure 8.2. Health care-related quality goals

Three strategies pertaining to Goal II are as follows [1]:

- Establish a system plan for addressing information needs concerning quality management, including a pivotal clinical data set, common definitions, and enhanced analysis of available information.
- Document and share critical quality performance and outcome studies throughout the system and assess the implications of new developments in the evolution of electronic medical records.
- Further develop the competencies and skills of individuals associated with quality through user conferences and other appropriate means.

Two of the strategies concerning Goal III are as follows [1]:

- Develop further and apply case management models across the continuum of services.
- Determine the ways the development of integrated delivery systems can help to promote access and quality of care.

Three strategies associated with Goal IV are as follows [1]:

- Actively involve physicians when developing treatment protocols and improving care systems.
- Develop appropriate programs on TQM for people such as physicians, board members, and employees.
- Establish and apply appropriate management models that help to promote effective teamwork and participatory decision making.

Figure 8.3. presents ten steps that can be used in improving quality in the health care system [12].

There have been varying reactions to TQM by physicians over the years. Some of the typical ones are as follows [2]:

- TQM basically is quality assurance in different clothing.
- Physicians have always used the scientific method; thus the scientific method advocated by TQM is nothing new.
- The TQM concept is applicable to administrative systems and industrial processes, but not to the clinical care of patients.
- The application of the TQM concept will wrest control of the patient care process from physicians.
- The TQM concept is another cost-cutting mechanism by management that will limit access to resources physicians require for their patients.
- The application of the TQM concept is a further encroachment on the physician-patient relationships, as patient care cannot be standardized like industrial processes.
- The application of the TQM concept will lead to additional committee meetings for time-constrained physicians.

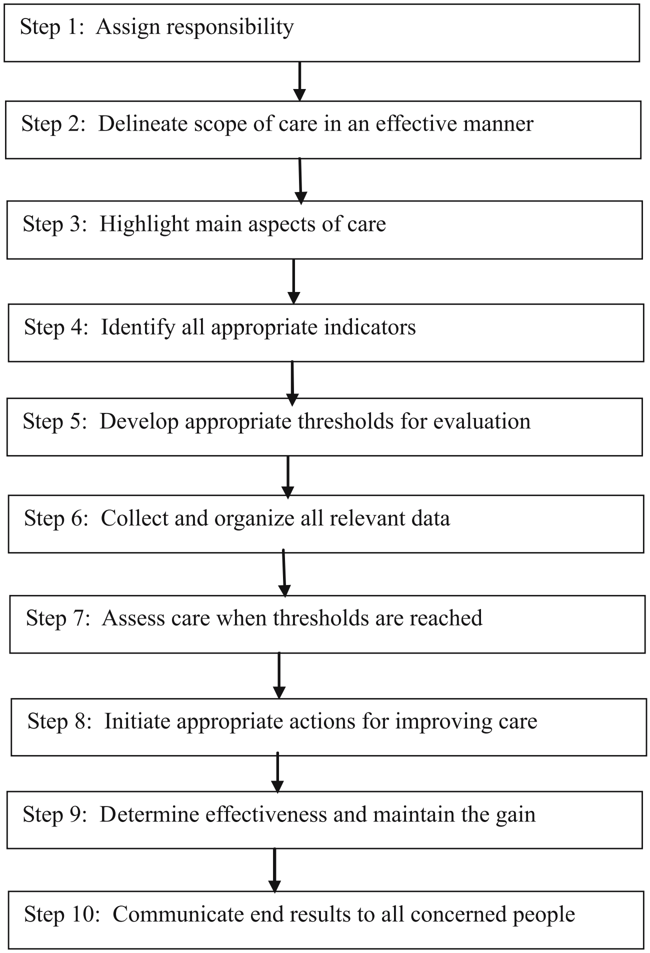

Figure 8.3. Steps for improving quality in health care

8.5 Quality Tools for Use in Health Care

There are many methods that can be used to improve quality in health care. Most of these methods are listed in Table 8.3 [5, 12]. The first five of these methods are described below (information on others can be found in Chapters 3 and 11, or in Refs. [5, 12, 13]).

Table 8.3. Methods for improving quality in health care

No.	Method
1	Brainstorming
2	Cost-benefit analysis
3	Multivoting
4	Force field analysis
5	Check sheets
6	Cause and effect diagram
7	Scatter diagram
8	Pareto chart
9	Histogram
10	Control chart
11	Process flowchart
12	Affinity diagram
13	Prioritization matrix
14	Proposed options matrix

8.5.1 Group Brainstorming

The objective of brainstorming in health care quality is to generate ideas, options or identify problems, concerns. It is often referred to as a form of divergent thinking because the basic purpose is to enlarge the number of ideas being considered. Thus, brainstorming may simply be described as a group decision-making approach designed to generate many creative ideas by following an interactive process. The team concerned with health care quality can make use of brainstorming to get its ideas organized into a quality method such as a cause and effect diagram or a process flow diagram.

Past experiences indicate that questions such as listed below can be quite useful to start a brainstorming session concerned with health care quality [12].

- What are the major obstacles to improving quality?
- What are the health care organization's three most pressing unsolved quality problems?
- What type of action plan is required to overcome these problems?
- What are the most pressing areas that require such action plan?

Some of the useful guidelines for conducting effective brainstorming sessions are shown in Figure 8.4 [14, 15].

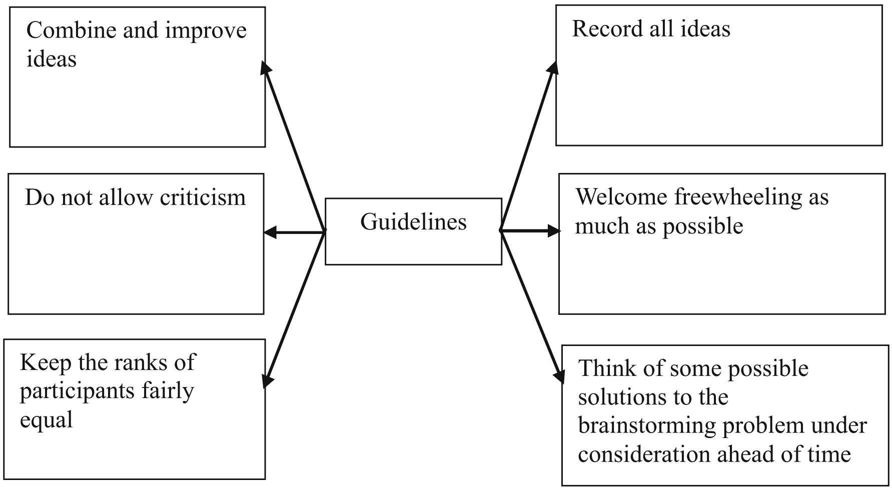

Figure 8.4. Useful guidelines for conducting effective brainstorming sessions

8.5.2 Cost–Benefit Analysis

Cost–benefit analysis may simply be described as a weighing-scale approach to decision-making, where all plusses (*i. e.*, cash flows and other intangible benefits) are grouped and put on one side of the balance and all the minuses (*i. e.*, costs and drawbacks) are grouped and put on the other. At the end the heavier side wins.

The main purpose of the application of the cost–benefit analysis method in the health care quality area is that the quality team members consider the total impact of their recommended actions. Additional information on this method is available in Refs. [2, 16−17].

8.5.3 Multivoting

This is useful method for reducing a large number of ideas to a manageable few judged important by the participating individuals. Usually by following this approach, the number of ideas is reduced to three to five [2]. Another thing that can be said about multivoting is that it is a form of convergent thinking because the objective is to reduce the number of ideas being considered. Needless to say, multivoting is considered to be a useful tool for application in the health care quality area, and additional information on the method is available in Ref. [18].

8.5.4 Force Field Analysis

This method was developed by Kurt Lewin for identifying the forces that are related to a certain issue under consideration [13, 19]. The method is also known as barriers and aids analysis [2]. In this approach, the issue/problem statement is written at the top of a sheet and two columns are created below it for writing negative forces on one side and the positive on the other.

Subsequently, these forces are ranked and appropriate ways and means to mitigate the negative forces and accentuate the positive forces are explored. Additional, information on the method is available in Refs. [2, 13, 19].

8.5.5 Check Sheets

Check sheets are basically used for collecting data on occurrence frequency of specified events. A check sheet, for example, can be utilized in determining the occurrence frequency of, say, four to six problems highlighted during multivoting [2]. In the quality areas, check sheets are usually used in a quality improvement process for collecting frequency-related data later displayed in a Pareto diagram.

Although there is no standard design of check sheets, the basic idea is to document all types of important information relative to nonconformities and nonconforming items, so that the sheets can facilitate improvement in the process. Additional information on check sheets is available in Refs. [20–22].

8.6 Implementation of Six Sigma Methodology in Hospitals and Its Potential Advantages and Implementation Barriers

The history of Six Sigma as a measurement standard may be traced back to Carl Frederick Gauss (1777−1855), the father of the concept of the normal curve. In the 1980s Motorola explored this standard and created the methodology and necessary cultural change associated with it.

Six Sigma may simply be described as a methodology implementation directed at a measurement-based strategy that develops process improvements and varied cost reductions throughout an organizational set up. In many organizations, Six Sigma simply means a measure of quality that strives for near perfection.

Over the past few years, a number of health care organizations have also started to apply the Six Sigma methodology into their operations. A total of nine steps, as shown in Figure 8.5, are involved in the implementation of define, measure, analyze, improve, control (DMAIC) Six Sigma methodology in an industrial organization [23]. These steps can be tailored accordingly for the implementation of the methodology in hospitals.

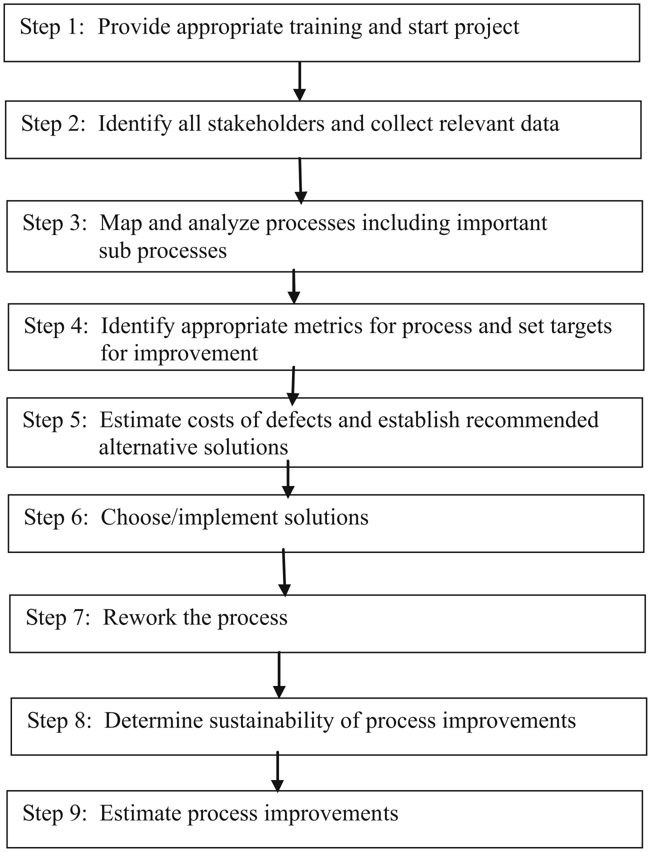

Figure 8.5. Steps involved in the implementation of DMAIC Six Sigma methodology

Some of the important potential advantages of implementation of Six Sigma methodology in hospitals are as follows [23]:

- Measurement of essential health care performance requirements on the basis of commonly used standards.
- Establishment of shared accountability with respect to continuous quality improvement.
- The implementation of the methodology with emphasis on improving customers' lives, could result in the involvement of more health care professionals and support personnel in the quality improvement effort.
- Better job satisfaction of health care employees.

There are many potential barriers to the implementation of Six Sigma programs in hospitals. Some of these are shown in Figure 8.6 [23].

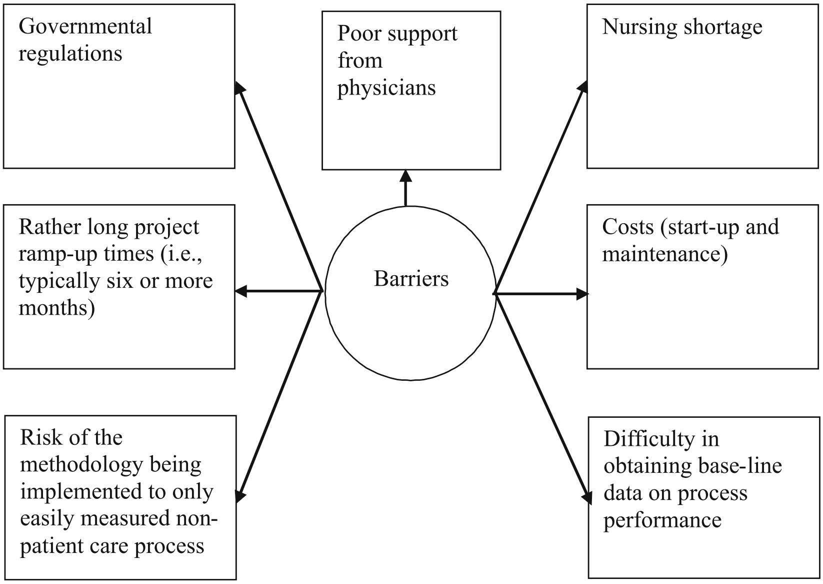

Figure 8.6. Potential barriers to the implementation of Six Sigma methodology in hospitals

8.7 Problems

1. Write a short essay on the historical developments in quality in health care.
2. Define the following three terms:
   - Quality of care
   - Health care
   - Clinical audit
3. What are the main reasons for rising health care costs?
4. Compare traditional quality assurance and total quality management with respect to health care.
5. Discuss health care-related quality goals.
6. Discuss physician reactions to total quality management.
7. List at least ten quality tools useful for application in the health care sector.
8. Discuss the implementation of Six Sigma methodology in hospitals and its benefits.
9. What are the ten useful steps for improving quality in health care.
10. Discuss the following three methods considered useful for improving quality in health care:
    - Force field analysis
    - Multivoting
    - Group brainstorming

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9

Software Quality

9.1 Introduction

Today computers are widely used for applications ranging from-day-to day personal use to control of space systems. As the computers are made up of both hardware and software elements, the proportion of the total computer cost spent on software has changed quite dramatically over the years. For example, in 1955 the software component (*i. e.*, including software maintenance) accounted for 20% of the total computer cost and 30 years later, in 1985, this percentage has increased to 90% [1]. Needless to say, the introduction of computers into products in the late 1970s has led to the software quality assurance for all types of software [2].

Furthermore, it can be added that no product is of greater quality than the quality of its elements, and if one of the elements is a computer, then the quality of software or program controlling that computer will certainly affect the quality of the product. The prime objective of a quality assurance program is to assure that the end software products are of good quality, through properly planned and systematic activities or actions to achieve, maintain, and determine that quality [3–4]. This chapter presents various different important aspects of software quality.

9.2 Software Quality Terms and Definitions

There are many terms and definitions used in the software quality area. Some of the commonly used terms and definitions are as follows [2, 5–7]:

- **Software quality.** This is the fitness for use of the software item/product.
- **Software quality control.** This is the independent evaluation of the capability of the software process to produce a usable software product/item.

- **Software quality assurance.** This is the set of systematic activities or actions providing evidence of software process's capability to produce a software product/item that is fit to use.
- **Software quality testing.** This is a systematic series of evaluation actions or activities carried out to validate that the software fully satisfies performance and technical requirements.
- **Software reliability.** This is the ability of the software to carry out its specified function under stated conditions for a given period of time.
- **Software maintenance.** This is the process of modifying a software system or element after delivery, to rectify faults, enhance performance or other appropriate attributes, or adapt to a changed environment.
- **Verification and validation.** This is the systematic process of analyzing, evaluating, and testing system and software code and documentation for ensuring maximum possible reliability, quality, and satisfaction of system needs and goals.
- **Software process management.** This is the effective utilization of available resources both to produce properly engineered products/items and to enhance the software engineering capability of the organization.
- **Software process improvement.** This is a deliberate, planned methodology following standardized documentation practices for capturing on paper (and in practice) the approaches, activities, practices, and transformations that individuals use for developing and maintaining software and the associated products.
- **Software.** This is computer programs, procedures, and possibly associated data and documentation pertaining to the operation of a computer.

9.3 Software Quality Factors and Their Subfactors

The large variety of issues concerning various attributes of software and its use and maintenance, as outlined in software requirement documentation, may be categorized into content groups known as quality factors. Over the years, many models of software quality factors and their classification in factor categories have been proposed by various authors [8]. One of these models classifies all software requirements into 11 software quality factors grouped under 3 categories as shown in Figure 9.1 [8]. These categories are product operation factors (Category I), product revision factors (Category II), and product transition factors (Category III).

The product operation factors are concerned with requirements that directly affect the daily operation of the software. Five specific factors that belong to this category are correctness, usability, integrity, reliability, and efficiency. The product revision factors are concerned with requirements that affect all software maintenance activities: adaptive maintenance (*i. e.*, adapting the current software to additional customers and circumstances without making many changes to the software), perfective maintenance (*i. e.*, enhancing and improving the current software with respect to locally limited issues), and corrective maintenance (*i. e.*, correcting software faults and failures). Three specific factors that belong to this category are testability, maintainability, and flexibility.

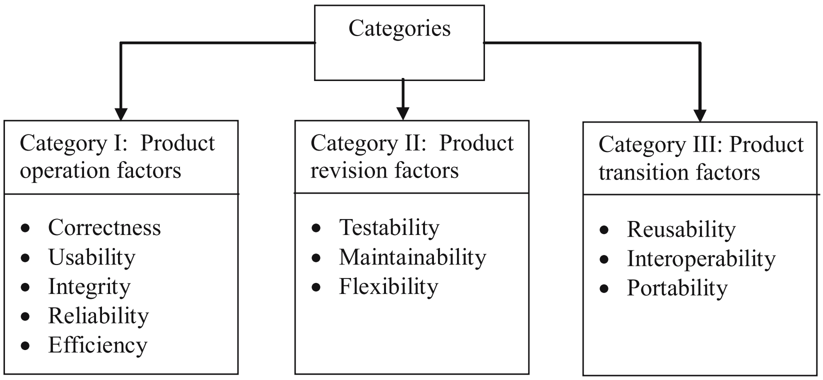

Figure 9.1. Three categories of the software quality factors

The product transition factors are concerned with the adaptation of software to other environments as well as its interaction with other software systems. Three specific factors that belong to this category are reusability, interoperability, and portability.

Each of the above specific software quality factors belonging to Categories I, II, and III are discussed below [9, 10].

- **Correctness.** Correctness requirements are outlined in a list of required outputs of the software system. The subfactors of the correctness are completeness, availability (response time), accuracy, up-to-dateness, compliance (consistency), and coding and documentation guidelines.
- **Usability.** Usability requirements are concerned with the scope of staff resources required for training a new employee as well as to operate the software system. Two subfactors of the usability are operability and training.
- **Integrity.** Integrity requirements are concerned with the software system security, *i. e.*, requirements for preventing access to unauthorized individuals, to distinguish between the majority of individuals permitted to view the information (“read permit”) and a limited number of individuals who will be permitted to add and change data (“write permit”), etc. Two subfactors of the integrity are access control and access audit.
- **Reliability.** Reliability requirements are concerned with failures to provide an appropriate level of service. Furthermore, they determine the maximum permitted failure rate of the software system and can refer to the total system or one or more of its separate functions. Four subfactors of the reliability are system reliability, hardware failure recovery, application reliability, and computational failure recovery.

- **Efficiency.** Efficiency requirements are concerned with the hardware resources required for carrying out the entire functions of the software system, in conformance to all other requirements. Four subfactors of the efficiency are efficiency of processing, efficiency of storage, efficiency of communication, and efficiency of power usage (for portable units).
- **Testability.** Testability requirements are concerned with the testing of an information system as well as with its specified operation. Three subfactors of the testability are traceability, user testability, and failure maintenance testability.
- **Maintainability.** Maintainability requirements are concerned with determining the efforts that will be required by all potential users and maintenance people for identifying the reasons for the occurrence of software failures, to rectify the failures, and to verify the success of the rectifications or corrections. Six subfactors of the maintainability are modularity, simplicity, compliance (consistency), document accessibility, coding and documentation guidelines, and self-descriptiveness.
- **Flexibility.** Flexibility requirements are concerned with the capabilities and efforts needed to support adaptive maintenance activities. Four subfactors of the flexibility are simplicity, modularity, generality, and self-descriptiveness.
- **Reusability.** Reusability requirements are concerned with the use of software modules, originally designed for one particular project, in a new software project being developed. Seven subfactors of the reusability are simplicity, generality, modularity, document accessibility, self-descriptiveness, application independence, and software system independence.
- **Interoperability.** Interoperability requirements are concerned with creating interfaces with other software systems or with other equipment/product firmware. Four subfactors of the interoperability are modularity, commonality, system compatibility, and software system independence.
- **Portability.** Portability requirements are concerned with the adaptation of a software system in question to other environments composed of different operating systems, different hardware, etc. Three subfactors of the portability are modularity, self descriptive, and software system independence.

9.4 Useful Quality Tools for Use During the Software Development Process

There are many quality tools that can be used, to improve software quality, during the software development process. Seven of these tools are listed in Table 9.1 [11]. Some of these are briefly described below (detailed information of these or other quality tools can be found in Chapters 3, 8, 11, or in Refs [12–14]).

- **Run charts.** Run charts are often used for software project management and serve as real-time statements of quality as well as work load. An example of the application of run charts is the monitoring of weekly arrival of software defects and defect backlog during the formal machine testing phases. Another example of the run chart application is tracking the percentage of software fixes that exceed the fix response time criteria, in order to ensure timely deliveries of fixes to customers. Needless to say, during the software development process, often run charts are compared to the projection models and historical data so that all the associated interpretations can be placed into appropriate perspectives. Additional information on run charts with respect to their application during the software development process is available in Ref. [11].

- **Pareto diagram.** Pareto diagrams are probably the most applicable tool in the software quality area because past experiences indicate that software defects or defect density never follow a uniform distribution. Pareto diagrams are an effective tool to identify focus areas that cause most of the problems in a software project under consideration. For example, Motorola successfully used the Pareto diagram to identify main sources of software requirement changes that enabled in-process corrective measures to be taken [15]. Another example is that Hewlett-Packard through Pareto analysis was able to achieve significant software quality improvements [16]. Additional information on Pareto diagrams with respect to their application during the software development process is available in Ref. [11].
- **Checklists.** Checklists play a significant role in the software development process because they are useful to software developers/programmers to ensure that all tasks are complete, and for each of these tasks the important factors or quality characteristics are taken into consideration. The use of checklists is quite pervasive. Checklists, used daily by the software development people, are developed and revised on the basis of accumulated experience.

Checklists are frequently an element of the process documents, and past experiences indicate that their daily application is quite useful to keep the software development processes alive. Additional information on check sheets with respect to their application during the software development process, is available in Ref. [11].

Table 9.1. Quality tools for use during the software development process

No.	Quality tools
1	Scatter diagram
2	Run charts
3	Control chart
4	Checklist
5	Histogram
6	Cause and effect diagram
7	Pareto diagram

9.5 A Manager's Guide to Total Quality Software Design

In order to have good quality end software products, it is important to take proper quality-related measures during the software development life cycle (SDLC). A SDLC includes five stages as shown in Figure 9.2 [17]. Each of these stages with respect to assuring quality is discussed below, separately.

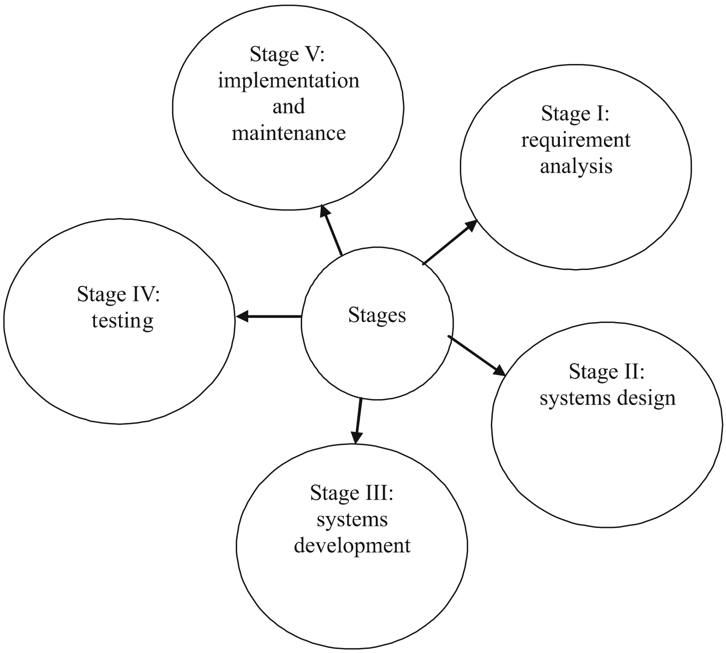

Figure 9.2. Software development life cycle (SDLC) stages

9.5.1 Stage I: Requirements Analysis

Over the years, it has been estimated that around 60–80% of system development failures are the result of poor understanding of user requirements [18]. In this regard, usually major software vendors make use of the quality function development (QFD) during the software development process. Software quality function deployment (SQFD) is a useful tool for focusing on improving the quality of the software development process by implementing quality improvement approaches to the SDLC requirements solicitation phase. More specifically, SQFD is a front-end requirements collection approach that quantifiably solicits and defines critical customer requirements. Thus it is a quite useful tool to solve the problem of poor systems specification during SDLC. Some of the main advantages of SQFD are establishing better communications among departments and with customers, quantifying qualitative customer requirements, fostering better attention to customers' requirements, and reaching features consensus faster [17].

9.5.2 Stage II: Systems Design

This is the most critical stage of quality software development because a defect in design is hundreds of times more costly to rectify than a defect during the production stage. More specifically, it basically means that every dollar spent to increase design quality has at least a hundred-fold payoff during the implementation and operation stages [19]. Concurrent engineering is a widely used method to change systems design and also it is a useful method of implementing total quality management [17]. Additional information on concurrent engineering is available in Refs. [20, 21].

9.5.3 Stage III: Systems Development

Software total quality management (TQM) calls for the integration of quality into the total software development process. After the establishment of a quality process into the first two stages of software development cycle, the task of coding becomes much easier [17]. Nonetheless, for document inspections, the method of design and code inspections can be used [22]. Furthermore, for tracking the metrics of the effectiveness of code inspections, control charts can be used.

9.5.4 Stage IV: Testing

Testing activities should be properly planned and managed from the start of software development, in addition to designing them properly at each stage of the software development life cycle [23]. Nonetheless, a TQM-based software testing process must have a clear set of testing objectives. A six step metric-driven method can fit with such testing objectives. Its steps are establish structured test objectives, select appropriate functional methods to derive test case suites, run functional tests and assess the degree of structured coverage achieved, extend the test suites until the achievement of the desired coverage, calculate the test scores, and validate testing by recording errors not discovered during testing [17].

9.5.5 Stage V: Implementation and Maintenance

Most of the software maintenance activities are reactive. More specifically, programmers frequently zero in on the immediate problem, fix it, and wait until the occurrence of the next problem [17, 24]. As statistical process-control (SPC) can be used to monitor the quality of software system maintenance, a TQM-based system must adapt to the SPC process to assure maintenance quality. Additional information concerning quality during software maintenance is available in Refs. [17, 25].

9.6 Software Quality Metrics

There is a large number of metrics that can be used to improve or assure software quality. Two main objectives of software quality metrics are to highlight conditions that need or enable development or maintenance process improvement in the form of corrective or preventive measures initiated within the organization and to facilitate an appropriate level of management control including planning and executing of proper management interventions.

For their successful applicability, it is essential that these metrics must satisfy requirements such as comprehensive (*i. e.*, applicable to a wide variety of implementations and situations), reliable (*i. e.*, generate similar results when applied under similar environments), valid (*i. e.*, successfully measure the required attribute), relevant (*i. e.*, related to an attribute of substantial importance), mutually exclusive (*i. e.*, do not measure attributes measured by other metrics), easy and simple (*i. e.*, the implementation of the metrics data collection is simple and straight forward and is carried out with minimal resources), do not require independent data collection, and immune to biased interventions by interested parties [9]. Some of the software quality metrics are presented below [9, 26].

9.6.1 Metric I

Metric I is one of the error density metrics and is expressed by

$$CE_{\mathrm{d}} = \frac{TN_{\mathrm{ce}}}{LC} \tag{9.1}$$

where

CE_{d} is the code error density.

LC is the thousands of lines of code.

TN_{ce} is the total number of code errors detected in the software code through inspections and testing. Data required for this measure are obtained from code inspection and testing reports.

9.6.2 Metric II

Metric II is one of the error severity metrics and is expressed by

$$CE_{\mathrm{as}} = \frac{WCED}{TN_{\mathrm{ce}}} \tag{9.2}$$

where

CE_{as} is the average severity of code errors.

$WCED$ is the weighted code errors detected. Data required for this measure are also obtained from code inspection and testing reports.

9.6.3 Metric III

Metric III is one of the error removal effectiveness metrics and is defined as follows:

$$DE_{re} = \frac{NDCE}{NDCE + TNSFD} \tag{9.3}$$

where

DE_{re} is the development error removal effectiveness.

$TNSFD$ is the total number of software failures detected during a one year period of maintenance service.

$NDCE$ is the number of design and code errors detected in the software development process. Usually data for this measure are obtained from design and code reviews and testing reports.

9.6.4 Metric IV

Metric IV is one of the software process timetable metrics and is expressed by

$$TT_{of} = \frac{TNMC}{TNM} \tag{9.4}$$

where

TT_{of} is the time table observance factor.

TNM is the total number of milestones.

$TNMC$ is the total number of milestones completed on time.

9.6.5 Metric V

Metric V is one of the software process productivity metrics and is defined by

$$SDP = \frac{HIDSS_{w}}{LC} \tag{9.5}$$

where

SDP is the software development productivity.

$HIDSS_{w}$ is the total number of working hours invested in the development of the software system.

9.6.6 Metric VI

Metric VI is one of the help desk service (HDS) calls density metrics and is expressed as follows:

$$HDSCD = \frac{TNHDC}{LMSC} \tag{9.6}$$

where

HDSCD is the HDS calls density.
LMSC is the thousands of lines of maintained software code.
TNHDC is the total number of HDS calls during one year period of service.

9.6.7 Metric VII

Metric VII is concerned with measuring the success of the HDS and is defined by

$$HDSS = \frac{NHDSC}{TNHDC} \tag{9.7}$$

where

HDSS is the HDS success factor.
NHDSC is the total number of HDS calls completed on time during one year period of service.

9.6.8 Metric VIII

Metric VIII is concerned with measuring the average severity of the HDS calls and is expressed by

$$ASHDSC = \frac{NWHDSC}{TNHDC} \tag{9.8}$$

where

ASHDSC is the average severity of HDS calls.
NWHDSC is the total number of weighted HDS calls received during one year period of service.

9.6.9 Metric IX

Metric IX is one of the HDS productivity metrics and is defined as follows:

$$HDSP = \frac{HDSWHS}{LMSC} \tag{9.9}$$

where

HDSP is the HDS productivity factor.

HDSWHS is the number of annual working hours invested in help desk servicing of the software system.

9.6.10 Metric X

Metric X is concerned with measuring the software corrective maintenance effectiveness and is expressed by

$$CME = \frac{CMHS}{TNSF} \tag{9.10}$$

where

CME is the corrective maintenance effectiveness.

CMHS is the number of annual working hours invested in the corrective maintenance of the software system.

TNSF is the total number of software failures detected during one year period of maintenance service.

9.7 Software Quality Cost

Software quality cost can be classified as shown in Figure 9.3 [9]. The figure shows two main classifications (*i. e.*, cost of controlling failures and cost of the failure of control) and four subclassifications (*i. e.*, prevention costs, appraisal costs, internal failure costs, and external failure costs.)

The cost of controlling failures is associated with activities performed to detect and prevent software errors, in order to reduce them to an acceptable level. Two subcategories of the cost of controlling failures are prevention costs and appraisal costs. Prevention costs are associated with activities such as developing a software quality infrastructure, improving and updating that infrastructure, and carrying out the regular activities required for its operation. Appraisal costs are concerned with activities pertaining to the detection of software errors in specific software systems/projects. Typical components of appraisal costs are the cost of reviews, cost of software testing, and cost of assuring quality of external participants (*e. g.*, subcontractors).

The cost of the failure of control is concerned with the cost of failures that occurred because of failure to detect and prevent software errors. Two subcategories of the cost of the failure of control are internal failure costs and external failure costs. Internal failure costs are associated with correcting errors found through design reviews, software tests, and acceptance tests, prior to the installation of the software at customer sites. Similarly, the external failure costs are associated with correcting failures detected by customers/maintenance teams after the installation of the software system at customer sites.

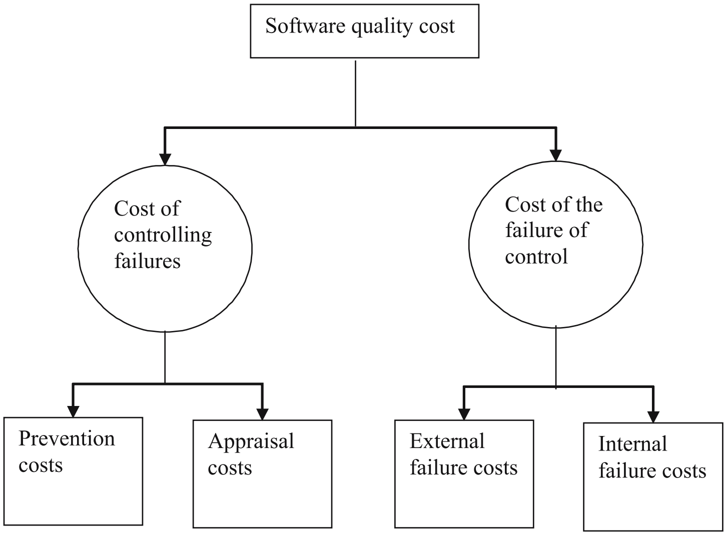

Figure 9.3. Classifications and subclassifications of software quality cost

9.8 Problems

1. Write an essay on software quality.
2. Define the following three terms:
   - Software quality control
   - Software quality
   - Software quality assurance
3. What are the software quality factors? List at least nine of them.
4. Describe run charts.
5. List at least four quality tools that can be used during the software development process.
6. What are the main stages of the software development life cycle?
7. What is a software metric?
8. Define at least three software quality metrics.
9. Define software quality cost.
10. What are the four categories of the software quality cost?

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10

Quality Control in the Textile Industry

10.1 Introduction

Each year billions of dollars are spent to produce various types of textiles, and the world production of fibres was predicted to be around 50 million tons for the year 2,000. The United States has only 4.3 percent of the world's population, but it consumes almost 20 percent of the world's textiles [1, 2].

The history of quality control in the textile industry may be traced back to Zhou Dynasty (11th to 8th centuries B.C.) in China. For example, one dynasty decree stated that "Cottons and silks of which the quality and size are not up to the standards are not allowed to be sold on the market" [2, 3]. In the modern context, the first application of statistical quality control concepts appeared to be in yarn-manufacturing products during the late 1940s and 1950s [2]. In 1981, one of the largest textile companies in the world, Milliken & Company, launched its total quality management efforts specifically directed to make a commitment to customer satisfaction pervading all company levels and locations. By 1989, it was ahead of its competition with respect to all measures of customer satisfaction in the United States and won the Baldridge Quality Award [4].

Currently, there are around 30,000 textile-related companies in the United States, and many of them have implemented quality management initiatives for reducing costs and improving both products and customer satisfaction. This chapter presents various important aspects of quality control in the textile industry.

10.2 Quality-related Issues in Textiles and Quality Problems Experienced in Apparel

Some of the quality-related issues directly or indirectly associated with textiles are as follows [5–6]:

- Poor understanding of the customer needs and satisfaction.
- Inadequate training of operators in their jobs and in quality issues.
- Quality is not a pressing issue until it becomes a problem.
- Often quality enters downstream, more specifically, at final assembly, rather than in the design and development stages (*i. e.*, early stages).
- Quality-related problems are observed with vendors.
- Quality costs are considered to be too high.
- Management appears to sacrifice quality when costs and scheduling conflict.

The main quality problems, and their corresponding percentages in parentheses, experienced in apparel are shown in Figure 10.1 [7]. These are material failure, construction/stitching failure, customer misuse, and faulty trimmings. Material failure consists of loose dye during exposure to items such as washing, sea water, rubbing, ironing, perspiration, water, dry cleaning, light, and chlorinated water; dimensional instability due to shrinkage and stretching; and poor wear and appearance due to factors such as slippage, pilling, abrasion, and snagging. Construction failure consists of faulty seams due to factors such as wrong machine settings, poor quality of design, incorrect machinery relative to fabric, and weak sewing thread and faulty interlining due to delamination. Customer misuse includes unfair wear and tear and wrong washing methods.

Faulty trimmings consist of broken fasteners, broken zips, buttons incorrectly stitched, and button dye.

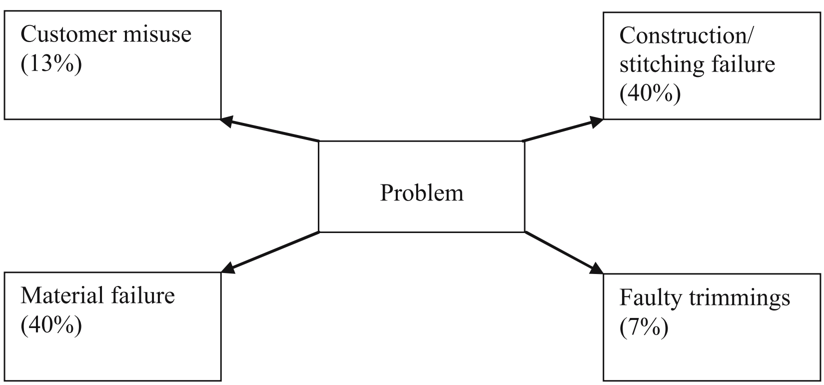

Figure 10.1. Main quality problems experienced in apparel

10.3 Fibres and Yarns

The basic raw materials of the textile industry are fibres. Normally, they are transformed into yarn and then into fabric. There are two main categories of fibres: naturally occurring and man made [8]. The natural fibres may be of vegetables (*e. g.*, cotton and linen), animal (*e. g.*, hair and wool), or mineral (*e. g.*, asbestos) origin. The man-made fibres can be grouped as synthetic polymers (*e. g.*, polypropylene, polyester, etc.), natural polymers (*e. g.*, acetate, viscose rayon, etc.), and others (*e. g.*, glass, metal, carbon, etc.).

Besides the above two broad categories of fibres, additional classification is made by measuring fibre density, checking extensibility, observing any reaction to staining, testing for the presence of certain elements such as chlorine and nitrogen, a drying twist test, differential thermal analysis, a refractive index test for glass fibres, treating with a series of solvents either at room temperature or the boiling point until one is found in which the fibres dissolve, etc. [8].

Although each category of fibre may be used individually or in blends, nowadays it is a common practice to blend natural with man-made fibres for achieving an optimum combination of physical properties and cost/price.

The physical properties of fabrics and yarns are subject to various factors including the fibre properties. A careful analysis of fibre properties along with experience, can give a broad idea about the likelihood of the end result when the fibres are spun into yarn.

A yarn may simply be described as an assembly of fibres and/or filaments normally bound together by twist. The basic specification of a yarn includes at least the materials, the twist, and the count. Nonetheless, some of the important items pertaining to yarn are as follows [8]:

- **Count.** Yarn count may be described directly as mass per unit length or indirectly as length per unit mass.
- **Diameter.** Diameter is a measure of yarn covering power (*i. e.*, the extent to which cloth area is covered by single set of threads) when in the fabric and is measured by throwing yarn shadow (silhouette) on to a graduated glass scale.
- **Twist.** This may simply be described as the number of turns per unit length of yarn. It causes frictional trappings between the fibres and hence imparts appropriate strength to the yarn. The twist factor is a measure of twist hardness and it relates twist to the linear density. It is expressed by

$$TF = (twist)\,(linear\ density)^{\frac{1}{2}} \tag{10.1}$$

where
TF is the twist factor.

- **Friction.** The tension of yarn in processing basically depends on friction as it passes around machinery parts or yarn guides. The coefficient of friction of a yarn as it runs around a test object is measured by the yarn friction tester.

- **Crimp of yarn in fabric.** Precise and accurate measurement of yarn length is absolutely important in estimating crimp (take up, regain, shrinkage, etc.) in woven fabrics, in measuring the count of short lengths of yarn, and in calculating course and loop-length in knitted fabrics. The following formula is used to calculate crimp in percentage [8]:

$$C = \frac{(SL - LIF)(100)}{LIF} \tag{10.2}$$

where
C is the crimp expressed in percentage.
SL is the straightened length.
LIF is the length in fabric.

10.4 Textile Quality Control Department Functions

Quality control departments play a pivotal role in producing good quality textile products in a textile organizational/mill/factory. They perform functions such as shown in Figure 10.2 [9]. Assigning control responsibilities is concerned with defining and assigning control responsibilities for items such as checking, control measurements, and weighing of waste throughout the factory/mill. Training mill/factory manpower is concerned with planning and providing appropriate quality-related training to factory/mill personnel. Establishing and maintaining the testing laboratory is concerned with setting up and maintaining the testing laboratory with appropriate equipment and qualified manpower. Ensuring prompt execution of corrective measures is concerned with coordinating corrective actions in such a manner that take minimum time between the discovery of faulty operation and corrective measure.

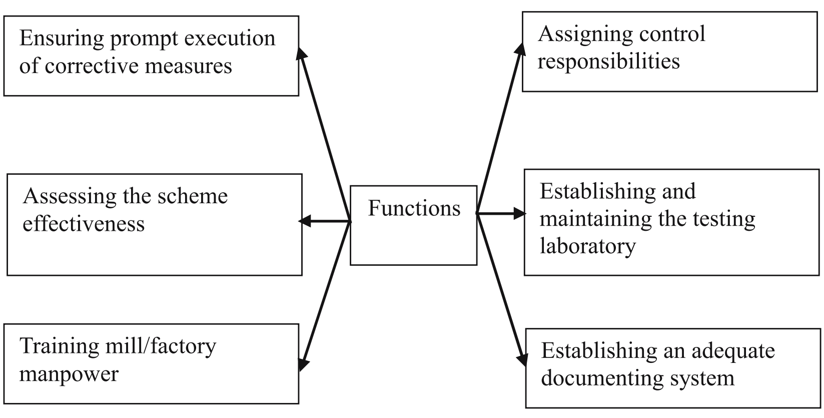

Figure 10.2. Main functions of a textile quality control department

Assessing the scheme effectiveness is concerned with regularly reviewing the scheme and making changes as considered appropriate. Establishing an adequate documenting system is concerned with designing forms for purposes such as recording measurements, calculations, summaries of measurement changes with time, and control charts.

10.5 Textile Test Methods

Over the years a large number of test methods have been developed to determine various different aspects of textiles that may directly or indirectly affect textile quality [10]. Some of these aspects are presented in Table 10.1 [10]. Five test methods considered, directly or indirectly, useful in textile quality control work are briefly described below.

Table 10.1. Some aspects of textiles determined by the textile test methods

No.	Test method for determining (Textile aspect)
1	Moisture in textiles
2	Length of yarns and threads
3	Breaking strength of fabrics
4	Breaking strength of yarns
5	Tearing strength
6	Flame resistance
7	Water resistance
8	Air permeability
9	Resistance to pilling
10	Yarn crimp

10.5.1 Test Method I

This method is concerned with determining the conditioned mass of fabrics by taking specimens of known dimensions from fabric in moisture equilibrium with the standard atmosphere. The method calls for using a balance capable of determining specimen mass with an accuracy of $\pm 0.1\%$ as well as a rigid scale graduated in millimetres and centimetres. Additional information on the method is available in Ref. [10].

10.5.2 Test Method II

This method is concerned with determining the tearing strength of woven fabrics by measuring the maximum force observed in the propagation of a tear across the fabric when the force applied is parallel to the yarns ruptured in the tear. The method calls for using a suitable recording tensile testing machine of the inertia less or pendulum type. Additional information on the method is available in Ref. [10].

10.5.3 Test Method III

This method is concerned with determining the rate at which a strip of fabric burns when a flame is applied to a vertical specimen's lower edge until it ignites. The time is estimated for the upper portion of the flame to travel a distance of 650 mm up the fabric strip. The method uses a small burner, a stop watch, and a shield about 300-mm wide, 300-mm deep, and 1.2-m high, with an open top and a sliding/hinged glass front for protecting the specimen from draft. This method is described in detail in Ref. [10].

10.5.4 Test Method IV

This method is concerned with determining the amount of crimp in yarns taken from woven fabric. The difference between a measured length of fabric and the straightened length of a yarn subtracted from it is estimated and presented as a percentage of the fabric's measured length. The apparatus required for this test are a rigid scale and a tensioning device (*e. g.*, a twist tester). This method is described in detail in Ref. [10].

10.5.5 Test Method V

This method is concerned with determining the tearing strength of woven fabrics by the single-rip approach. In this method the force needed for propagating a single-rip tear through a fabric, is estimated and then its maximum values in successive equal size tearing intervals are averaged. The method requires a suitable recording tensile testing machine. Additional information on this method is available in Ref. [10].

10.6 Quality Control in Spinning and Fabric Manufacture

The main objective in spinning is to manufacture a yarn of defined count and quality at the minimum cost [9]. The quality should be adequate for ensuring that the yarn performs effectively in subsequent processes as well as the end product is with in acceptable limits. Factors such as the yarn's uniformity, tensile strength, elongation, and freedom from imperfections determine quality. The relative importance of factors such as these depends on subsequent processes and the end product. The basic characteristics of spinning are count and count uniformity since yarn is designated by count and both these characteristics affect strength and strength variability, the performance in subsequent processes, and the fabric appearance.

Waste is an important factor in spinning economics and is becoming increasingly important due to factors such as the need for large capital investment in machinery, global competition, and the growing costs of raw material and labour. The amount of waste may increase with either decreases/increases in quality, or it may be totally independent of quality. Some of the important factors for excess waste could be inadequate operating procedures, poor management/supervision, poor training, operator carelessness, and lack of operator skill.

The main goals of quality control in fabric/cloth manufacturing are to achieve the specified level of quality with minimum waste, and maintain optimum level of machine and labour productivity so that the profit is at maximum [9]. Fabric defects in weaving result from defects in the preparatory process, poor work practices, wrong loom settings, and end breakages (because of poor loom maintenance).

The fabric mechanical properties are appeared to be mainly influenced by the stitch length and the yarn shear and bending. As the long-term retention properties such as abrasion resistance and lack of pilling involve so many factors, an examination of the finished fabric is the only reasonable test. Nonetheless, the three factors that should be tested are yarn variables, process variables, and fabric variables.

Yarn variables involve checks on count, checks on knots, slobs, and thin spots, and measurement of yarn irregularity. Furthermore, to prevent press-offs and broken loops, yarn strength and strength variability need to be controlled. Process variables basically involve daily checks on input tension and stitch length and visual inspection of fabric for correct pattern selector operation.

Fabric variables involve tests for abrasion, pilling, and dimensional stability and inspection for irregular and dropped stitches, and rough dimensional checks. All in all, some organizations or factories rely totally on these checks for quality control.

10.7 Quality Control in Finishing and in the Clothing Industry

Quality control at the finishing stage involves many different functions. They may be grouped under four distinct categories as shown in Figure 10.3 [9].

Two of these categories are discussed below. Control of raw materials is essential, since they are often purchased from a specific source on the basis of price rather than on quality. It is very important to carry out a careful testing of a raw material where its behaviour in processing is crucial and its cost is a major element in the cost of the final product.

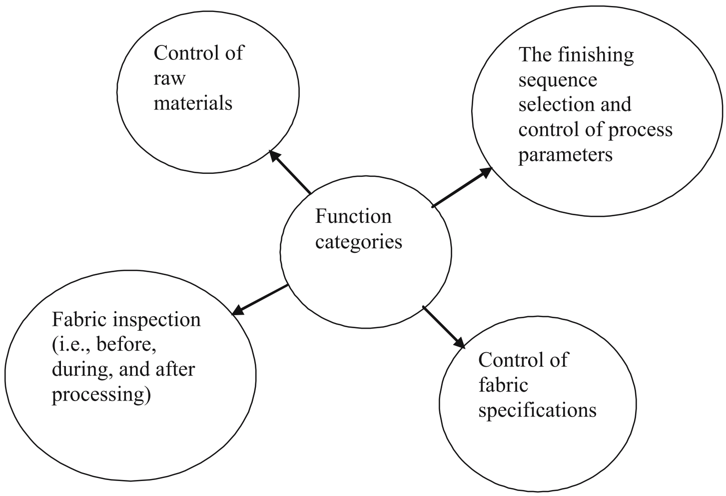

Figure 10.3. Quality control function categories at the finishing stage

The selection of the appropriate processing sequence and processing parameters depends on many parameters, including the type of fabric, the properties required, and the fibres used. To suit a specific fibre blend, processes may have to be modified or changed and more effective control may be required to minimize faults. Additional features of quality control in finishing are good machine maintenance, cleanliness, and tidiness.

Quality control in the clothing industry is not very clear-cut due to various reasons including yarn properties, a wide variety of fabrics to be handled by clothing manufacturers, the dependence of quality on the fibres used, the manufacturing parameters, and the finishing variables [9]. Nonetheless, quality control may be divided into three distinct areas: performance testing, acceptance testing, and product inspection.

Performance testing involves particular tests on properties critical to specific types of fabrics. Some examples of these tests are fabric-to-fabric adhesion in fusible interlinings, inflammability of children's garments, air permeability in wind-proof fabrics, and shower-proofing for rainwear.

Acceptance testing incorporates the testing of all types of raw materials used, including elasticized waist-band fabric, tapes, pocketing, linings, padding, sewing threads, interlinings, stiffening, and basic fabric and auxiliaries such as zippers, press studs, buttons, hooks, and eyes.

Product inspection is concerned with removing processing faults, and it ensures that no further work is done on garments or items already identified as faulty and the final appropriate inspection prevents their sale. The degree of inspection to be performed depends on factors such as the type of garment, the specified quality, and the price range. All in all, the application of the quality control concept in the clothing industry is very challenging basically due to two reasons: the variability of input raw materials and the large range and short production runs of the product [9].

10.8 Organizations that Issue Textile Standards

There are many organizations around the world that issue textile-related standards, directly or indirectly, useful to quality control in the textile industry. Some of these organizations along with their addresses are as follow [9]:

- International Standards Organization (ISO)

  1 Rue de Varembe
  1211 Geneva 20
  Switzerland

- International Wool Textile Organization (IWTO)

  Hastlegate, Bradford
  Yorkshire BD1 1DE
  Untied Kingdom

- National Bureau of Standards

  Washington, D.C.
  USA

- British Standards Institution (BSI)

  Textile Division
  10 Blackfriars Street
  Manchester M3 5DR
  United Kingdom

- Council of the European Economic Community

  200 rue de la Loi
  B-1040 Brussels
  Belgium

- American Society for Testing and Materials (ASTM)

  1916 Race Street
  Philadelphia, PA 19103
  USA

- Pan American Standards Commission

  c/o Argentine Standards Institute (IRAM)
  Chile 1192
  Buenos Aires
  Argentine

- Canvas Products Association International

  600 Endicott Buildings
  St. Paul, MN 55101
  USA

10.9 Problems

1. Write an essay on quality control in the textile industry.
2. List at least seven quality-related issues associated with textiles.
3. Discuss major quality problems experienced in apparel.
4. What is a yarn?
5. What are the main functions of a textile quality control department?
6. Discuss quality control in the area of spinning.
7. Discuss quality control in the following two areas:
   - Finishing
   - Fabric manufacture
8. Write an essay on fibers.
9. List at least eight different aspects of textiles determined by the textile test methods.
10. What are the important organizations useful for obtaining textile quality-related standards?

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11

Quality Control in the Food Industry

11.1 Introduction

The food industry is a huge global business, for example, people in the United States alone eat about 870 million meals a day [1]. In this industry, quality is usually an integrated measure of purity, texture, appearance, flavour, workmanship, and color. Quality is becoming an important issue due to various factors including food borne disease, caused by improper food handling or storage. For example, during the period 1993 to 1997, in the United States a total of 2,751 outbreaks of food borne disease involving around 86,000 people, were reported [2]. The main causes for the disease were identified as bacteria, viruses, parasites, and chemical agents.

The history of laws, directly or indirectly, concerned with food quality can be traced back to 1202 when King John of England proclaimed the first English food law, the Assize of Bread, which prohibited adulteration of bread with such ingredients as beans or peas. Nonetheless, some of the main objectives of quality control in the food industry are as follows:

- To assure that food laws are complied with in an effective manner.
- To protect people from dangers (*e. g.*, contaminated foods) and ensure that they get the proper quality and weight as per payments.
- To provide protection to the business from cheating by its suppliers, damage to equipment (*e. g.*, stones in raw materials), and false accusations by customers, suppliers, or middlemen.

This chapter presents various important aspects of quality control in the food industry.

11.2 Factors Affecting Food Quality and Basic Elements of a Food Quality Assurance Program

There are many factors responsible for poor quality food. The major factors responsible for significant quality changes are listed below [3]:

- Wrong temperatures and timing
- Poor packaging
- Inadequate machine maintenance program
- Wrong pre-cooking, cooking, and post-cooking approaches or methods
- Poor ware washing
- Poor sanitation
- Presence of pesticides
- Incompatible water conditions
- Presence of vermin
- Incorrect formulations, stemming from wrong weight of the food, or its elements/components
- Spoilage due to chemical, biochemical, microbiological, or physical factors

All in all, any of the above factors can contribute to poor food quality as well as effect changes that could be evident in the food's appearance, texture, consistency, and flavour.

Ten basis elements of a food quality assurance program are shown in Figure 11.1 [3]. Some of these elements are described below.

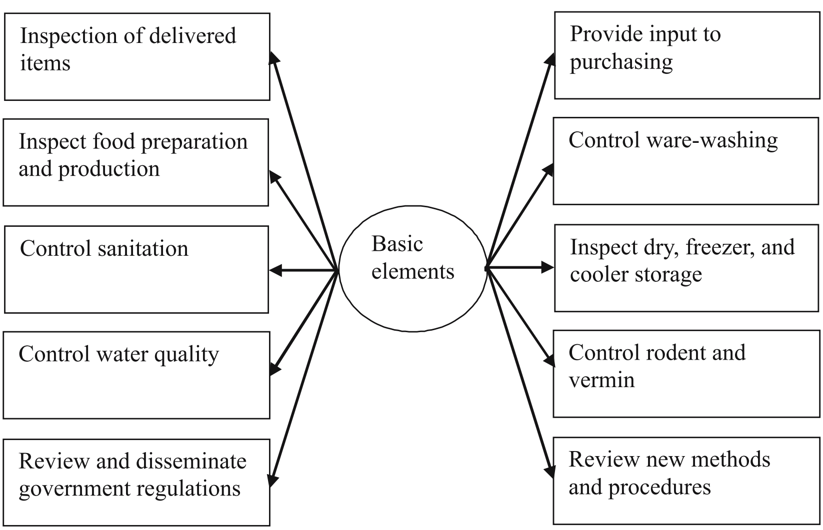

Figure 11.1. Basic elements of a food quality assurance program

The inspection of delivered items is concerned with actions such as follows:

- Conducting comparison tests to compare the delivered items with purchase specifications.
- Inspecting the product for visual signs of contamination and freshness.
- Recording the temperature of the frozen food.
- Determining product weight.
- Recording pack data and product code.
- Checking label nomenclature for conformity to labelling standards.
- Checking canned merchandise for dents and "swells".

The element "provide input to purchasing" is concerned with items such as developing procedures for test panels and cooking tests, and establishing specifications and formulations for each food and beverage item to be purchased.

The element "inspect food preparation and production" is concerned with actions such as follows:

- Testing quality of finished food, beverages, garnishing, and plating.
- Checking efficiency of all cooking equipment with respect to temperature, timing, and physical condition.
- Controlling sanitation to eliminate problems of off-tastes, off-flavours, and food spoilage.
- Ensuring against over-production.
- Updating and reviewing recipe cards and other data useful for formulating and preparing food.

The element "inspect dry, freezer, and cooler storage" is concerned with actions such as evaluating storage temperature, establishing procedures for proper storage of left-over food, controlling sanitation, and developing orderly stacking procedures. The element "control ware-washing" is concerned with assuring the total removal of soap, grease, and soil residues.

The element "control sanitation" is concerned with sanitation control for refuse collection and disposal area. The element "review new methods and procedures" is concerned with reviewing new procedures and approaches pertaining to food production, packaging, and handling. The element "review and disseminate government regulations" is concerned with reviewing and disseminating local, state, and federal government health-related regulations pertinent to the establishment.

11.3 Total Quality Management Tools for Application in the Food Industry

As total quality management (TQM) is based on many ideas, it means thinking about quality in terms of all functions of the food processing or other organization [3]. TQM makes use of many tools to successfully achieve the desired objectives.

The TQM tools considered useful for application in the food industry can be divided into two groups (*i. e.*, Group I and Group II). Group I tools are concerned with analyzing and interpreting numerical data whereas Group II with management and planning.

Some of the most useful tools belonging to the Group I Category are briefly discussed below [4–7].

- **Histogram.** Histogram can be used to summarize and display the distribution of a given food process dataset. A histogram is quite useful to answers questions such as what is the most frequent system response? And what distribution (*i. e.*, shape, center, and variation) do the data have? Additional information on histograms is available in Refs. [4–6].
- **Flowchart.** Flowcharts are an excellent project development and documentation tool. A flowchart visually records the decisions, steps, and actions of a given service or manufacturing operation as well as defines the system and its associated pivotal points, activities, and role performances. Additional information on flowcharts is available in Refs [4–6].
- **Control chart.** Control charts are one of the most technically sophisticated methods of statistical quality control, and they can be used to identify statistically significant changes that may happen in a food-related process. A control chart may simply be described as a graphic presentation of data collected over a period of time, which shows upper and lower control limits for the process to be controlled. Thus, each control chart is comprised of three lines: upper control limit (UCL), lower control limit (LCL), and the center line. In the food industry, control charts are often used for net weight control. Control charts are described in detail in Refs. [1, 5, 8].
- **Pareto diagram.** A pareto diagram a kind of frequency chart in which bars are arranged in descending order (*i. e.*, from left to right) and which provides order to activity. A Pareto diagram is used to highlight areas for a concerted effort (*i. e.*, to decide what steps need to be taken for quality improvement). More specifically, a Pareto diagram is a valuable tool for seeking answers to questions such as what 20% of sources are responsible for 80% of the problems? And what are the most pressing issues facing a business or team? Additional information on this method is available in Refs. [4–7].
- **Scatter diagram.** A scatter diagram is quite similar to a line graph, but with one exception, *i. e.*, the data values are plotted without a connecting line drawn between them. The scatter diagram is used to study all possible relationships between two given variables. Although it cannot prove that one variable causes the other, but it does indicate the existence of a relationship as well as that relationship's strength. Additional information on this approach is available in Refs. [4–6].

Similarly, five of the most useful tools belonging to the Group II category are briefly described below [4–6].

- **Inter-relationship diagraph.** An inter-relationship diagram is used to find solutions to problems having complex causal relationships. An inter-relationship diagraph may simply be described as a process that allows for multidirectional rather than linear thinking to be used. All in all, the inter-relationship diagraph is an excellent tool for untangling and finding the logical relations among the intertwined causes and effects and is described in detail in Refs. [4–6, 9].
- **Affinity diagram.** An affinity diagram is a process used by a team or group for collecting and organizing opinions, issues, ideas, etc. from a raw list into classifications of similar thoughts that make sense and can be handled more easily or effectively. Some of the situations when the affinity diagram can be used are when pre-existing ideas need to be clarified or overcome, when there is a definite need to create unity within a group, and when thoughts/facts are uncertain and need to be organized. Additional information on the affinity diagram is available in Refs. [4–6, 10].
- **Tree diagram.** Tree diagrams are used for mapping out a full range of tasks and paths that must be performed in order to accomplish a specified primary goal and associated subgoals. The tree diagram permits breaking any broad objectives or goals, graphically, into increasing levels of detailed actions that must or could be accomplished to successfully achieve the specified goals. This method is described in detail in Ref. [10].
- **Process decision program chart.** Process decicsion program chart is a powerful approach that graphically displays various alternatives and contingencies to a given problem, which can be determined in advance to chose a strategy for handling them. The process decision program chart can be used for purposes such as implementing countermeasures to minimize non-conformities in the manufacturing process, exploring all possible contingencies that could occur in the implementation of any new or untried risky plan, and establishing an implementation plan for management by objectives [4]. Additional information on this method is available in Refs. [4–6].
- **Matrix diagram.** Matrix diagrams are used to visually examine the relationship between data sets. The diagram is composed of a number of rows and columns whose intersections are compared to determine the nature and strength of the problem under consideration. This permits the user to come up with the most promising ideas, analyze the relationship or its absence at the intersection, and determine a useful way of pursuing the problem-solving approach. The matrix diagram is described in detail in Refs. [4–6].

11.4 Hazard Analysis and Critical Control Points (HACCP) Concept

Today, the Hazard Analysis and Critical Control Points (HACCP) concept is widely used in the food industry. It was developed in the 1960s by the Pillsbury Corpor–ation in conjunction with the National Aeronautics and Space Administration

(NASA) and the US Army Natick Laboratories to ensure the safety of food for astronauts [4, 11–13]. Nowadays, HACCP has clearly become a technical management program in which food safety is addressed by controlling chemical, physical, and biological hazards in all areas of the food industry (*i. e.*, from growing, harvesting, processing, and distribution to preparing all types of food for consumption).

In developing an HACCP program, there are five basic tasks that must be accomplished successfully prior to the application of the HACCP principles to a certain product and process [4, 14]. These five tasks are as follows [4, 14]:

- Forming the HACCP team with appropriate individuals with appropriate expertise in required areas.
- Describing the food product and its distribution.
- Describing the food product's intended use and its potential consumers.
- Developing a flow diagram that describes the food product's manufacturing process.
- Verifying the flow diagram.

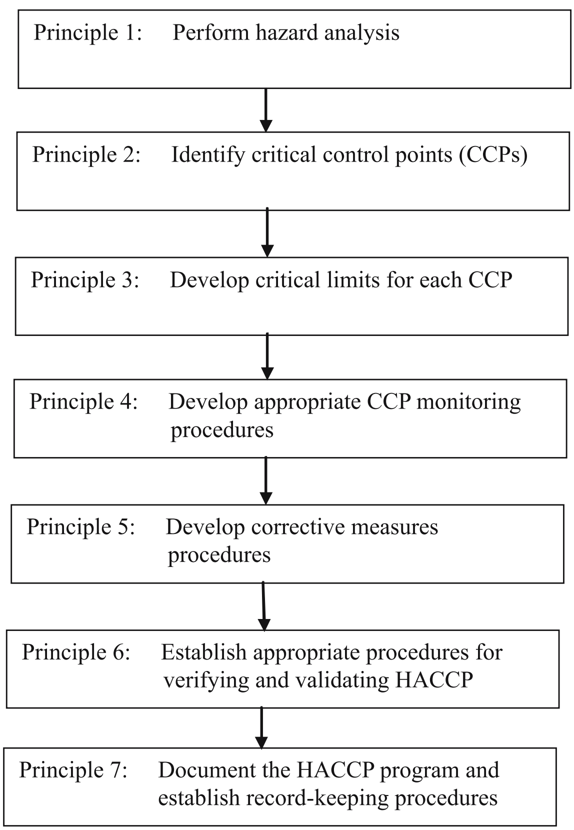

Figure 11.2. The seven HACCP principles

After the completion of the above five tasks, the seven principles of HACCP shown in Figure 11.2 are applied. Each of these principles is described in detail in Ref. [4].

11.4.1 HACCP Benefits

There are many benefits of the HACCP concept. Some of the important ones are as follows [4, 15]:

- HACCP is a useful tool to place responsibility for ensuring food safety on food manufacturers or distributors.
- HACCP is a useful tool that focuses on identifying and preventing hazards from contaminating food.
- HACCP is a useful tool that permits more effective and efficient government monitoring, primarily because of its record keeping, allows investigators to see how well an organization is complying with food safety-related laws over a period of time.
- HACCP is a useful tool for reducing barriers to international trade.
- HACCP is a useful tool that helps food companies to compete more effectively in the global market.

11.5 Fruits and Vegetables Quality

As the health benefits associated with regular consumption of fresh fruits and vegetables have been clearly demonstrated and encouraged by nutrition and health authorities, the increase in consumption of these products has been an important factor of the greater emphasis on their quality. There are many factors that affect the quality of fruits and vegetables. Most of these factors are shown in Figure 11.3 [16]. Each of these factors is described in detail in Ref. [16].

11.5.1 Main Causes of Post-harvest Losses and Poor Quality for Various Categories of Fruits and Vegetables

This section presents important causes of post-harvest losses and poor quality for the following five categories of fruits and vegetables [17]:

- **Category I: Root Vegetables.** This category includes vegetables such as beets, onions, sweet potatos, garlics, potatos, and carrots. Their main causes of post-harvest losses and poor quality are water loss, mechanical injuries, chilling injury, improper curing, decay, and sprouting.
- **Category II: Flower Vegetables.** This category includes vegetables such as cauliflower, broccoli, and artichokes. Their main causes of post-harvest losses

and poor quality are discoloration, water loss, mechanical injuries, and abscission of florets.

- **Category III: Leafy Vegetables.** This category includes vegetables such as spinach, cabbage, lettuce, green onions, and chard. Their main causes of post-harvest losses and poor quality are mechanical injuries, water loss, decay, loss of green color, and relatively high respiration rates.
- **Category IV: Immature Fruit Vegetables.** This category includes vegetables such as cucumbers, okra, peppers, eggplant, snap beans, and squash. Their main causes of post-harvest losses and poor quality are water loss, chilling injury, decay, bruising and other mechanical injuries, and over-maturity at harvest.
- **Category V: Mature Fruit Produce.** This category includes fruits such as apples, melons, bananas, grapes, tomatoes, stone fruit, and mangoes. Their main causes of post-harvest losses and poor quality are water loss, bruising, chilling injury, decay, compositional changes, and over-ripeness at harvest.

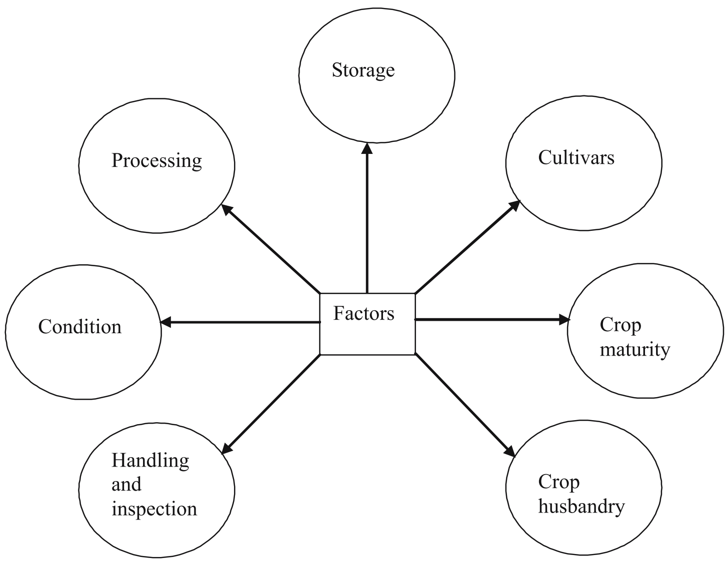

Figure 11.3. Factors affecting quality of fruits and vegetables

11.6 Vending Machine Food Quality

A vending machine may simply be described as a self-service device that upon insertion of coins, tokens, or debit cards automatically dispenses unit servings of food either in packaged form or in bulk. Today, vending machines are widely used throughout the world. For example, in Japan alone, there are around five million vending machines covering a wide range of products and services. Three major areas for quality control of food and beverage vending machines are shown in

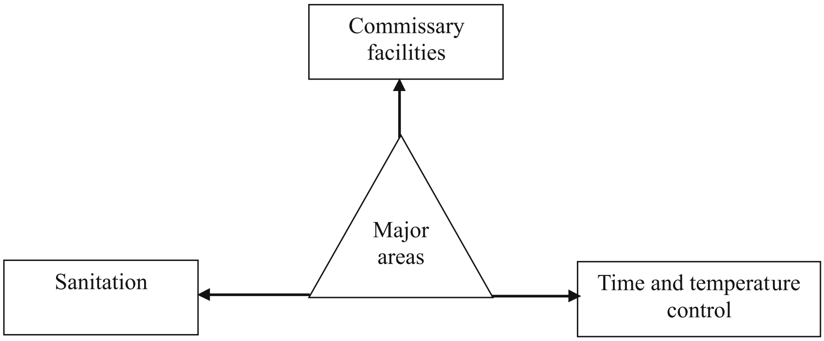

Figure 11.4. Major areas for quality control of food and beverage vending equipment

Figure 11.4 [18]. These are sanitation, time and temperature control, and commissary facilities.

Sanitation is basically concerned with cleaning and sanitizing all components of a vending machine that come into contact with food, in such a manner that prevents the contamination of food being served from the machine. Food-contact parts of a vending machine cannot be effectively cleaned with simply a rag and a dash of water, because of the machine complexity. This cleaning requires a careful attention and inspection. In addition, a professional job cannot be accomplished without proper sanitation equipment.

Although the need for sanitation items depends on type of machine, company procedures, and machine location, the suggested items for the sanitation kit are three buckets (*i. e.*, for the detergent solution, sanitizing solution, and hot water rinse), hand mops and sponges, insecticide spray, hand scrapers and soft wire brushes, cleaning cloths and paper and cloth towelling with high wet strength properties, brushes of various sizes, flashlight, spare water strainer and filter cartridge, spare tubing for replacement purposes, spare polyethylene waste bags, and detergents, approved sanitizers, urn cleaner and cleaner spray in bomb or bottle [18].

Time and temperature control calls for establishing a rigid program of time and temperature control of perishable foods and beverages. The safe recommended temperatures by the Public Health Department of the National Automatic Merchandising Association (USA), are 45°F (8°C) or lower for cold food and 140°F (60°C) or higher for hot food [18].

Commissary facilities are concerned with preparing foods such as salads, casseroles, stews, and sandwiches as well as performing the role of a storage and distribution center. The commissary operation and quality control procedures are basically identical to those needed for any other food service facility. However, their differences are quite apparent and include containerization of salads and other prepared foods, wrapping of pastries and sandwiches, and transporting all these items to vending machines.

11.6.1 Important Points in the Quality Control of Vended Hot Chocolate

Some important points in the quality control of vended hot chocolate are as follows [18]:

- Maintenance of water temperature at 200°F ± 5° (94°C ±3°).
- Avoiding the overload of hopper.
- Checking weekly the product quantity or throw.
- Flushing the mixing chamber after servicing a machine.
- Checking the hopper cover for ensuring snug and moisture-free fit to prevent the growth of surface mold and bacteria

11.6.2 Quality Control Factors for Soft Drink Vending Machines

Some of the quality control factors for soft drink vending machines are shown in Figure 11.5 [18].

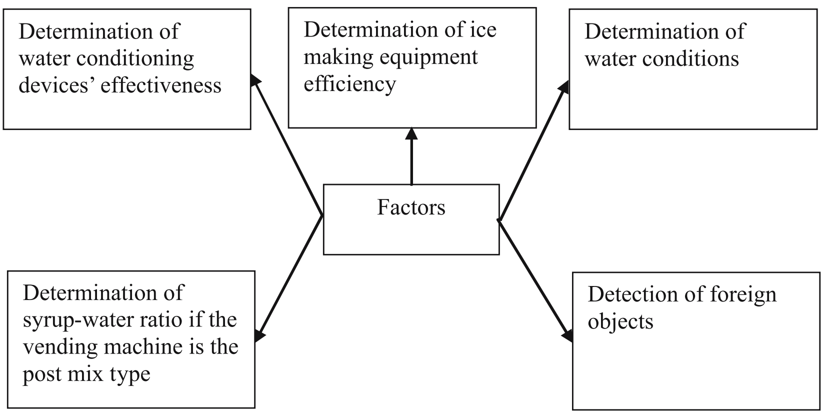

Figure 11.5. Quality control factors for soft drink vending machines

11.7 Food Processing Industry Quality Guidelines

Food processing industry quality guidelines are based upon ANSI Z1.15, an American National Standards Institute (ANSI) standard for establishing quality control systems in hardware manufacturing [1, 19]. More specifically, in the 1980s a committee of food quality experts modified this standard for use by the food processing industry. The modified version covers seven areas shown in Figure 11.5 [1]. These are administration, design assurance and design change

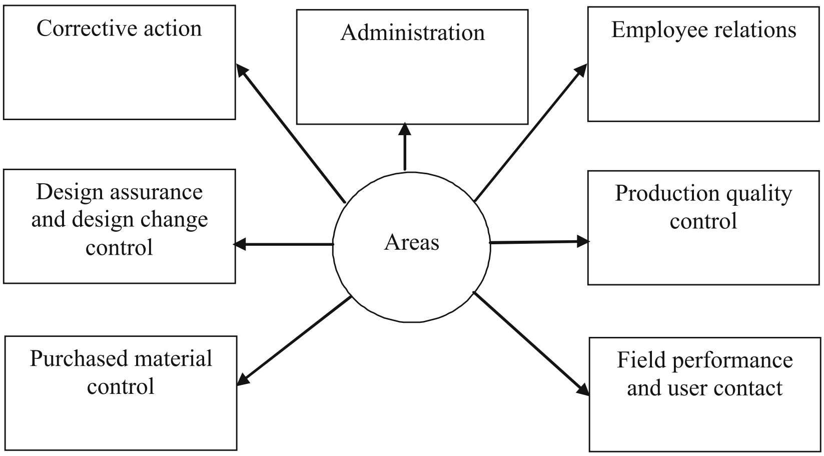

Figure 11.6. Areas covered by the quality standard for use by the food processing industry

control, purchased material control, production quality control, field performance and user contact, employee relations, and corrective action.

Administration includes items such as quality system, objectives, quality policy, planning quality manual, responsibility, reporting, quality cost management, and quality system audits. Each of these items is covered in significant depth. For example, the quality system covers items such as ingredients, sanitation, distribution, packaging, storage practices, pest management/control, vendor/contract processors relations, user contacts, complaint handling and analysis, shelf life, processing, and finished product.

Design assurance and design change control contains a total of twelve subsections concerned with design review, concept definition, market readiness reviews, etc. The purchased material control provides a summary of supplier certification requirements such as system requirements, specifications, assistance to suppliers, and facility inspection.

Production quality control contains a total of twenty four detailed requirements under many subheadings: finished product inspection, planning and controlling the process, quality information, product and container marking, and handling, storage, and shipping.

Field performance and user contact includes items such as complaints and analysis, product objective, advertising, and acceptance surveys. The employee relations area includes selection, motivation, and training. Finally, corrective action covers items such as diction, documentation, and incorporating change.

11.8 Problems

1. Write an essay on quality control in the food industry.
2. List at least of ten the most important factors responsible for significant quality changes.
3. What are the basic elements of a food quality assurance program? Discuss at least five of them.
4. Discuss at least five total quality management tools useful for application in the food industry.
5. What are the seven principles associated with the hazard analysis and critical control points (HACCP) concept?
6. What are the advantages of HACCP?
7. What are the factors that affect the quality of fruits and vegetables?
8. Discuss three major areas for quality control of food and beverage vending equipment.
9. List important points in the quality control of vended hot chocolate.
10. Discuss main causes of post-harvest losses and poor quality for at least three different categories of fruits and vegetables.

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Appendix

Bibliography: Literature on Applied Reliability and Quality

A.1 Introduction

Over the years, a large number of publications, directly or indirectly, related to various areas of applied reliability and quality have appeared in the form of journal articles, conference proceedings articles, books, etc. This appendix presents an extensive list of such publications [1–857] on all the applied reliability and quality areas covered in the book. These publications are separated into each of these applied areas: quality in healthcare ([1–50] for the period 1989–2005), Internet reliability ([51–117] for the period 1995–2004), quality control in the food industry ([118–203] for the period 1979–2006), quality control in the textile industry ([204–255] for the period 1960–2005), software quality ([256–560] for the period 1990–2005), robot reliability ([561–636] for the period 1993–2004), power system reliability ([637–836] for the period 1990–2006), and medical equipment reliability ([837–857] for the period 2000–2005).

The main objective of this listing is to provide readers with sources for obtaining additional information on applied reliability and quality.

A.2 Publications

A.2.1 Quality in Healthcare

1 Al-Assaf, A.F., Schmele, J.A., The Textbook of Total Quality in Healthcare, St. Lucie Press, Delray Beach, Florida, 1993.

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A.2.6 Robot Reliability

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A.2.8 Medical Equipment Reliability

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Author Biography

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Prof. Dhillon has served as a consultant to various organizations and bodies and has many years of experience in the industrial sector. At the University of Ottawa, he has been teaching reliability, quality, engineering management, design, and related areas for over 26 years. He has also lectured in over 50 countries, including keynote addresses at various international scientific conferences held in North America, Europe, Asia, and Africa. In March 2004, Dr. Dhillon was a distinguished speaker at the Conf./Workshop on Surgical Errors (sponsored by White House Health and Safety Committee and the Pentagon), held at the Capitol Hill (One Constitution Avenue, Washington, D.C.).

Professor Dhillon attended the University of Wales, where he received a BS in electrical and electronic engineering and an MS in mechanical engineering. He received a Ph.D. in industrial engineering from the University of Windsor.

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