Life Cycle Costing for Engineers
Life Cycle Costing for Engineers

B.S. DHILLON
This book is affectionately dedicated to my dear friend,

Dr. G. S. Guram, in thanks for his guidance, honesty, support,

and friendship over the years.
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Preface

Today, in the global economy, the procurement decisions for many engineering products, particularly expensive ones, are not made on initial procurement costs alone, but rather on their life cycle costs. Past experiences indicate that often product ownership cost exceeds the procurement cost. In fact, according to some studies, the product ownership cost (i.e., logistics and operating cost) can vary from 10 to 100 times the original acquisition cost.

Over the past 20 years, a large number of journal and conference proceedings articles on life cycle costing have appeared; however, to my knowledge, only two or three books specifically covering certain areas of civil engineering have been published. More specifically, no general book on life cycle costing was published during this period. In 1989, I published a general book on the topic by reviewing and listing all the journal and conference proceedings articles up to 1989.

The absence of an up-to-date general book on the topic has caused a great deal of difficulty for information seekers because they have had to consult many different and diverse sources. Thus, the main objective of this book is to cover all the latest and most useful aspects of life cycle costing in a single volume and thus eliminate the need to consult many different and diverse sources to obtain desired information. The sources of most of the material presented are listed in the reference section at the end of each chapter. These will be useful to readers who desire to delve more deeply into a specific area or topic.

The book contains a chapter on life cycle costing economics and another on introductory engineering reliability and maintainability concepts considered useful to understanding other chapters of the book. The topics covered in the book are treated in such a manner that the reader does not need previous knowledge to understand the contents. At appropriate places, the book contains examples, along with their solutions; at the end of each chapter, numerous problems test reader comprehension. An extensive list of publications on life cycle costing covering the period from 1988 to 2008 is provided in the bibliography at the end of this book to give readers a view of the intensity of developments on the topic.

The book is composed of 11 chapters. Chapter 1 presents a historical background of life cycle costing, frequently used terms and definition in life cycle costing, useful information on life cycle costing, and the scope of the book. Chapter 2 is devoted to economics concepts considered useful to perform life cycle cost analysis; it also covers topics such as simple interest, compound interest, effective annual interest rate, time-dependent economics formulas, and depreciation methods.
Chapter 3 presents various aspects of life cycle costing fundamentals, including the need and information required for life cycle costing, life cycle costing application areas, approach for incorporating life cycle costing into the planning process for proposals and contracts, areas for evaluating the life cycle costing program, life cycle costing advantages and disadvantages, and life cycle costing data sources. A number of life cycle cost models and cost estimation methods are covered in Chapter 4. The life cycle cost models in the chapter are divided into two areas: general and specific.

Chapter 5 is devoted to reliability, quality, safety, and manufacturing costing. Some of the topics covered in the chapter are reliability cost classifications, models for estimating the cost of reliability-related tasks, quality cost classifications, quality cost indexes, safety cost and its related facts and figures, safety cost estimation models, and manufacturing cost estimation models. Chapter 6 presents various important aspects of maintenance, maintainability, usability, and warranty costing. It covers topics such as reasons for maintenance costing, factors influencing maintenance cost, types of maintenance costs, preventive and corrective maintenance labor cost estimation, maintenance cost data collection, maintainability investment cost elements, manufacturer warranty and reliability improvement warranty costs, usability costing and related facts and figures, and principal costs of ignoring product usability and product usability cost estimation.

Chapters 7 and 8 are devoted to computer system life cycle costing and transportation system life cycle costing, respectively. Some of the topics covered in Chapter 7 are computer system life cycle cost models, computer system maintenance cost, software life cycle cost influencing factors and model, and software cost estimation methods and models. Chapter 8 includes topics such as aircraft life cycle cost, aircraft turbine engine life cycle cost, aircraft cost drivers, cargo ship life cycle cost, ship operating and support costs, urban rail life cycle cost, and city bus life cycle cost estimation models.

Chapter 9 presents various important aspects of civil engineering structures and energy systems life cycle costing. Some of the topics covered in the chapter are building life cycle cost, steel structure life cycle cost, bridge and waste treatment facilities life cycle costs, building energy cost estimation, appliance life cycle costing, and an energy system life cycle cost estimation model.

Chapter 10 is devoted to miscellaneous cost estimation models and it presents a total of 12 such models. Some of these models include the plant cost estimation model, program error cost estimation model, satellite procurement cost estimation model, and tank gun system life cycle cost estimation model.

Finally, Chapter 11 presents various introductory aspects of engineering reliability and maintainability. The topics covered in the chapter include bathtub hazard rate curve; common reliability networks; general reliability, mean time to failure, and hazard rate formulas; maintainability measures; and reliability and maintainability tools.
This book will be useful to many individuals, including engineering professionals at large, engineering undergraduate and graduate students, engineering administrators, cost analysts, engineering researchers and instructors, and procurement professionals.

I am deeply indebted to many individuals, including colleagues, students, and friends, for their input and encouragement throughout the project. I thank my children, Jasmine and Mark, for their patience, as well as intermittent disturbances that resulted in many desirable breaks! Last, but not least, I thank my boss, other half, and wife, Rosy, for typing various portions of this book and for her timely help in proofreading and tolerance.

B. S. Dhillon
Ottawa, Ontario
The Author

B. S. Dhillon is a professor of engineering management in the Department of Mechanical Engineering at the University of Ottawa. He has served as a chairman/director of the Mechanical Engineering Department/Engineering Management Program for over 10 years at the same institution. He has published 343 articles (201 journal articles and 142 conference proceedings) on reliability, safety, engineering management, etc. He is or has been on the editorial boards of nine international scientific journals. In addition, Dr. Dhillon has written 35 books on various aspects of reliability, design, safety, quality, and engineering management published by Wiley (1981), Van Nostrand (1982), Butterworth (1983), Marcel Dekker (1984), Pergamon Press (1986), etc. His books are being used in over 100 countries and many of them have been translated into languages such as German, Russian, and Chinese. He served as general chairman of two international conferences on reliability and quality control held in Los Angeles and Paris in 1987.

Professor 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 taught reliability, quality, engineering management, design, and related areas for over 29 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 Conference/Workshop on Surgical Errors (sponsored by the White House Health and Safety Committee and the Pentagon) held on Capitol Hill.

Professor Dhillon attended the University of Wales, where he received a BS degree in electrical and electronic engineering and an MS degree in mechanical engineering. He received a PhD degree in industrial engineering from the University of Windsor.
1

Introduction

1.1 Background

Today, in the global economy and due to various other market pressures, the acquisition decisions of many engineering systems, particularly the expensive ones, are not made based on initial procurement costs but rather on their life cycle costs. Past experiences indicate that often engineering system ownership costs exceed acquisition costs. In fact, according to various studies [1], the engineering system ownership cost (i.e., logistic and operating cost) can vary from 10 to 100 times the original acquisition cost.

The life cycle cost of a system may be defined simply as the sum of all costs incurred during its life span (i.e., the total of acquisition and ownership costs). The term life cycle costing was used for the first time in 1965 in a report entitled “Life Cycle Costing in Equipment Procurement” [2]. This report was prepared by the Logistics Management Institute, Washington, D.C., for the assistant secretary of defense for installations and logistics, U.S. Department of Defense, Washington, D.C.


In 1974, the concept of life cycle costing was formally adopted by the state of Florida and, in 1975, a project entitled “Life Cycle Budgeting and Costing as an Aid in Decision Making” was initiated by the United States Department of Health, Education, and Welfare [7]. In 1978, the U.S. Congress passed the National Energy Conservation Policy Act, which made it mandatory for every new federal building to be life cycle cost effective [8].

Since 1974, states such as New Mexico, Alaska, Maryland, North Carolina, and Texas have passed legislation that make life cycle cost analysis mandatory in the planning, design, and construction of all state buildings [8]. In 1981, a journal article presented a comprehensive list of publications on life cycle costing [9]. In 1989, Dhillon presented a list of over 500 publications on various aspects of life cycle costing [8].
Since 1989, many people have contributed to the subject of life cycle costing. An extensive list of publications on life cycle costing covering 1988–2007 is presented in the bibliography at the end of this book.

1.2 Terms and Definitions

Many terms and definitions are used in the area of life cycle costing. Some of the frequently used terms and definitions that are directly or indirectly related to life cycle costing include [8,10–15]:

- **Cost** is the amount of money paid or payable for the acquirement of materials, property, or services.
- **Procurement cost** is the total of investment or acquisition costs (non-recurring and recurring).
- **Ownership cost** is the total of all costs other than the procurement cost during the life span of an item.
- **Life cycle cost** is the sum of all costs incurred during the life span of an item or system (i.e., the total of procurement and ownership costs).
- **Recurring cost** is the cost that recurs periodically during the life span of a project or item.
- **Nonrecurring cost** is the cost that is not repeated.
- **Reliability** is the probability that an item or system will perform its function satisfactorily for the desired period when used according to specified conditions.
- **Maintainability** is the probability that a failed item or system will be restored to its satisfactory working state within a stated total downtime when maintenance action is started per specified conditions.
- **Downtime** is the total time during which the item or system is not in a condition to perform its specified mission or function.
- **Manufacturing cost** is the sum of fixed and variable costs chargeable to the manufacture of a specified item or system.
- **Maintenance** is all scheduled and unscheduled actions necessary to keep an item or system in a serviceable state or restore it to serviceability. It includes inspection, servicing, modification, repair, etc.
- **Repair cost** is the cost of restoring an item, system, or facility to its original performance or condition.
• **Maintenance cost** is the materials and labor expense required for maintaining items in satisfactory use condition.

• **Mean time to repair** is the average or mean time required to repair an item or system.

• **Failure** is the termination of the ability of an item or system to perform its specified function or mission.

• **Failure rate** is the number of failures of an item or system per unit measure of life (e.g., hours).

• **Compound amount** is the future value of money loaned or invested at compound interest.

• **Redundancy** is the existence of more than one means to perform a specified function.

• **Annuity** is a series of equal payments at equal time intervals.

• **Cost model** is an approach, based on programmatic and technical parameters, for calculating concerned costs.

• **Cost estimating relationship** is an equation that relates cost as the dependent variable to one or more independent variables.

• **Useful life** is the length of time an item or system functions within an acceptable level of failure rate.

• **Mission time** is the time during which the item or system is carrying out its stated mission.

### 1.3 Useful Information on Life Cycle Costing

There are many sources for obtaining, directly or indirectly, life cycle costing–related information. Some of the most useful sources are listed under the following various different categories.

#### 1.3.1 Journals

• *IEEE Transactions on Reliability*

• *Information and Management*

• *Journal of Quality in Maintenance Engineering*

• *International Power Generation*

• *Microelectronics and Reliability*

• *Better Roads*

• *Journal of Infrastructure Systems*

• *International Journal of Production Research*
1.3.2 Conference Proceedings

- Proceedings of the Annual Reliability and Maintainability Symposium
- Proceedings of the Annual ISSAT International Conference on Reliability and Quality in Design
- Proceedings of the Annual Reliability Engineering Conference for the Electric Power Industry
- Proceedings of the Annual American Society for Quality Control (ASQC) Conference
- Proceedings of the IEEE Annual Conference on Industrial Electronics
- Proceedings of the Annual Offshore Technology Conference
- Proceedings of the Annual Canadian Society for Civil Engineering Conference
- Proceedings of the Annual Petroleum and Chemical Industry Conference
- Proceedings of the IEEE Annual Pulp and Paper Industry Technical Conference
- Proceedings of the Annual Conference of the Urban and Regional Information Systems Association

1.3.3 Technical Reports and Manuals


1.3.4 Books

• B. S. Blanchard, Design and Manage to Life Cycle Cost, M/A Press, Portland, OR, 1978


1.3.5 Data Information Sources

- Government Industry Data Exchange Program (GIDEP)
  GIDEP Operations Center
  Naval Weapons Station
  U.S. Department of Navy
  Seal Beach
  Corona, CA 91720

- National Technical Information Center (NTIS)
  5285 Port Royal Road
  Springfield, VA 22151

- Defense Technical Information Center
  DTIC-FDAC
  8725 John J. Kingman Road, Suite 0944
  Fort Belvoir, VA 22060-6218

- Reliability Analysis Center
  Rome Air Development Center
  Griffiss Air Force Base
  Rome, NY 13441-5700

- American National Standards Institute (ANSI)
  11 W. 42nd Street
  New York, NY 10036

- Technical Services Department
  American Society for Quality
  611 W. Wisconsin Avenue
  P.O. Box 3005
  Milwaukee, WI 53201-3005

1.3.6 Organizations

- American Society of Civil Engineers (ASCE)
  1801 Alexander Bell Drive
  Reston, VA 20190-4400.
1.4 Scope of the Book

Nowadays, life cycle costing is receiving increasing attention in various sectors of the economy, including government procurements and industry. Over the past two decades, a large number of journal and conference proceedings articles have appeared; however, to the best of the author’s knowledge, only two or three books specifically covering certain areas of civil engineering have been published. More specifically, no general book on life cycle costing has been produced during this period.

Professionals and others involved in life cycle costing need up-to-date information on the subject and generally face a great deal of difficulty
because they have to consult many different and diverse sources. This book is an attempt to satisfy this specific need. The book is written after reviewing the currently available literature on life cycle costing. Therefore, all the effort was directed to covering important past and present issues in the field.

Previous knowledge is not generally required to understand the material covered in this book because two chapters on fundamental economics and reliability and maintainability basics are provided to give sufficient background to potential readers. The book will find use in many diverse disciplines and will be useful to engineering professionals at large, engineering undergraduate and graduate students, procurement professionals, engineering instructors and researchers, and engineering administrators.

**Problems**

1. Write an essay on the historical developments in life cycle costing.
2. List at least five sources for obtaining life cycle costing–related information.
3. List at least five books considered important for obtaining life cycle costing-related information.
4. Define the following three terms:
   - life cycle cost
   - ownership cost
   - nonrecurring cost
5. List three of the most important organizations for obtaining life cycle costing-related information.
6. List five important journals from which to obtain life cycle costing-related information.
7. Define the following terms:
   - repair cost
   - maintenance cost
   - procurement cost
8. What is the difference between the terms maintainability and maintenance?
9. Compare the meanings of the following terms:
   - recurring cost
   - nonrecurring cost
10. What is the difference between the terms equipment reliability and equipment maintainability?
References

2

Life Cycle Costing Economics

2.1 Introduction

The discipline of economics plays a key role in life cycle costing because, to calculate the life cycle cost of items, various types of economics-related information are required. Life cycle costing requires that all potential costs be calculated by taking into consideration the time value of money. In modern society, interest and inflation rates are utilized to take into consideration the time value of money.

In fact, the concept of interest is not new; its history may be traced back to 2000 BC in Babylon, where interest on borrowed commodities (e.g., grain) was paid in the form of grain or through other possible means [1]. Thus, in a similar manner in modern times, the future value of present dollars will be greater because of earned interest or smaller because of inflation. Similarly, the present value of an amount of money to be received in the future would generally be less.

In life cycle costing, future costs, such as operation and maintenance costs associated with an item, have to be discounted to their present values before adding them to the item’s acquisition or procurement cost. Over the years, many formulas have been developed in the area of economics for converting money from one point of time to another. Such formulas are considered indispensable in life cycle costing.

This chapter presents various aspects of economics considered useful in performing life cycle costing studies.

2.2 Simple Interest

This is the simplest form of interest and it means that the interest is paid only on the original amount of money borrowed, rather than on the accrued interest. Thus, the total interest paid on the borrowed amount of money is expressed by

\[ I = (P)(n)(i) \]  

(2.1)
where
$I$ is total interest.
$P$ is principal amount (i.e., borrowed).
$n$ is total number of interest periods (e.g., years).
$i$ is interest rate per specified period.

The total amount of money, $A$, at the end of, say, $n$ years is expressed by

$$A = P + I$$

(2.2)

By substituting Equation (2.1) into Equation (2.2), we get

$$A = P + (P)(n)(i)$$

$$= P(1 + ni)$$

(2.3)

**Example 2.1**

A company borrowed $300,000 for a period of 3 years at an annual simple interest rate of 5% to procure engineering equipment. Calculate the total amount of money the company has to pay to the lender at the end of 3 years.

By substituting the given data values into Equation (2.3), we get

$$A = (300,000)(1 + (0.05)(3))$$

$$= $345,000$$

Thus, the total amount of money the company has to pay to the lender at the end of 3 years is $345,000.

### 2.3 Compound Interest

In this case, the interest earned on principal amount, $P$, during each interest period is added (at the end of each period) to the principal amount and thereafter begins earning interest itself for the remaining term of the loan or investment. Thus, at the end of the first interest period (e.g., a year) the total amount is expressed by

$$A_1 = P + (P)(i)$$

$$= P(1 + i)$$

(2.4)

where $A_1$ is the total amount at the end of the first interest period.
At the end of the second interest period (e.g., a year), the total amount is expressed by

\[ A_2 = A_1 (1 + i) \]  
(2.5)

By substituting Equation (2.4) into Equation (2.5), we obtain

\[ A_2 = P (1 + i) (1 + i) \]
\[ = P(1 + i)^2 \]  
(2.6)

where \( A_2 \) is the total amount at the end of the second interest period. Similarly, at the end of the third interest period (e.g., a year), the total amount is expressed by

\[ A_3 = A_2 (1 + i) \]  
(2.7)

By substituting Equation (2.6) into Equation (2.7), we get

\[ A_3 = P (1 + i)^2 (1 + i) \]
\[ = P(1 + i)^3 \]  
(2.8)

where \( A_3 \) is the total amount at the end of the third interest period. Thus, at the end of the \( n \)th interest period (e.g., a year), the total amount is generalized to the following form:

\[ A_n = A_{n-1} (1 + i) \]
\[ = P(1 + i)^n \]  
(2.9)

where
- \( n \) is number of interest periods (e.g., years).
- \( A_n \) is total or compound amount at the end of the \( n \)th interest period (e.g., a year).
- \( A_{n-1} \) is principal amount at the beginning of the \( n \)th interest period (e.g., a year).

The total compound interest earned after the \( n \)th interest period (e.g., a year) is given by

\[ I_c = A_n - P \]  
(2.10)
Example 2.2
Assume that a person deposited $80,000 in a bank for 7 years at annual interest rate of 7%, compounded annually. Calculate the total amount of money at the end of the specified period and the compound interest earned at the end of the same period.

By substituting the given data values into Equations (2.9) and (2.10), we get

\[ A_r = (80,000)(1 + 0.07)^7 \]

\[ = $128,462.52 \]

and

\[ I_c = (80,000)(1 + 0.07)^7 - (80,000) \]

\[ = $48,462.52 \]

Thus, the total amount of money and the compound interest earned at the end of 7 years are $128,462.52 and $48,462.52, respectively.

2.4 Effective Annual Interest Rate
This interest rate may be described simply as the true annual interest rate because it considers the effect of all compounding during the year. The effective annual interest rate can be calculated by using the following equation [2]:

\[ (1 + i_e) = \left( 1 + \frac{i}{m} \right)^m \]

(2.11)

where

\[ i_e \] is effective annual interest rate.

\[ i \] is annual nominal interest rate.

\[ m \] is total number of interest periods in a year.

Note that Equation (2.11) is developed by reasoning that the effective interest rate compounded once a year generates the same interest as a nominal interest rate compounded \( m \) times in a year. By rearranging Equation (2.11), we get

\[ i_e = \left( 1 + \frac{i}{m} \right)^m - 1 \]

(2.12)
Example 2.3
A person deposited $100,000 in a bank at a nominal interest rate of 8% compounded monthly, for 12 months. Estimate the value of the effective annual interest rate.

By substituting the specified data values into Equation (2.12), we get

\[
i_e = \left(1 + \frac{0.08}{12}\right)^{12} - 1
\]

\[
= 1.08299 - 1
\]

\[
= 0.08299
\]

\[
= 8.299\%.
\]

Thus, the value of the effective annual interest rate is 8.299%.

2.5 Time-Dependent Formulas for Application in Life Cycle Cost Analysis

In the published literature, many time-dependent formulas have been developed that can be used to perform life cycle cost analysis. Some of these formulas are presented next.

2.5.1 Single Payment Future Worth Formula

This formula for compound amount was developed earlier in the chapter (in the section on compound interest). Thus, from Equation (2.9), the future worth (compound amount) is

\[
W_f = A_n = P(1+i)^n
\]

(2.13)

where
- \(W_f\) is future worth or amount (i.e., principal amount plus interest earned).
- \(n\) is number of interest periods (e.g., years).
- \(P\) is principal amount.
- \(i\) is compound interest rate per specified period.

2.5.2 Single Payment Present Value Formula

From Equation (2.13), the present value of a future amount of money is given by

\[
V_p = P = \frac{W_f}{(1+i)^n}
\]

(2.14)

where \(V_p\) is the present value.
Example 2.4

Assume that the total operation and maintenance cost of a piece of engineering equipment after its 5-year usage will be $150,000. Calculate the present value of $150,000 if the annual compound interest rate is 6%.

By substituting the given data values into Equation (2.14), we get

\[ V_p = \frac{(150,000)}{(1+0.06)^5} \]

\[ = $112,088.7 \]

Thus, the present value of the engineering equipment total operation and maintenance cost is $112,088.70.

2.5.3 Uniform Periodic Payment Future Amount Formula

This formula is concerned with determining the future amount at the end of \( n \) interest periods (years) of equal payments made at the end of each interest period. All payments are invested at an annual compound interest rate \( i \). The formula is developed next.

At the end of the first year, after the first payment, the future amount is

\[ FA_1 = PA \]  

(2.15)

where

\( FA_1 \) is future amount at the end of the first year.

\( PA \) is payment made at the end of a year.

At the end of the second year, after the second payment and the interest earned on \( FA_1 \), using Equation (2.4) the future amount is

\[ FA_2 = PA + FA_1 (1+i) \]  

(2.16)

where

\( FA_2 \) is future amount at the end of the second year.

\( i \) is annual compound interest rate.

Substituting Equation (2.15) into Equation (2.16) yields

\[ FA_2 = PA + PA(1+i) \]  

(2.17)

At the end of the third year, after the third payment and the interest earned on \( FA_2 \), the future amount is

\[ FA_3 = PA + FA_2 (1+i) \]  

(2.18)

where \( FA_3 \) is the future amount at the end of the third year.
By substituting Equation (2.17) into Equation (2.18), we get

\[ FA_3 = PA + PA(1 + i) + PA(1 + i)^2 \]  

(2.19)

At the end of the fourth year, after the fourth payment and the interest earned on \( FA_3 \), the future amount is

\[ FA_4 = PA + FA_3(1 + i) \]  

(2.20)

where \( FA_4 \) is the future amount at the end of the fourth year.

Using Equation (2.19) in Equation (2.20) yields

\[ FA_4 = PA + PA(1 + i) + PA(1 + i)^2 + PA(1 + i)^3 \]  

(2.21)

At the end of the \( n \)th year, after the \( n \)th payment and the interest earned on \( FA_{n-1} \), the future amount is

\[ FA_n = PA + PA(1 + i) + \cdots + PA(1 + i)^{n-2} + PA(1 + i)^{n-1} \]  

(2.22)

where \( FA_n \) is the future amount at the end of the \( n \)th year.

Equation (2.22) is a geometric series that can be summed as follows: Multiply both sides of Equation (2.22) by \((1 + i)\) to obtain

\[ (1 + i)FA_n = PA(1 + i) + PA(1 + i)^2 + \cdots + PA(1 + i)^{n-2} + PA(1 + i)^n \]  

(2.23)

By subtracting Equation (2.22) from Equation (2.23), we get

\[ (1 + i)FA_n - FA_n = PA(1 + i)^n - PA \]  

(2.24)

After rearranging Equation (2.24), we obtain

\[ FA_n = \frac{PA[(1 + i)^n - 1]}{i} \]  

(2.25)

**Example 2.5**

Assume that a person deposits $30,000 at the end of each year for the next 8 years. Calculate the total future amount of the money deposited after the 8-year period, if the annual compound interest rate is 5%.

By substituting the given data values into Equation (2.25), we get

\[ FA = (30,000) \left[ \frac{(1 + 0.05)^8 - 1}{0.05} \right] \]

\[ = $286,473.26 \]

Thus, the total future amount of the money deposited after the 8-year period is $286,473.26.
2.5.4 Uniform Periodic Payment Present Value Formula

This formula is concerned with determining the present value or worth at the end of \( n \) interest periods (years) of equal payments made at the end of each interest period. All payments are invested at an annual compound interest rate \( i \).

The formula is developed as follows: At the end of the first year, after the first payment, the present value of that payment from Equation (2.14) is

\[
V_{p1} = \frac{PA}{(1+i)}
\]  

(2.26)

where

- \( V_{p1} \) is present value of the payment, \( PA \), made at the end of the first year.
- \( i \) is annual compound interest rate.

At the end of the second year, after the second payment, the present value of that payment from Equation (2.14) is

\[
V_{p2} = \frac{PA}{(1+i)^2}
\]  

(2.27)

where \( V_{p2} \) is present value of the payment, \( PA \), made at the end of the second year.

Similarly, at the end of the \( n \)th year, after the \( n \)th payment, the present value of that payment from Equation (2.14) is

\[
V_{pn} = \frac{PA}{(1+i)^n}
\]  

(2.28)

where

- \( V_{pn} \) is present value of the payment, \( PA \), made at the end of the \( n \)th year.
- \( n \) is number of interest periods or years.

Using Equations (2.26)–(2.28), we get the following equation for the present value of all payments:

\[
PV = V_{p1} + V_{p2} + \cdots + V_{pn}
\]  

\[
= \frac{PA}{(1+i)} + \frac{PA}{(1+i)^2} + \cdots + \frac{PA}{(1+i)^n}
\]  

(2.29)

Equation (2.29) is a geometric series that can be summed as follows: Multiply both sides of Equation (2.29) by \( \frac{1}{(1+i)} \) to obtain

\[
\frac{PA}{(1+i)} = \frac{PA}{(1+i)^2} + \frac{PA}{(1+i)^3} + \cdots + \frac{PA}{(1+i)^{n+1}}
\]  

(2.30)
By subtracting Equation (2.29) from Equation (2.30), we obtain

\[
\frac{PV}{(1+i)} - PV = \frac{PA}{(1+i)^{n+1}} - \frac{PA}{(1+i)}
\]  

(2.31)

After rearranging Equation (2.31), we get

\[
PV = PA \left[ \frac{1 - (1+i)^{-n}}{i} \right]
\]  

(2.32)

**Example 2.6**

Assume that a person deposits $50,000 at the end of each year for the next 5 years. Calculate the present value of all payments, if the annual compound interest rate is 4%.

By substituting the given data values into Equation (2.32), we get

\[
PV = 50,000 \left[ \frac{1 - (1+0.04)^{-5}}{0.04} \right]
\]

\[
= 222,591.10
\]

Thus, the present value of all payments is $222,591.10.

### 2.5.5 Formulas to Calculate Value of Annuity Payments When Annuity’s Present and Future Values Are Given

An annuity is a series of equal payments at equal time intervals. Thus, from Equation (2.25) the value of annuity payments when the future value of the annuity is known is given by

\[
PA_{f_0} = \frac{(FA_n)(i)}{(1+i)^n - 1}
\]  

(2.33)

where

- \(PA_{f_0}\) is the value of annuity payments when the future value of the annuity is given.
- \(FA_n\) is the future value of the annuity after \(n\) interest periods or years.
- \(n\) is total number of interest periods or years.
- \(i\) is annual compound interest rate.

Similarly, from Equation (2.32), the value of annuity payments when the present value of the annuity is given is expressed by

\[
PA_{p_0} = \frac{(PV)(i)}{1 - (1+i)^{-n}}
\]  

(2.34)
where

$PA_{pu}$ is the value of annuity payments when the present value of the annuity is known.

$PV$ is present value of all payments.

**Example 2.7**

Assume that a firm plans to acquire a facility at the end of the next 5 years. The estimated cost of the facility after the specified period is $800,000. The firm has decided to make deposits of equal amounts of money at the end of each of next 5 years so that the total amount accumulates to $800,000. Calculate the amount of money the firm should deposit at the end of each year, if the annual compound interest rate is 8%.

By substituting the given data values into Equation (2.33), we get

$$PA_{bu} = \frac{(800,000)(0.08)}{(1+0.08)^5 - 1}$$

$$= \$136,365.16$$

This means that the firm should deposit $136,365.16 at the end of each year to fulfill its objective.

**Example 2.8**

Assume that we have the following data values:

$PV = \$400,000$, $i = 4\%$, and $n = 7$ years

Using Equation (2.34), calculate the value of annuity payments.

Using the given data values in Equation (2.34) yields

$$PA_{pu} = \frac{(400,000)(0.04)}{1-(1+0.04)^{-7}}$$

$$= \$66,643.84$$

Thus, the value of annuity payments is $66,643.84.

### 2.6 Depreciation Methods

The term *depreciation* simply means decline in value. There are different types of depreciation with respect to engineering equipment: monetary depreciation, technological depreciation, physical depreciation, and
functional depreciation [3]. Over the years, a number of methods with respect to monetary depreciation have been developed. Three of these methods are presented next [2–4].

2.6.1 Sum-of-Years-Digits (SYD) Method

The name of this method is derived from the calculation procedure used. The method provides a larger depreciation charge during early life years of the equipment, system, or product than during its later life years.

The annual depreciation charge is expressed by [2,4]

\[
DC_a = (C_a - V_s) \left[ \frac{(L_s - n + 1)}{(1 + 2 + 3 + \cdots + L_s)} \right] \\
= (C_a - V_s) \frac{(L_s - n + 1)}{L_s (L_s + 1)}
\]

(2.35)

where
- \(DC_a\) is annual depreciation charge.
- \(C_a\) is product or item acquisition cost.
- \(V_s\) is product or item salvage value at the end of its service life.
- \(L_s\) is product or item service life expressed in years.
- \(n\) is total number of years of the product or item in actual service.

The book value of the product or item at the end of year \(n\) is given by [4]

\[
V_{bn} = 2(C_a - V_s) \left[ \frac{1 + 2 + 3 + \cdots + (L_s - n)}{L_s (L_s + 1)} \right] + V_s
\]

(2.36)

where \(V_{bn}\) is product or item book value at the end of year \(n\).

**Example 2.9**

Assume that the cost, useful life, and salvage value after the useful life of an engineering system are $900,000, 10 years, and $60,000, respectively. Calculate the system book value at the end of year 5 by using the SYD method.

By substituting the given data values into Equation (2.36), we obtain

\[
V_{bs} = 2 \cdot 900,000 - 60,000 \left[ \frac{1 + 2 + 3 + \cdots + (10 - 5)}{10(10 + 1)} \right] + 60,000
\]

\[= $289,090.90\]

Thus, the system book value at the end of year 5 is $289,090.90.
2.6.2 Straight-Line Method

This method assumes the linear decrease with time in the value of an item, product, or system. Thus, during the service life of the item, product, or system an equal sum of money is charged each year for depreciation. The annual depreciation is expressed by

\[ DC_a = (C_a - V_S)/L_S \]  
(2.37)

The book value of the product, item, or system at the end of year \( n \) is given by

\[ V_{bn} = C_a - n(DC_a) \]  
(2.38)

Using Equation (2.37) in Equation (2.38) yields

\[ V_{bn} = C_a - n\left[\frac{(C_a - V_S)}{L_S}\right] \]  
(2.39)

Example 2.10

Assume that the acquisition cost, the expected useful life, and salvage value after the useful life of a piece of equipment are $600,000, 12 years, and $30,000, respectively. The equipment annual depreciation charge is constant. Calculate the equipment annual depreciation charge.

By substituting the given data values into Equation (2.37), we get

\[ DC_a = (600,000 - 30,000)/12 \]

\[ = $47,500 \]

Thus, the equipment annual depreciation charge is $47,500.

2.6.3 Declining-Balance Method

This method is also known as the Matheson formula or the constant percentage method. In this approach, the annual depreciation is a fixed percentage of the book value at the beginning of the year. Although the annual depreciation is different for each year, the declining-balance (i.e., fixed-percentage) factor remains constant throughout the useful life of the equipment or item.

This method writes off the cost of the equipment or item early in its life at an accelerated rate and at correspondingly lower annual charges close to the final years of the equipment or item service. The depreciation factor or rate
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is expressed by

\[ R_d = 1 - \frac{V_S}{C_a}^{1/LS} \]  
(2.40)

where \( R_d \) is the depreciation rate or factor. Note that this method assumes that the salvage value of the equipment or item is always positive.

The book value of the equipment or item at the end of year \( n \) is defined by

\[ V_{bn} = C_a (1 - R_d)^n \]  
(2.41)

By inserting Equation (2.40) into Equation (2.41), we get

\[ V_{bn} = C_a \left(\frac{V_S}{C_a}\right)^{n/LS} \]  
(2.42)

The annual depreciation charge is defined by

\[ DC_a = [V_{b(n-1)}] R_d \]  
(2.43)

where \( V_{b(n-1)} \) is the equipment or item book value at \( (n-1) \) years.

Using Equation (2.40) in Equation (2.43) yields

\[ DC_a = [V_{b(n-1)}] \left[ 1 - \left(\frac{V_S}{C_a}\right)^{1/LS} \right] \]  
(2.44)

Example 2.11

Assume that the cost, useful life, and salvage value after the useful life of a piece of engineering equipment are $700,000, 15 years, and $80,000, respectively.

Calculate the equipment book value at the end of year 10 by using the declining-balance method.

By substituting the specified data values into Equation (2.42), we obtain

\[ V_{b10} = (700,000) \left[ \frac{80,000}{700,000} \right]^{0.15} \]

\[ = \$164,851.4 \]

Thus, the equipment book value at the end of year 10 is $164,851.40.
Problems

1. What is the difference between simple interest and compound interest?

2. Define the following terms:
   - present value
   - future amount
   - depreciation

3. A company borrowed $400,000 for a period of 5 years at an annual simple interest rate of 6% to procure an engineering system. Calculate the total amount of money the company has to pay to the lender at the end of 5 years.

4. Prove the following equation:

   \[ A_n = P(1 + i)^n \]  

   where
   - \( n \) is the number of interest periods.
   - \( A_n \) is the total or compound amount at the end of the \( n \)th interest period.
   - \( P \) is the principal amount (i.e., borrowed).

5. What is effective annual interest rate?

6. An individual deposited $90,000 in a bank at a nominal interest rate of 7% compounded monthly, for 10 months. Estimate the value of the effective annual interest rate.

7. Assume that the total operation and maintenance cost of an engineering system after its 7-year usage will be $100,000. Calculate the present value of $100,000 if the annual compound interest rate is 4%.

8. A company plans to procure a facility at the end of the next 7 years. The estimated cost of the facility after the specified period is $1,000,000. The company has decided to make deposits of equal sums of money at the end of each of the next 7 years so that the total amount accumulates to $1,000,000. Calculate the amount of money the company should deposit at the end of each year, if the annual compound interest is 6%.

9. Assume that the cost, useful life, and salvage value after the useful life of a piece of engineering equipment are $660,000, 8 years, and $40,000, respectively. The equipment annual depreciation charge is constant. Calculate the equipment annual depreciation charge by using the straight-line method.

10. Compare the SYD and declining-balance depreciation methods.
References

3

Life Cycle Costing Fundamentals

3.1 Introduction

Past experience indicates that engineering equipment procured at the lowest cost may not necessarily be that which also costs the least amount of money over its useful life. More specifically, the equipment ownership cost could be quite significant and frequently exceeds the procurement cost. For example, various studies performed by the U.S. Department of Defense indicate that the maintenance cost over equipment’s useful life could be many times the procurement cost [1,2].

In fact, by simply examining the Defense Department’s overall annual budget, it can easily be observed that operation and maintenance costs are an important factor. For example, in fiscal year 1974, 27% of the overall budget of the Department of Defense accounted for operation and maintenance activities and 20% was for procurement [3,4]. This simply means that, in equipment acquisition analysis, it is important to consider the cost of equipment ownership. Otherwise, procurement decisions based totally on the acquisition cost may not be the best decision in the long term.

The approach used for estimating the total life cycle cost of equipment procurement is known as life cycle costing. This chapter presents various fundamental aspects of this approach.

3.2 Need and Information Required for Life Cycle Costing

Life cycle costing is increasingly being used in the industrial sector around the world to make various types of decisions that directly or indirectly concern engineering equipment and systems. There could be many reasons for this upward trend, such as [4]

- competition;
- increasing operation and maintenance costs;
- budget limitations;
- expensive products or systems (e.g., military systems, space systems, and aircraft);
• rising inflation; and
• increasing awareness of cost effectiveness among product, equipment, and system users.

Various types of information are required to perform life cycle costing studies. These include the acquisition cost of the item, the useful operational life of the item in years, the annual maintenance cost of the item, transportation (delivery) and installation costs of the item, discount and escalation rates, the annual operating cost of the item, taxes (e.g., tax benefits from depreciation, investment tax credit), and the salvage value or disposal cost of the item [5].

In any case, prior to starting a life cycle costing study, it is considered useful to seek answers to questions on topics such as the following [6,7]:

• goal of the estimate;
• assumptions and ground rules;
• treatment of uncertainties;
• required data;
• required details of the analysis and analysis-related constraints;
• involved personnel and the responsibility of the cost analyst;
• controlling and auditing the life cycle costing process by the seller’s and purchaser’s management;
• estimating procedures to be followed;
• life cycle cost analysis users;
• life cycle cost analysis format;
• life cycle costing time schedule;
• required accuracy and precision of the analysis; and
• fund limitations.

### 3.3 Life Cycle Costing Application Areas

Life cycle costing can be used in a large number of areas. The six primary uses of life cycle cost include [6]:

• selecting among competing bidders for a project;
• long-range planning and budgeting;
• controlling an ongoing project;
• comparing competing projects;
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- deciding the replacement of aging equipment; and
- comparing logistics concepts.

Lamar [8] has presented the following somewhat more specific applications of life cycle cost analyses:

- determining cost drivers;
- forecasting future budget needs;
- selecting the most effective procurement strategy;
- improving comprehension of fundamental design-related parameters in equipment or system product design and development;
- formulating contractor incentives;
- making strategic decisions and design trade-offs;
- optimizing appropriate training needs;
- choosing among options;
- providing effective objectives for program control;
- assessing new technology application; and
- carrying out source selections.

3.4 Life Cycle Costing Activities and Associated Steps

Many activities are associated with life cycle costing. Some of these include [9]:

- defining an item’s or a product’s life cycle;
- identifying all cost drivers;
- establishing escalated and discounted life cycle costs;
- developing an accounting breakdown structure;
- establishing cost estimating relationships for each and every component in the life cycle cost breakdown structure;
- developing constant dollar cost profiles;
- defining activities that generate an item’s or a product’s ownership costs;
- conducting appropriate sensitivity analysis; and
- identifying cause and effect relationships.

Over the years, many authors have proposed steps for performing life cycle cost analysis [10–13]. Figure 3.1 shows 10 steps considered quite effective in
performing life cycle cost analysis [14]. Additional information on these steps is available in reference 14.

3.5 Approach for Incorporating Life Cycle Costing into the Planning Process for Proposals and Contracts

Over the years, equipment or system procurement contracts requiring contractor or manufacturer commitments for equipment or system life cycle cost have increased quite significantly. Many of these contractors and
manufacturers are not familiar with life cycle cost-related acquisitions. In order to overcome this shortcoming, a six-step approach for these contractors and manufacturers to prepare for life cycle cost-related acquisitions follows [15]:

- **Organize for life cycle costing.** This step is basically concerned with establishing a proper organization for life cycle costing and assigning life cycle cost responsibilities.
- **Gather and develop background information related to life cycle costing.** This step calls for becoming acquainted with the existing life cycle cost estimation models and components of the life cycle cost considered vital to the company’s product and equipment.
- **Perform analysis of all requirements for life cycle costing-related response.** This step involves tasks such as performing analysis of likely life cycle cost estimation model components to determine the types of data required for life cycle cost response and performing analysis of the information considered essential for management decision making.
- **Develop a plan for the life cycle costing technical proposal.** This step is basically concerned with planning the life cycle costing–related response for a technical proposal under consideration.
- **Develop a plan to identify and analyze life cycle cost risk.** This step calls for developing a plan to identify risk areas and address methods to analyze such risks when life cycle cost–related guarantees are committed as an element of a proposed procurement.
- **Develop a plan to achieve life cycle cost goals.** This step involves developing a plan to achieve the set life cycle cost goals during the specified contract period.

### 3.6 Areas for Evaluating a Life Cycle Costing Program

In order to keep a life cycle costing program in good order, it is essential to evaluate it periodically. There are many areas in which questions could be raised to determine the effectiveness of the life cycle costing program. Some of these areas include [4,6,16]:

- effectiveness of cost-estimating techniques used;
- cost model construction;
- broadness of cost-estimating database;
- identification of all cost drivers;
- proper consideration of discounting and inflation factors;
• performance of trade-off studies;
• inclusion of all life cycle costing–related requirements into design subcontracts;
• cost performance review of subcontractors;
• cost estimates’ validation through an independent appraisal;
• life cycle costing management representative’s qualifications;
• coordination of life cycle cost and design to cost-related activities;
• defining of cost priority with respect to factors such as product performance, delivery schedule, and other requirements by management;
• formal notifications to all organizations or departments involved in the life cycle costing program regarding their cost goals;
• compatibility of system safety, reliability, and maintainability programs with life cycle cost–related requirements; and
• awareness of the buyer regarding the top 10 cost drivers and proper suggestions to reduce such costs.

3.7 Life Cycle Costing Data Sources

In order to perform effective life cycle cost analysis, the availability of reliable cost data is vital. This means that the existence of good cost data banks is very important. Thus, in developing a new cost data bank, careful attention must be given to factors such as comprehensiveness, size, uniformity, flexibility, responsiveness, ready accessibility, orientation, and expansion or contraction capability [17]. Furthermore, at a minimum, a life cycle costing data bank should incorporate information such as user pattern records, descriptive records (hardware and site), cost records, and procedural records (operation and maintenance).

Although data for life cycle cost analysis can be obtained from many sources, their amount and quality may vary quite considerably. Therefore, prior to starting a life cycle cost study, it is important to examine carefully factors such as data bias, data applicability, data availability, data comparability to other existing data, data orientation toward the problem under consideration, and data coordination with other information. Some of the important sources for obtaining cost-related data include [4,17,18]:

• costs for pressure vessels [19];
• American Building Owners and Managers Association (BOMA) handbook;
• costs for solid waste shredders [20];
• costs for heat exchangers [21–23];
• unit price manuals: Marshall and Swift, means, Dodge, Richardson, and building cost file;
• cost analysis cost estimating (CACE) model [24,25];
• costs for varieties of process equipment [26–29];
• budgeting annual cost estimating (BACE) model [24,25];
• programmed review of information for costing and evaluation (PRICE) model [24]; and
• costs for motors, storage tanks, centrifugal pumps, etc. [30,31].

3.8 Life Cycle Costing Advantages and Disadvantages and Related Important Points

Over the years, various advantages and disadvantages of life cycle costing have been identified by various professionals. Some of the important advantages of life cycle costing are shown in Figure 3.2 [4]. In contrast, some of the main disadvantages of life cycle costing include that it

• is time consuming;
• is costly;
• has doubtful data accuracy; and
• is a trying task when attempting to obtain data for analysis.

![Diagram of life cycle costing advantages](K10869_Book.indb)

**FIGURE 3.2**
Life cycle costing advantages.
Many important points are associated with life cycle costing, some of which include:

- The main goal of life cycle costing is to get the maximum benefit from limited resources.
- Management plays a key role in making life cycle costing a worthwhile effort.
- Risk management is the essence of life cycle costing in general.
- The availability of good data is very important for good life cycle cost estimates.
- The life cycle cost model must include all program-related costs.
- There is a definite need for both the product manufacturer and the user to organize effectively to control life cycle cost.
- There is a definite need to perform trade-offs among life cycle cost, design to cost, and performance throughout the life of the program.
- Some surprises may still occur, even when the estimator is very competent.
- Life cycle costing is gaining importance as a method for performing design optimization, making strategic decisions, conducting detailed trade-off studies, etc.
- A highly knowledgeable and experienced cost analyst may compensate for various database-related difficulties.

3.9 Life Cycle Costing Concept Application in Selecting Equipment from Competing Manufacturers

From time to time, equipment or system users are faced with selecting the most cost-effective equipment or system from a number of competing manufacturers. In situations such as these, life cycle costing becomes a useful tool. The application of the life cycle costing concept in selecting the most cost-effective equipment from competing manufacturers is demonstrated through Example 3.1.

Example 3.1

A company using machining equipment to manufacture a certain type of engineering part is contemplating replacing it with a better version. Four different pieces of machining equipment, manufactured by four different manufacturers, are being considered for its replacement; their data are presented in Table 3.1.
Determine which of the four pieces of machining equipment should be procured to replace the existing one in regard to their life cycle costs.

**Life Cycle Cost Analysis: Machining Equipment A**

The expected cost, $C_{fa}$, of failure per year of machining equipment A is given by

$$C_{fa} = (2,000)(0.08)$$

$$= 160$$

where $C_{fa}$ is the machining equipment A annual expected failure cost.

Using Chapter 2 and reference 4, the present value, $PV_{fa}$, of machining equipment A life cycle failure cost is expressed by

$$PV_{fa} = C_{fa} \left[ \frac{1-(1+i)^{-k}}{i} \right]$$  \hspace{1cm} (3.1)

where

- $PV_{fa}$ is present value of machining equipment A life cycle failure cost.
- $i$ is annual interest rate.
- $k$ is machining equipment’s expected useful life in years.

By substituting the preceding calculated value and the given data values into Equation (3.1), we get

$$PV_{fa} = (160) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]$$

$$= 1176.61$$

---

**TABLE 3.1**

Data for Four Types of Machining Equipment under Consideration

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Machining Equipment A</th>
<th>Machining Equipment B</th>
<th>Machining Equipment C</th>
<th>Machining Equipment D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Procurement cost</td>
<td>$300,000</td>
<td>$270,000</td>
<td>$290,000</td>
<td>$350,000</td>
</tr>
<tr>
<td>2</td>
<td>Expected useful life in years</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Annual failure rate</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>Cost of a failure</td>
<td>$2,000</td>
<td>$2,500</td>
<td>$3,000</td>
<td>$1,000</td>
</tr>
<tr>
<td>5</td>
<td>Annual interest rate</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>6</td>
<td>Annual operating cost</td>
<td>$6,000</td>
<td>$7,000</td>
<td>$6,500</td>
<td>$8,000</td>
</tr>
</tbody>
</table>
Similarly, using Chapter 2 and reference 4, the present value, $PV_{ao}$, of machining equipment A life cycle operating cost is given by

$$PV_{ao} = C_{oa} \left[ \frac{1-(1+i)^{-k}}{i} \right]$$

(3.2)

where
- $PV_{ao}$ is present value of machining equipment A life cycle operating cost.
- $C_{oa}$ is machining equipment A annual operating cost.

By substituting the given data values into Equation (3.2), we get

$$PV_{ao} = (6,000) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]$$

$$= $44,160.52$$

Thus, the life cycle cost of machining equipment A is given by

$$LCC_a = PC_a + PV_{ao} + PV_{ao}$$

(3.3)

where
- $LCC_a$ is machining equipment A life cycle cost.
- $PC_a$ is machining equipment A procurement cost.

By substituting the given data value and the preceding calculated values into Equation (3.3), we obtain

$$LCC_a = 300,000 + 1176.61 + 44,160.52$$

$$= $345,337.13$$

**Life Cycle Cost Analysis: Machining Equipment B**

The expected cost, $C_{fb}$, of failure per year of machining equipment B is given by

$$C_{fb} = (2,500)(0.07)$$

$$= $175$$

where $C_{fb}$ is machining equipment B annual expected failure cost.

Using Chapter 2 and reference 4, the present value, $PV_{bf}$, of machining equipment B life cycle failure cost is given by

$$PV_{bf} = C_{fb} \left[ \frac{1-(1+i)^{-k}}{i} \right]$$

(3.4)

where $PV_{bf}$ is present value of machining equipment B life cycle failure cost.
By substituting the preceding calculated value and the given data values into Equation (3.4), we get

\[
P_{V_{ld}} = (175) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]
\]

\[= \$1,288.01\]

Similarly, using Chapter 2 and reference 4, the present value, \(P_{V_{bo}}\) of machining equipment B life cycle operating cost is expressed by

\[
P_{V_{bo}} = C_{ob} \left[ \frac{1-(1+i)^{-k}}{i} \right]
\]

(3.5)

where

\(P_{V_{bo}}\) is present value of machining equipment B life cycle operating cost.

\(C_{ob}\) is machining equipment B annual operating cost.

By substituting the given data values into Equation (3.5), we obtain

\[
P_{V_{bo}} = (7,000) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]
\]

\[= \$51,520.61\]

Thus, the life cycle cost of machining equipment B is given by

\[
LCC_{b} = PC_{b} + P_{V_{ld}} + P_{V_{bo}}
\]

(3.6)

where

\(LCC_{b}\) is machining equipment B life cycle cost.

\(PC_{b}\) is machining equipment B procurement cost.

By substituting the given data value and the preceding calculated values into Equation (3.6), we get

\[
LCC_{b} = 270,000 + 1,288.01 + 51,520.61
\]

\[= \$322,808.62\]

Life Cycle Cost Analysis: Machining Equipment C

The expected cost, \(C_{fc}\) of failure per year of machining equipment C is given by

\[
C_{fc} = (3,000)(0.06)
\]

\[= \$180\]

where \(C_{fc}\) is machining equipment C annual expected failure cost.
Using Chapter 2 and reference 4, the present value, \( PV_{cf} \) of machining equipment C life cycle failure cost is expressed by

\[
PV_{cf} = C_k \left[ \frac{1 - (1 + i)^{-k}}{i} \right]
\]  

(3.7)

where \( PV_{cf} \) is present value of machining equipment C life cycle failure cost.

By substituting the preceding calculated value and the given data values into Equation (3.7), we get

\[
PV_{cf} = (180) \left[ \frac{1 - (1 + 0.06)^{-10}}{0.06} \right]
\]

= $1,324.81

Similarly, using Chapter 2 and reference 4, the present value, \( PV_{co} \) of machining equipment C life cycle operating cost is expressed by

\[
PV_{co} = C_{oc} \left[ \frac{1 - (1 + i)^{-k}}{i} \right]
\]  

(3.8)

where

\( PV_{co} \) is present value of machining equipment C life cycle operating cost.

\( C_{oc} \) is machining equipment C annual operating cost.

By substituting the given data values into Equation (3.8), we get

\[
PV_{co} = (6,500) \left[ \frac{1 - (1 + 0.06)^{-10}}{0.06} \right]
\]

= $47,840.56

Thus, the life cycle cost of machining equipment C is given by

\[
LCC_c = PC_c + PV_{cf} + PV_{co}
\]  

(3.9)

where

\( LCC_c \) is machining equipment C life cycle cost.

\( PC_c \) is machining equipment C procurement cost.

By substituting the given data value and the preceding calculated values into Equation (3.9), we get

\[
LCC_c = 290,000 + 1,324.81 + 47,840.56
\]

= $339,165.37
Life Cycle Cost Analysis: Machining Equipment D

The expected cost, $C_{fd}$, of failure per year of machining equipment D is given by

$$C_{fd} = (1,000)(0.04)$$

$$= \$40$$

where $C_{fd}$ is machining equipment D annual expected failure cost.

Using Chapter 2 and reference 4, the present value, $PV_{df}$, of machining equipment D life cycle failure cost is expressed by

$$PV_{df} = C_{fd} \left[ \frac{1-(1+i)^{-k}}{i} \right]$$

(3.10)

where $PV_{df}$ is present value of machining equipment D life cycle failure cost.

By substituting the preceding calculated value and the given data values into Equation (3.10), we get

$$PV_{df} = (40) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]$$

$$= \$294.40$$

Similarly, using Chapter 2 and reference 4, the present value, $PV_{do}$, of machining equipment D life cycle operating cost is given by

$$PV_{do} = C_{od} \left[ \frac{1-(1+i)^{-k}}{i} \right]$$

(3.11)

where

- $PV_{do}$ is present value of machining equipment D life cycle operating cost.
- $C_{od}$ is machining equipment D annual operating cost.

By substituting the given data values into Equation (3.11), we obtain

$$PV_{do} = (8,000) \left[ \frac{1-(1+0.06)^{-10}}{0.06} \right]$$

$$= \$58,880.69$$

Thus, the life cycle cost of machining equipment D is expressed by

$$LCC_D = PC_d + PV_{df} + PV_{do}$$

(3.12)

where

- $LCC_D$ is machining equipment D life cycle cost.
- $PC_d$ is machining equipment D procurement cost.
By substituting the given data value and the preceding calculated values into Equation (3.12), we get

\[ LCC_d = 350,000 + 294.40 + 58,880.69 \]
\[ = \$409,175.09 \]

Thus, the life cycle costs of machining equipment A, B, C, and D are $345,337.13, $322,808.62, $339,165.37, and $409,175.09, respectively. By examining these values, it is concluded that machining equipment B should be purchased because its life cycle cost is the lowest.

Problems

1. Write an essay on life cycle costing fundamentals.
2. Discuss the need for life cycle costing.
3. List at least 10 specific applications of life cycle cost analyses.
4. List at least eight activities associated with life cycle costing.
5. What are the steps used to perform life cycle cost analysis?
6. Describe the six-step approach for unfamiliar contractors and manufacturers to prepare for life cycle cost–related acquisitions.
7. List at least 12 areas on which questions could be raised to determine the effectiveness of a life cycle costing program.
8. List at least 10 important sources for obtaining cost-related data.
9. What are the advantages and disadvantages of life cycle costing?
10. A company using a machine to manufacture a certain type of engineering part is contemplating replacing it with a better one. Two different machines are being considered for its replacement and their data are presented in Table 3.2. Determine which of the two machines should be procured to replace the existing machine in regard to their life cycle costs.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Machine A</th>
<th>Machine B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Procurement cost</td>
<td>$140,000</td>
<td>$170,000</td>
</tr>
<tr>
<td>2</td>
<td>Annual failure rate</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>Expected useful life in years</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Annual operating cost</td>
<td>$6,000</td>
<td>$4,000</td>
</tr>
<tr>
<td>5</td>
<td>Cost of a failure</td>
<td>$12,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>6</td>
<td>Annual interest rate</td>
<td>8%</td>
<td>8%</td>
</tr>
</tbody>
</table>
References

4

Life Cycle Cost Models and Cost Estimation Methods

4.1 Introduction

Over the years, a large number of life cycle cost models have been developed that include both general and specific models [1,2]. No single life cycle cost model has been accepted as a standard model in the industrial sector. There could be many reasons for not having a standard model, including the inclinations of users, the nature of the problem, the existence of many different cost data collection systems, and many different types of equipment, devices, or systems. Nonetheless, irrespective of the types of models used in performing life cycle cost analysis, they all must be effective in representing equipment, systems, or subsystems, transparent and visible.

Cost estimating is an important activity because estimated cost has to be as close as possible to actual value; otherwise, an incorrect estimate may lead to serious consequences of various types. Currently, many methods are used to estimate various types of costs. Each one has its advantages and disadvantages. More specifically, a cost estimation method or approach may be very effective in one type of application and rather weak in another. This simply means that utmost care is necessary in selecting a cost estimation method for a specific application.

This chapter presents some of the life cycle cost models and cost estimation methods considered useful in performing life cycle cost analysis.

4.2 Types of Life Cycle Cost Models and Their Inputs

Over the years, life cycle cost models have been classified under various categories [3–6]. For example, Gupta [3] and Sherif and Kolarik [5] have classified life cycle cost models under three categories: conceptual models, analytical models, and heuristic models. The conceptual models are quite flexible but have rather limited applications; they are usually based on the hypothesized relationships of variables given in a qualitative fashion. One example of the conceptual models is available in Goldman and Slattery [7].
The analytical models are based on some sort of mathematical relationship and their subcategories include logistic support models, design trade models, and the total cost models. Finally, the heuristic models may be described simply as the ill-structured version of the analytical models. An example of these models is available in Kolarik [8]. Overall, in this chapter, the life cycle cost models are simply classified under two categories: general life cycle cost models and specific life cycle cost models.

There are many inputs to life cycle cost models. These include [6,9]:

- warranty coverage period;
- average material cost of a failure;
- cost of training;
- cost of installation;
- system’s or item’s listed price;
- cost of carrying spares in inventory;
- mean time between failures;
- mean time to repair;
- spares’ requirements;
- cost of labor per corrective maintenance action; and
- time spent for travel.

### 4.3 General Life Cycle Cost Models

The general life cycle cost models are not tied to any specific system or equipment. Some of these models are presented next.

#### 4.3.1 General Life Cycle Cost Model I

In this case, the equipment or system life cycle cost is divided into two main parts: recurring cost and nonrecurring cost. Thus, the system or equipment life cycle cost is expressed by [10]

\[
LCC = RC + NRC
\]

(4.1)

where

- \(LCC\) is item or system life cycle cost.
- \(RC\) is recurring cost.
- \(NRC\) is nonrecurring cost.
The recurring cost, RC, is expressed by

\[ RC = OC + IC + SC + MC + MTC \] (4.2)

where
- OC is operating cost.
- IC is inventory cost.
- SC is support cost.
- MC is manpower cost.
- MTC is maintenance cost.

The nonrecurring cost, NRC, is expressed by

\[ NRC = C_p + C_i + C_q + C_r + C_t + C_{rm} + C_s \] (4.3)

where
- \( C_p \) is procurement cost.
- \( C_i \) is installation cost.
- \( C_q \) is qualification approval cost.
- \( C_r \) is research and development cost.
- \( C_t \) is training cost.
- \( C_{rm} \) is reliability and maintainability improvement cost.
- \( C_s \) is support cost.

### 4.3.2 General Life Cycle Cost Model II

In this case, the equipment or system life cycle cost is divided into three main parts: procurement cost, initial logistic cost, and recurring cost. Thus, the system or equipment life cycle cost is expressed by [11]

\[ LCC = C_1 + C_2 + C_3 \] (4.4)

where
- \( LCC \) is item or system life cycle cost.
- \( C_1 \) is acquisition or procurement cost.
- \( C_2 \) is initial logistic cost.
- \( C_3 \) is recurring cost.

The initial logistic cost, \( C_2 \), is composed of one-time costs such as the cost of procurement of new support equipment not accounted for in the life cycle costing solicitation and training, the cost of existing support equipment modifications, and the cost of initial technical data management.
The three main components of the recurring cost, $C_3$, are operating cost, management cost, and maintenance cost.

### 4.3.3 General Life Cycle Cost Model III

This model was developed by the U.S. Navy to estimate life cycle cost of major weapon systems [12,13]. The system life cycle cost is divided into five main parts: research and development cost, the cost of associated systems, investment cost, termination cost, and operating and support cost. Thus, the system life cycle cost is expressed by

$$LCCC = C_1 + C_2 + C_3 + C_4 + C_5$$  \hspace{1cm} (4.5)

where
- $LCC$ is system life cycle cost.
- $C_1$ is research and development cost.
- $C_2$ is cost of associated systems.
- $C_3$ is investment cost.
- $C_4$ is termination cost.
- $C_5$ is operating and support cost.

The two main components of the research and development cost, $C_1$, are full-scale development cost and validation cost. Similarly, the two main elements of the cost of associated systems, $C_2$, are their investment cost and their operating and support cost.

The investment cost, $C_3$, is also made up of two main components: the government investment cost and the procurement cost. The termination cost, $C_4$, is expressed by

$$C_4 = \sum_{i=1}^{m} x_i c_i$$  \hspace{1cm} (4.6)

where
- $m$ is total number of years in the life cycle.
- $x_i$ is total number of major system items put out of action during year $i$.
- $c_i$ is terminal cost of the major system item.

Finally, the elements of the operating and support cost are depot supply cost, depot maintenance cost, operating cost, personnel support and training costs, sustaining investment cost, installation support cost, second destination transportation cost, and organizational and intermediate maintenance activity cost.
4.3.4 General Life Cycle Cost Model IV

In this case, the life cycle cost is expressed by [2,14]

\[ LCC = C_{cp} + C_{dp} + C_{pp} + C_{op} \]  \hspace{1cm} (4.7)

where

- \( LCC \) is life cycle cost.
- \( C_{cp} \) is cost associated with the conceptual phase.
- \( C_{dp} \) is cost associated with the definition phase.
- \( C_{pp} \) is cost associated with the procurement phase.
- \( C_{op} \) is cost associated with the operational phase.

The costs of conceptual and definition phases are relatively small in comparison to the costs of procurement and operational phases. They are basically associated with the labor effort.

The four main elements of the procurement phase cost are the cost of the prime equipment or system, the cost of acquisition personnel, the cost of support equipment, and the cost of program management. Finally, the operational phase cost is expressed by

\[ C_{op} = C_m + C_{fo} + C_{oa} \]  \hspace{1cm} (4.8)

where

- \( C_m \) is maintenance cost.
- \( C_{fo} \) is functional operating cost.
- \( C_{oa} \) is operational administrative cost.

Additional information on this model is available in Dhillon [2] and Stordahl and Short [14].

4.3.5 General Life Cycle Cost Model V

In this case, the life cycle cost is expressed by [6,15]

\[ LCC = C_{rd} + C_{pc} + C_{os} + C_{rt} \]  \hspace{1cm} (4.9)

where

- \( LCC \) is life cycle cost.
- \( C_{rd} \) is research and development cost.
- \( C_{pc} \) is production and construction cost.
- \( C_{os} \) is operation and support cost.
- \( C_{rt} \) is retirement and disposal cost.
The research and development, $C_{rd}$, is expressed by

$$C_{rd} = \sum_{j=1}^{7} C_{rdj}$$  \hspace{1cm} (4.10)

where $C_{rdj}$ is the $j$th cost element of the research and development cost for

- $j = 1$ (means product planning);
- $j = 2$ (means engineering design);
- $j = 3$ (means product or system life cycle management);
- $j = 4$ (means system or product test and evaluation);
- $j = 5$ (means product or system research);
- $j = 6$ (means product or system software); and
- $j = 7$ (means design documentation).

The production and construction cost, $C_{pc}$, is defined by

$$C_{pc} = \sum_{j=1}^{5} C_{pcj}$$  \hspace{1cm} (4.11)

where $C_{pcj}$ is the $j$th cost element of the production and construction cost for

- $j = 1$ (means manufacturing);
- $j = 2$ (means construction);
- $j = 3$ (means quality control);
- $j = 4$ (means initial logistics support); and
- $j = 5$ (means industrial engineering and operations analysis).

The operation and support cost, $C_{os}$, is expressed by

$$C_{os} = \sum_{j=1}^{3} C_{osj}$$  \hspace{1cm} (4.12)

where $C_{osj}$ is the $j$th cost element of the operation and support cost for

- $j = 1$ (means system or product operations);
- $j = 2$ (means product or system distribution); and
- $j = 3$ (means sustaining logistic support).

The retirement and disposal cost, $C_{rt}$, is defined by

$$C_{rt} = C_{wr} + [\theta K (C_{ld} - r_y)]$$  \hspace{1cm} (4.13)
where
- \( C_{ur} \) is ultimate retirement cost of the system or product.
- \( \theta \) is the condemnation factor.
- \( K \) is total number of unscheduled maintenance actions.
- \( C_{id} \) is item disposal cost.
- \( r_u \) is reclamation value.

### 4.3.6 General Life Cycle Cost Model VI

This model was developed by the Material Command of the U.S. Army and is composed of three main components: investment cost, research and development cost, and operating and support cost [16–18]. Thus, the life cycle cost is expressed mathematically by [6,16–18]

\[
LCC = C_1 + C_2 + C_3
\]

where
- \( LCC \) is life cycle cost.
- \( C_1 \) is research and development cost.
- \( C_2 \) is investment cost.
- \( C_3 \) is operating and support cost.

The research and development cost, \( C_1 \), is composed of the following 10 components:

- research and development data cost;
- cost of research and development tooling;
- cost of research and development facilities;
- development engineering cost;
- prototype manufacturing cost;
- research and development test and evaluation cost;
- producibility engineering and planning cost;
- research and development system or project management cost;
- research and development training services and equipment cost; and
- other research and development costs.

The investment cost, \( C_2 \), is composed of 11 components:

- cost of production;
- initial training cost;
• transportation cost;
• cost of data;
• cost of engineering changes;
• nonrecurring investment cost;
• cost of system test and evaluation;
• production phase system or project management cost;
• cost of initial spares and repair parts;
• operational or site activation cost; and
• other investment costs.

Finally, the operating and support cost, $C_3$, is composed of six major components:

• cost of indirect support operations;
• cost of depot maintenance;
• cost of material modifications;
• consumption cost;
• cost of military personnel; and
• cost of other direct support operations.

Additional information on this model is available in references 16–18.

4.4 Specific Life Cycle Cost Models

Over the years, many mathematical models have been developed to estimate life cycle cost of specific systems or items. Some of these models are presented next.

4.4.1 Specific Life Cycle Cost Model I

This model is concerned with estimating the life cycle cost of switching power supplies, which is expressed by [19]

\[
LCC_s = IC + FC
\]  

(4.15)

where

$LCC_s$ is life cycle cost of switching power supplies.
$IC$ is initial cost.
$FC$ is failure cost.
The failure cost, \( FC \), is expressed by

\[
FC = \lambda (n)(C_r + C_s)
\]  
(4.16)

where
- \( \lambda \) is unit constant failure rate.
- \( n \) is expected life of the product/unit.
- \( C_r \) is repair cost.
- \( C_s \) is cost of spares.

The cost of spares, \( C_s \), is defined by

\[
C_s = C_u (K)
\]  
(4.17)

where
- \( C_u \) is unit spare cost.
- \( K \) is fractional number of spares for each active unit.

### 4.4.2 Specific Life Cycle Cost Model II

This model is concerned with estimating the life cycle cost of health care facilities. The health care facility life cycle cost is expressed by [6,13]

\[
LCC_h = C_i + C_o
\]  
(4.18)

where
- \( LCC_h \) is health care facility life cycle cost.
- \( C_i \) is capital cost.
- \( C_o \) is operating cost.

The capital cost, \( C_o \), is composed of the following eight cost components:

- land acquisition cost;
- financing cost;
- collateral equipment cost;
- direct construction or purchase cost;
- indirect cost;
- demolition and site preparation cost;
- alteration and replacement cost; and
- denial of use cost.
Similarly, the operating cost, $C_o$, is composed of the following 19 cost components:

- utilities and fuel cost;
- structural maintenance cost;
- heating system operations and maintenance cost;
- painting cost;
- equipment (furnishings) maintenance cost;
- exterior building cleaning cost;
- electrical system operations and maintenance cost;
- space changes cost;
- exterior restoration cost;
- grounds and roads maintenance cost;
- equipment (fixed equipment and specific construction) maintenance cost;
- insect and rodent control cost;
- incinerator and trash removal cost;
- building internal cleaning cost;
- special mechanical systems operations and maintenance cost;
- elevator, escalator, and dumbwaiter operations cost;
- plumbing and sewage systems operations and maintenance cost;
- fire protection systems maintenance cost; and
- air conditioning and ventilating system operations and maintenance cost.

### 4.4.3 Specific Life Cycle Cost Model III

This model is concerned with estimating the life cycle cost of an early warning radar system. The radar life cycle cost is expressed by [6]

$$ LCC_r = C_p + C_o + C_s $$

(4.19)

where

$LCC_r$ is early warning radar life cycle cost.
$C_p$ is radar procurement cost.
$C_o$ is radar operation cost.
$C_s$ is radar logistic support cost.

The radar procurement cost, $C_p$, is expressed by

$$ C_p = FC + ICC + DC + DOC $$

(4.20)
where

- \( FC \) is fabrication cost.
- \( ICC \) is installation and checkout cost.
- \( DC \) is design cost.
- \( DOC \) is document cost.

The radar operation cost, \( C_o \), is defined by

\[
C_o = C_1 + C_2 + C_3
\]  

(4.21)

where

- \( C_1 \) is fuel cost.
- \( C_2 \) is cost of personnel.
- \( C_3 \) is cost of power.

The radar logistic support cost, \( C_s \), is expressed by

\[
C_s = CRL + CRM + CIS + CRS + CIT + AC
\]  

(4.22)

where

- \( CRL \) is cost of repair labor.
- \( CRM \) is cost of repair material.
- \( CIS \) is cost of initial spares.
- \( CRS \) is cost of replacement spares.
- \( CIT \) is cost of initial training.
- \( AC \) is age cost.

The life cycle cost predicted breakdown percentages for a specific early warning radar are available in Dhillon [6].

### 4.4.4 Specific Life Cycle Cost Model IV

This model is concerned with estimating the life cycle cost of inertial systems. The inertial systems life cycle cost is expressed by [20]

\[
LCC_{is} = RDTC + PC + OMC
\]  

(4.23)

where

- \( LCC_{is} \) is inertial systems life cycle cost.
- \( RDTC \) is research, development, test, and evaluation cost.
- \( PC \) is procurement cost.
- \( OMC \) is operation and maintenance cost.
The research, development, test, and evaluation cost, RDTC, is composed of eight elements:

- software cost;
- testing cost;
- program management cost;
- cost of conceptual studies;
- cost of engineering change proposals;
- cost of design engineering;
- cost of technical data; and
- training cost.

The 12 distinct components of the procurement cost include:

- cost of new facilities;
- cost of spares;
- support equipment acquisition cost;
- system recurring acquisition cost;
- cost of technical data;
- initial training course cost;
- training equipment cost;
- cost of production tooling and test equipment;
- production program start-up cost;
- cost of initial item management;
- field engineering cost; and
- equipment installation cost.

The operation and maintenance cost, OMC, is expressed by

\[
OMC = \sum_{j=1}^{3} \sum_{i=1}^{n} OMC_{ji} \tag{4.24}
\]

where

- \( n \) is total number of years.
- \( OMC_{ji} \) is operation and maintenance cost at the \( j \)th level of maintenance in the \( i \)th year.

Additional information on the model is available in DeBurkarte [20].
4.4.5 Specific Life Cycle Cost Model V

This model is concerned with estimating the life cycle cost of software. Sometimes, the model is called the “Boeing C-14 model” [21,22]. The software life cycle cost is expressed by [21,22]

\[ LCC_s = AC_s + SC_s \]  \hspace{1cm} (4.25)

where

- \( LCC_s \) is life cycle cost of software.
- \( AC_s \) is acquisition cost of software.
- \( SC_s \) is support cost of software.

The support cost of software, \( SC_s \), is expressed by

\[ SC_s = \left( 2.5(LC) \sum SMM_j \right)(1 + \alpha) + SC_a \]  \hspace{1cm} (4.26)

where

- \( LC \) is direct labor cost per man-month.
- \( \sum SMM_j \) is required man-months for support in month \( j \).
- \( \alpha \) is overhead factor.
- \( SC_a \) is additional (other) support costs.

Additional information on the model is available in references 21 and 22.

4.5 Cost Estimation Methods

Over the years, many methods have been developed to estimate costs [23–26]. Some of the methods considered useful for application in the area of life cycle costing are presented next.

4.5.1 Cost Estimation Method I

This method is considered quite useful to obtain quick approximate cost estimates for similar new plants, projects, or equipment of different capacities. The cost-capacity relationship is defined by

\[ C_n = C_o \left( \frac{K_n}{K_o} \right)^u \]  \hspace{1cm} (4.27)
Life Cycle Costing for Engineers

where

\( C_n \) is cost of the new plant, project, or equipment under consideration.

\( C_o \) is cost of the old but similar equipment, plant, or project.

\( K_n \) is capacity of the new plant, project, or equipment.

\( K_o \) is capacity of old but similar equipment, plant, or project.

\( \alpha \) is the cost-capacity factor whose frequently used value is 0.6. The proposed values for this factor for items such as heat exchangers, heaters, pumps, and tanks are 0.6, 0.8, 0.6, and 0.7, respectively [23,27,28].

**Example 4.1**

An electric utility spent $900 million to construct a 1,000 megawatt (MW) nuclear power generating station. In order to satisfy the increasing demand for electricity, the company is planning to construct a 2,000 MW nuclear power generating station. Calculate the cost of the new station, if the value of the cost-capacity factor is 0.6.

By substituting the given data values into Equation (4.27), we get

\[
C_n = \left[ \frac{2,000}{1,000} \right]^{0.6}
\]

Thus, the construction cost of the new nuclear power station will be $1,364.15 million.

4.5.2 Cost Estimation Method II

This method is known as the Lang factor method, after its originator, H. L. Lang [29]. The method is used for obtaining quick order-of-magnitude cost estimates by utilizing historical average cost factors. Lang proposed to estimate total plant costs from the delivered equipment cost by using three factors as multipliers: \( n = 3.10 \) (for solid process plants), \( n = 3.63 \) (for solid-fluid plants), and \( n = 4.74 \) (for fluid process plants) [29].

Thus, the total estimate for plant cost is obtained by using

\[
TPC = (n)(DEC)
\]  \hspace{1cm} (4.28)

where

\( TPC \) is the total estimate for plant cost.

\( n \) is the Lang factor, whose value depends on the nature of the plant.

\( DEC \) is delivered equipment cost.

**Example 4.2**

Assume that a fluid-processing plant’s delivered equipment cost is $40 million. Calculate the total plant cost.
By substituting the given data value and information into Equation (4.28), we get

\[ TPC = (4.74)(40) \]

\[ = \$189.6 \text{ million} \]

Thus, the total plant cost will be \$189.6 million.

4.5.3 Cost Estimation Method III

This method is basically a refinement of the Lang factor method and is known as the Hand method, after its originator, W. E. Hand [30]. In the refinement, Hand proposed the use of different factors for various groups of equipment.

The total installed cost for each equipment group is defined by [25,30]

\[ IC_t = (m)(DEC) \]

(4.29)

where

- \( IC_t \) is total installed cost of each equipment group.
- \( m \) is the Hand factor that covers field materials (structures, insulation, piping, electrical, finishes, and foundations), labor, and indirect costs.
  - The values of the Hand factor for various groups of equipment are 2 (fired heaters), 2.5 (compressors), 2.5 (miscellaneous equipment), 3.5 (heat exchangers), 4 (pumps), 4 (pressure vessels), 4 (instruments), and 4 (fractionating towers).
- \( DEC \) is delivered equipment cost.

Note that the Hand factors do not incorporate a contingency allowance. Additional information on this method is available in references 25, 30, and 31.

4.5.4 Cost Estimation Method IV

This method is quite useful to make an order-of-magnitude approximation of operating labor requirements in the absence of a Manning table. The method is known as the Wessell method. Thus, the Wessell equation is expressed by [32]

\[ \frac{OH}{\lambda} = \alpha \left[ \frac{K}{(P)^{0.76}} \right] \]

(4.30)

where

- \( OH \) is number of operating man-hours.
- \( \lambda \) is tons of product.
- \( K \) is total number of process steps.
- \( P \) is capacity expressed in tons per day.
The values of $\alpha$ are 23 (for a batch operation with maximum labor), 10 (for a well-instrumented continuous process operation), and 17 (for an operation with average labor requirements). Additional information on this method is available in Humphreys [32].

4.5.5 Cost Estimation Method V

This method is known as the turnover ratio method and is considered the most efficient approach to estimating plant costs. However, it is probably the least accurate. The turnover ratio is defined by [6,32]

$$TOR = \frac{AS}{I} \quad (4.31)$$

where

- $TOR$ is turnover ratio.
- $AS$ is gross annual sales.
- $I$ is fixed capital investment.

The gross annual sales, $AS$, is expressed by

$$AS = (SP)(PR) \quad (4.32)$$

where

- $SP$ is unit selling price.
- $PR$ is yearly production rate.

Note that the value of the turnover ratio, $TOR$, usually varies from around 0.2 to 8.

Example 4.3

Assume that a factory is to manufacture 50,000 units/year of a certain product. The selling price of a unit is $500. Calculate the fixed capital investment, if the turnover ratio is 4.

By substituting Equation (4.32) into Equation (4.31) and then substituting the given data values into the resulting equation, we get

$$4 = \frac{(500)(50,000)}{I} \quad (4.33)$$

By rearranging Equation (4.33), we obtain

$$I = \frac{(500)(50,000)}{4}$$

$$= 6.25 \text{ million}$$

Thus, the fixed capital investment for the factory is $6.25 million.
Problems

1. Write an essay on life cycle cost models and cost estimation methods.
2. Discuss three types of life cycle cost models.
3. Write down life cycle cost equations for two general life cycle cost models.
4. Write down life cycle cost equations for two specific life cycle cost models.
5. Compare the general life cycle cost models with the specific life cycle cost models.
6. Write down a life cycle cost equation for switching power supplies.
7. What is the “Boeing C-14 model”? 
8. Discuss the following two types of cost estimation methods: 
   • the Hand method 
   • the Wessell method
9. A solid-processing plant's delivered equipment cost is $20 million. Calculate the total plant cost by using the Lang factor method.
10. An electric power generation company spent $1,500 million to construct a 600 MW nuclear power generating station. In order to meet the increasing demand for electricity, the company is planning to construct a 1,500 MW nuclear power generating station. Calculate the cost of the new station, if the value of the cost-capacity factor is 0.7.

References


5

Reliability, Quality, Safety, and Manufacturing Costing

5.1 Introduction

Reliability, quality, safety, and manufacturing costs play an important role in the total cost of engineering products. Therefore, they must be considered with care. Reliability cost is an important factor in any reliability program associated with an engineering product. It is associated with activities such as reliability allocation, prediction, and testing [1].

Quality costs usually form a significant component of the selling price of an engineering product. They cross department lines by involving various company activities such as design, manufacturing, purchasing, and service. Safety costs are becoming an important element of the economy. For example, in 1995, the cost of workplace accidents in the United States was estimated to be around $75 billion [2]. Needless to say, safety costs are associated with areas such as lawsuits, insurance, analysis, and corrective measures.

The manufacturing cost may be described as the sum of fixed and variable costs chargeable to the manufacture of a given product or item. Usually, this cost (i.e., manufacturing cost) excludes the costs associated with corporate administration, selling, research and development, and transportation and distribution.

This chapter presents various important aspects of reliability, quality, safety, and manufacturing costing.

5.2 Reliability Cost Classifications

Reliability cost may be categorized under the following four classifications [3]:

- Prevention cost includes items such as hourly and overhead rates for design engineers, reliability engineers, material engineers, technicians, and test and evaluation personnel; hourly cost and overhead rates for reliability screens; cost of yearly reliability training per capita; and cost of preventive maintenance programs.
• **Appraisal cost** involves items such as cost for vendor audit, new vendor qualification, and new part qualification; hourly and overhead rates for reliability evaluation, reliability demonstration, reliability qualification, environmental testing, and life testing; cost of test result reports; and average cost per part of assembly testing, auditing, screening, inspection, and calibration.

• **Internal failure cost** is composed of items such as cost of replaced parts or components; cost of spare part inventory; hourly and overhead rates for failure analysis, retesting, and troubleshooting and repair; and cost of production change administration.

• **External failure cost** includes items such as cost of liability assurance, cost of warranty administration and reporting, cost of failure analysis, cost of spare part inventory, cost of service kit, cost of replaced parts, and cost to repair a failure.

### 5.3 Models for Estimating Costs of Reliability-Related Tasks

Over the years, many mathematical models have been developed to estimate man-hours required to perform reliability-related tasks and, in turn, the cost of performing such tasks. Some of these models are presented next [1,4,5].

#### 5.3.1 Model I

This model is concerned with estimating the total number of man-hours required to perform reliability prediction. This number is expressed by [1,4,5]

\[
TMH_p = (4.54) \alpha^2 \theta^2 \beta
\]  

(5.1)

where

- \( TMH_p \) is total number of man-hours required to perform reliability prediction.
- \( \alpha \) is the factor whose value depends on the type of report required: \( \alpha = 1 \) means an internal report is required; \( \alpha = 2 \) means a formal report is required.
- \( \theta \) is the integer factor whose value varies from 1 to 3 depending on the level of detail: 1 = prediction exists, 2 = prediction is to be performed using similar system data, and 3 = full MIL-HDBK-217 [6] stress prediction is needed.
- \( \beta \) is the integer factor whose values vary from 1 to 4 depending on the percentage of commercial hardware used in the system or item under consideration: 1 = 76–100\%, 2 = 51–75\%, 3 = 26–50\%, and 4 = 0–25\%. 


5.3.2 Model II
This model is concerned with estimating the total number of man-hours required to perform the reliability testing task. The number is defined by [1,4,5]

\[ TMH_i = (182.07)(HCF) \] (5.2)

where

- \( TMH_i \) is the total number of man-hours required to perform the reliability testing task.
- \( HCF \) is the integer factor whose value varies from 1 to 3 depending on the degree of the hardware complexity: 1 = parts or components that are less than 15,000; 2 = parts or components that are 15,000–25,000; and 3 = parts or components that are greater than 25,000.

5.3.3 Model III
This model is concerned with estimating the total number of man-hours required for preparing the reliability and maintainability program plan. This number is defined by [1,4,5]

\[ TMH_{pp} = (2.073)\gamma^2 \] (5.3)

where

- \( TMH_{pp} \) is the total number of man-hours required to prepare the reliability and maintainability program plan.
- \( \gamma \) is the number of MIL-STD-785/470 [6] tasks required. The recommended minimum and maximum values of \( \gamma \) are 4 and 22, respectively.

5.3.4 Model IV
This model is concerned with estimating the number of man-hours required for performing failure modes and effect analysis (FMEA). The number of man-hours required to perform this task is defined by [1,4,5]

\[ TMH_f = (17.79)n \] (5.4)

where

- \( TMH_f \) is the total number of man-hours needed to perform FMEA.
- \( n \) is the total number of unique items requiring FMEA (e.g., number of circuit cards for piece-part and circuit-level FMEA or the number of pieces of equipment for equipment-level FMEA). The recommended minimum and maximum values of \( n \) are 3 and 206, respectively.
5.3.5 Model V

This model is concerned with estimating the total number of man-hours required to perform reliability allocation and modeling. The number of man-hours needed to carry out this task is defined by \([1,4,5]\)

\[
TMH_{am} = (4.05)(CF_{am})K
\]  

(5.5)

where

- \(TMH_{am}\) is total number of man-hours required to perform reliability allocation and modeling.
- \(CF_{am}\) is the allocation and modeling complexity. The recommended values of the \(CF_{am}\) are 1, 2, and 3 for a series system, simple redundancy, and very complex redundancy, respectively.
- \(K\) is total number of items in the allocation process. The recommended minimum and maximum values of \(K\) are 7 and 445, respectively.

5.4 Quality Cost Classifications and Their Distribution in the Industrial Sector

Quality costs may be divided into four classifications, as shown in Figure 5.1 [7]: prevention cost, appraisal cost, internal failure cost, and external failure cost. Each of these classifications is described separately in the following sections.

---

**FIGURE 5.1**
Quality cost classifications.
5.4.1 Prevention Cost

This cost is basically concerned with planning, implementing, and maintaining the quality system and is expressed by

\[ C_p = C_{qe} + C_{qt} + C_{qp} + C_{qd} \]  \hspace{1cm} (5.6)

where

- \( C_p \) is prevention cost.
- \( C_{qe} \) is cost of quality engineering. This is concerned with the development and implementation of the inspection plan, the overall quality plan, etc.
- \( C_{qt} \) is cost of quality training. This includes the cost of developing and maintaining quality-related training programs.
- \( C_{qp} \) is cost of quality planning by functions excluding quality control.
- \( C_{qd} \) is cost associated with design and development of quality control and measurement equipment.

5.4.2 Appraisal Cost

This cost is concerned with determining the degree of conformance to quality-related specifications. It has many elements, including the cost of conducting product quality audits, the cost of testing and inspection of incoming material, the cost of materials and services consumed in testing, the cost of inspection and testing of items being manufactured, and the cost of maintenance and calibration of equipment used for evaluating quality.

5.4.3 Internal Failure Cost

This cost occurs when manufactured items fail to meet specified quality requirements prior to their ownership transfer to customers. The subcategories of the internal failure cost include repair cost, failure analysis cost, scrap cost, and re-inspection and retest cost.

5.4.4 External Failure Cost

This cost occurs when manufactured items fail to meet quality specifications after their delivery to customers. The external failure cost is expressed by

\[ C_{ef} = C_r + C_w + C_a + C_h \]  \hspace{1cm} (5.7)

where

- \( C_{ef} \) is external failure cost.
- \( C_r \) is cost of repairing returned items.
- \( C_w \) is cost of warranties.
- \( C_a \) is cost of adjusting complaints.
- \( C_h \) is cost of replacement and handling of rejected (returned) items.
Although the distribution of quality costs may vary from one industrial sector to another and from one organization to another, their distribution in the banking and the electronic equipment manufacturing industries is as follows [8,9]:

- **Banking industry:** In this area, quality costs account for approximately 25% of a bank’s total operating costs. The estimates of their distribution among prevention, appraisal, internal failure, and external failure cost classifications are 2, 28, 41, and 29% (of the total quality cost), respectively.

- **Electronic equipment manufacturing industry:** In this area, quality costs account for around 14% of the sales. The estimates of their distribution among prevention, appraisal, internal failure, and external failure cost classifications are approximately 45, 36, 13, and 6% (of the total quality cost), respectively.

### 5.5 Quality Cost Indexes and Quality Cost Reduction Approach

Many organizations use various types of quality cost indexes to monitor their performance. The values of such indexes are plotted on a periodic basis and their trends are monitored. Three of these indexes are presented next [10–13].

**Index I** is defined by

\[
\theta_1 = \left[ \frac{(C_q)(100)}{V_o} \right] + 100
\]  

(5.8)

where

- \( \theta_1 \) is quality cost index.
- \( C_q \) is total quality cost.
- \( V_o \) is value of output.

The values of this index (\( \theta_1 \)) may be interpreted as follows [14]:

- \( \theta_1 = 105 \) can readily be achieved in a real-life environment.
- \( \theta_1 = 110–130 \) occurs in companies where the quality costs are totally ignored.
- \( \theta_1 = 100 \) means that there is absolutely no defective output.

**Index II** is defined by

\[
\theta_2 = \frac{(C_q)(100)}{T_s}
\]  

(5.9)

where \( T_s \) is the total sales. Note that \( \theta_2 \) is expressed as a percentage.
Index III is defined by

\[
\theta_3 = \frac{(C_q)(100)}{C_d}
\]  

(5.10)

where \( C_d \) is the direct labor cost. Note that \( \theta_3 \) is also expressed as a percentage. Usually, this index is used to eliminate inflation effects.

Although quality costs can be reduced in many different ways, the six-step approach shown in Figure 5.2 is considered quite useful for this purpose [14]. Additional information on the approach is available in Williams [14].

5.6 Safety Cost and Its Related Facts and Figures

Nowadays, the cost of safety has become an important factor in the life cycle cost of many engineering systems. Each year, the cost of safety in general is increasing at a significant rate. Some of the safety cost–related facts and figures are as follows:

- In 2000, work-related injuries cost the United States around $131 billion [15].
- The cost of the accident in 1979 at the Three Mile Island nuclear power plant was estimated to be approximately $4 billion [16].
• In 1993, a Virginia jury awarded $8 million to a worker for a back injury caused by a piece of equipment that fell [16].
• In 1996, a Paris-bound Trans World Airlines jet crashed due to a fuel-tank fire and killed all persons on board. A subsequent task force concluded that adding nonflammable gases (fuel-tank inverting) would decrease the risk of fuel-tank explosions quite significantly, but recommended against such changes because of the cost of between $10 billion and $20 billion [17].
• In 1997, three workers sued a computer equipment manufacturer for musculoskeletal disorders (MSDs) because they firmly believed that these disorders were due to keyboard entry activities [16]. The workers were awarded around $5.8 million.

5.7 Safety Cost Estimation Models

Over the years, many models to estimate safety cost have been developed. Some of these models are presented next.

5.7.1 Model I

This model is concerned with estimating the safety cost of a product over its life span and is expressed by [16,18]

\[ LCSC_p = C_1 + C_2 + C_3 + C_4 - R \]  

(5.11)

where

- \( LCSC_p \) is product life cycle safety cost.
- \( C_1 \) is cost of an accident prevention program.
- \( C_2 \) is cost of insurance.
- \( C_3 \) is recall cost.
- \( C_4 \) is program cost.
- \( R \) is reimbursements.

5.7.2 Model II

This is another mathematical model that can also be used to estimate the safety cost of a product over its life span. This is expressed by [16,18]

\[ LCSC_p = SC_1 + SC_2 + SC_3 + SC_4 \]  

(5.12)

where

- \( LCSC_p \) is product life cycle safety cost.
- \( SC_1 \) is safety cost during the product research and development phase. This cost is associated with the safety-related studies performed during this phase.
SC₂ is safety cost during the product production and construction phase. This cost is associated with the safety-related measures taken during this phase.

SC₃ is safety cost during the product operation and support phase. This cost is associated with safety-related activities performed during this phase.

SC₄ is safety cost during the product retirement and disposal phase. This cost is associated with safety-related actions taken to dispose of the product.

5.7.3 Model III

This model is concerned with estimating the total hidden cost of an accident and is expressed by

\[
AHC = C_d + C_m + C_{hap} + C_{wsp} + C_{inw} + C_{e} + C_{sp} + C_{nw} + C_{um} + C_{ro} \quad (5.13)
\]

where

- \(AHC\) is total hidden cost of an accident.
- \(C_d\) is cost of damage to equipment or material.
- \(C_m\) is miscellaneous cost.
- \(C_{hap}\) is cost of time spent by clerical and higher supervisory personnel.
- \(C_{wsp}\) is cost of wages paid to uninjured workers for the time lost.
- \(C_{inw}\) is cost of wages paid to injured workers for the time lost.
- \(C_{e}\) is extra cost of overtime work necessitated by the accident under consideration.
- \(C_{sp}\) is cost of wages paid to supervisory individuals for their time spent on activities necessitated by the accident under consideration.
- \(C_{nw}\) is cost of the learning period required by new workers replacing injured workers.
- \(C_{um}\) is uninsured medical cost borne by the organization or company.
- \(C_{ro}\) is wage cost due to reduction in output of injured individuals after their return to work.

5.7.4 Model IV

This model is concerned with estimating total safety cost, which is defined by

\[
C_{st} = ILC + PMC + WIC + IC + IMC + MIC + LIC + RRC \quad (5.14)
\]

where

- \(C_{st}\) is total safety cost.
- \(ILC\) is cost of immediate losses due to accidents.
- \(PMC\) is cost of accident prevention measures.
- \(WIC\) is cost of welfare-related issues.
- \(IC\) is cost of insurance.
- \(IMC\) is cost associated with the immeasurable.
MIC is cost of miscellaneous safety-related issues.
LIC is cost of safety-related legal issues.
RRC is rehabilitation and restoration cost.

5.8 Manufacturing Costs

Manufacturing costs form a significant proportion of the life cycle cost of engineering products, equipment, and systems. They may be broken down into five categories, as shown in Figure 5.3 [19,20]. For new processes, the elements of the direct manufacturing cost include [19,20]:

- maintenance and repair cost;
- labor cost;
- cost of utilities;
- packaging and shipping cost;
- raw materials cost;
- royalties (if applicable);
- direct overhead cost (usually plant supervision);
- laboratory charges (process control and quality control work);
- factory supplies (house supplies, wiping cloths, instrument charts, etc.); and
- development cost (if applicable).

Similarly, the elements of the indirect manufacturing cost are plant indirect overhead cost (e.g., plant office expense), property taxes, depreciation, and insurance [19,20].

![Figure 5.3](image_url)

**FIGURE 5.3**
Manufacturing cost categories.
5.9 Manufacturing Cost Estimation Models

Over the years, many mathematical models have been developed to estimate various types of manufacturing cost. Some of these models are presented next.

5.9.1 Model I

This model is concerned with estimating the direct cost of material used in manufacturing, which is expressed by [20,21]

\[
C_{dm} = (W)(P) \left[ 1 + \sum_{j=1}^{3} \alpha_j \right] - P_s
\]  

(5.15)

where

- \( C_{dm} \) is direct material cost of a unit.
- \( W \) is weight of a unit, usually expressed in pounds.
- \( P \) is price of material expressed per linear foot, per pound, or per volume.
- \( \alpha_j \) is jth losses expressed in decimals for \( j = 1 \) (due to shrinkage), \( j = 2 \) (due to scrap), and \( j = 3 \) (due to waste).
- \( P_s \) is unit price of expected material salvage expressed in dollars per unit.

Additional information on this model is available in Ostwald [21].

5.9.2 Model II

This model is concerned with estimating machining cost, which is expressed by [22–24]

\[
MC = \frac{1}{60} \left[ \frac{C_m (1 + r_1)}{100} + \frac{r_2 (1 + r_3)}{100} \right] (MT + T_i)
\]  

(5.16)

where

- \( MC \) is machining cost.
- \( C_m \) is machine cost expressed in dollars per hour.
- \( r_1 \) is machine overhead rate expressed in percentage.
- \( r_2 \) is operator labor rate expressed in dollars per hour.
- \( r_3 \) is overhead rate of the operator expressed in percentage.
- \( MT \) is machining time.
- \( T_i \) is nonproduction or idle time.

Additional information on this model is available in references 22–24.
5.9.3 Model III

This model is concerned with estimating the tool cost associated with a cutting tool brazed to the tool holder. This cost is defined by [22]

\[ C_t = \frac{(RSC) \beta + TC}{(\beta + 1)} \]  

(5.17)

where
- \( C_t \) is tooling cost associated with a cutting tool brazed to the tool holder.
- \( RSC \) is cost associated with resharpening expressed in dollars.
- \( \beta \) is number of resharpenings.
- \( TC \) is tool cost expressed in dollars.

In the case of a throwaway (insert) tool, the cost, \( C_t \), is expressed by

\[ C_t = \frac{THC}{n_1} + \frac{TIC}{n_2} \]  

(5.18)

where
- \( THC \) is cost of the tool holder.
- \( n_1 \) is total number of cutting edges in the life of the tool holder.
- \( TIC \) is tool insert cost expressed in dollars.
- \( n_2 \) is number of cutting edges.

5.9.4 Model IV

This model is concerned with estimating the average unit cost for a single-point, rough-turning operation. This cost is expressed by [21]

\[ C_a = HC + TC + MC + THC \]  

(5.19)

where
- \( C_a \) is average unit cost for a single-point, rough-turning operation.
- \( HC \) is handling cost.
- \( TC \) is tool cost.
- \( MC \) is machining cost.
- \( THC \) is tool-changing cost.

Equations for estimating \( HC, TC, MC, \) and \( THC \) follow.

The handling cost, \( HC \), is expressed by

\[ HC = (T_h)(OTC) \]  

(5.20)

where
- \( T_h \) is total handling time per work piece expressed in minutes.
- \( OTC \) is total operating time cost expressed in dollars per minute.
The tool cost, $TC$, is expressed by

$$TC = \frac{(WPT_m)(C_e)}{MTL}$$

(5.21)

where
- $WPT_m$ is machining time of work piece expressed in minutes per piece.
- $C_e$ is tool cost expressed as dollars per cutting edge.
- $MTL$ is mean tool life expressed in minutes.

The machining cost, $MC$, is expressed by

$$MC = (OTC)(WPT_m)$$

(5.22)

Finally, the tool-changing cost, $THC$, is expressed by

$$THC = \frac{(OTC)(WPT_m)(T_c)}{MTL}$$

(5.23)

where $T_c$ is the tool-changing time expressed as minutes per operation.

Additional information on this model is available in Ostwald [21].

**Problems**

1. List and discuss reliability cost classifications.
2. Write an essay on reliability, quality, and safety costing.
3. What are the quality cost classifications?
4. Compare quality cost classifications with reliability cost classifications.
5. Discuss an approach that can be used to reduce quality costs.
6. List at least five safety cost-related facts and figures.
7. List and discuss manufacturing cost categories.
8. Define at least two quality cost indexes.
9. Define a mathematical model that can be used to estimate the total hidden cost of an accident.
10. Compare reliability cost with safety cost.

**References**

1. RADC reliability engineer’s toolkit. 1988. Published by the Systems Reliability and Engineering Division, Rome Air Development Center (RADC), Air Force Systems Command (AFSC), Griffiss Air Force Base, Rome, NY.
6

Maintenance, Maintainability, Usability, and Warranty Costing

6.1 Introduction

Each year billions of dollars are spent to produce various types of engineering products. Past experiences indicate that, in many cases, the cost of procuring an engineering product is less than the cost of ownership over its life span. According to Blanchard, Verma, and Peterson [1], the hidden costs related to equipment operation and support can account for as high as 75% of the equipment life cycle cost. Maintenance, maintainability, usability, and warranty costs play an important role in the life cycle cost of an engineering product. Therefore, careful consideration must be given to estimating such costs.

The maintenance cost may be described simply as the labor and materials expense required for maintaining engineering products in suitable use condition. In some systems—particularly military systems—the maintenance cost can be as high as 70% of life cycle costs [2]. Maintainability is an important factor in the total cost of equipment because increase in maintainability can result in reduction in equipment operation and support costs. Thus, maintainability costs are basically concerned with equipment design.

Usability costs are concerned with a wide range of activities employed in developing effectively usable engineering products. Some examples of these activities are establishing a definition for end user requirements, developing specifications for usability objectives, performing task analysis, and conducting usability testing. Warranty costs occur when engineering equipment manufacturers provide buyers with written statements guaranteeing the integrity of their equipment. The responsibilities of the manufacturers are outlined by these statements in situations when their equipment happens to be defective.

This chapter presents various important aspects of maintenance, maintainability, usability, and warranty costing.
6.2 Reasons for Maintenance Costing, Factors Influencing Maintenance Cost, and Types of Maintenance Costs

There are many reasons for maintenance costing. Some of the important ones include [3]:

- to prepare budgets;
- to make equipment replacement decisions;
- to control costs;
- to compare maintenance costs' effectiveness with industry averages;
- to identify maintenance cost drivers;
- to improve productivity;
- to compare competing maintenance methods;
- to provide appropriate inputs in the design of new equipment or items; and
- to perform equipment or item life cycle cost studies.

Some of the important factors influencing maintenance costs are shown in Figure 6.1 [3,4].

**FIGURE 6.1**
Factors influencing maintenance costs.
There are basically two main categories of maintenance costs: preventive maintenance cost and corrective maintenance cost. The former is concerned, directly or indirectly, with actions performed on a planned, periodic, and specific schedule for keeping a piece of equipment or item in stated working condition through the process of rechecking and reconditioning. More specifically, these actions are precautionary measures undertaken to forestall or decrease the probability of failures or an unacceptable level of degradation in subsequent service, rather than rectifying failures after their occurrence.

The corrective maintenance cost is directly or indirectly concerned with the unscheduled maintenance and repair to return equipment or items to a specified condition. These actions are carried out because involved maintenance personnel or users perceive deficiencies or failures.

6.3 Equipment Maintenance Cost

The maintenance cost of the entire ownership cycle of equipment is expressed by [4,5]

\[
EMC_p = \lambda_c \cdot CMC + \lambda_p \cdot PMC \left[ \frac{1 - (1 + j)^{-m}}{j} \right]
\]

(6.1)

where

- \(EMC_p\) is present value of the maintenance cost of the entire ownership cycle of equipment.
- \(\lambda_c\) is constant corrective maintenance rate of equipment per year.
- CMC is expected cost of a corrective maintenance action.
- \(\lambda_p\) is constant preventive maintenance rate of equipment per year.
- PMC is expected cost of a preventive maintenance action.
- \(m\) is equipment expected life expressed in years.
- \(j\) is annual interest rate.

Example 6.1

Assume that annual preventive and corrective maintenance rates of an engineering system are 5 and 2, respectively. Each preventive and corrective action costs $200 and $1,000, respectively. Calculate the present value of the system maintenance cost, if the expected system life and annual interest rate are 10 years and 5%, respectively.

By substituting the given data values into Equation (6.1), we get

\[
EMC_p = \left[ (2)(1,000) + (5)(200) \right] \left[ \frac{1 - (1 + 0.05)^{-10}}{0.05} \right]
\]

\[
= 23,165.20
\]

Thus, the present value of the system maintenance cost is $23,165.20.
6.3.1 Maintenance Equipment Cost

This is expressed by [6]

\[
MEC = C_{rd} + \alpha C_a
\]  

(6.2)

where

- \( MEC \) is maintenance equipment cost.
- \( C_{rd} \) is research and development cost associated with the maintenance equipment.
- \( \alpha \) is number of pieces of maintenance equipment.
- \( C_a \) is maintenance equipment unit acquisition cost.

6.4 Preventive and Corrective Maintenance Labor Cost Estimation

The preventive maintenance labor cost is expressed by [7]

\[
PMLC = (LR) \left[ \sum_{j=1}^{K} f_j \frac{APMT_j}{f_j} \right] \left[ \sum_{j=1}^{K} f_j \right]
\]  

(6.3)

where

- \( PMLC \) is equipment preventive maintenance labor cost.
- \( LR \) is hourly labor rate.
- \( K \) is number of data points.
- \( f_j \) is frequency of \( j \)th preventive maintenance action expressed in actions per operating hour, after adjustment for equipment duty cycle, for \( j = 1, 2, 3, \ldots, K \).
- \( APMT_j \) is average time, in hours, required to carry out \( j \)th preventive maintenance action for \( j = 1, 2, 3, \ldots, K \).

Similarly, the corrective maintenance labor cost is given by [7]

\[
CMLC = \frac{T_{so} (LC)(MTTR)}{MTBF}
\]  

(6.4)

where

- \( CMLC \) is equipment annual corrective maintenance labor cost.
- \( T_{so} \) is equipment annual scheduled operating hours.
- \( LC \) is hourly corrective maintenance labor cost.
- \( MTTR \) is equipment mean time to repair.
- \( MTBF \) is equipment mean time between failures.
Example 6.2
Assume that a system is scheduled to operate for 2,500 hours annually and its mean time between failures and mean time to repair are 700 hours and 3 hours, respectively. Calculate the system annual corrective maintenance labor cost, if the hourly corrective maintenance labor cost is $30.

By inserting the given data values into Equation (6.4), we get

\[ C_{MLC} = \frac{(2500)(30)(3)}{700} \]

\[ = 321.43 \]

Thus, the system annual corrective maintenance labor cost is $321.43.

6.5 Repair Manpower, Maintenance Material, and Spare and Repair Parts Costs

According to a U.S. military document [6], repair cost with respect to manpower can be estimated by using the following equation:

\[ RMC = \theta (1 - F_{rs}) RC_{um} \]  \hspace{1cm} (6.5)

where

- \( RMC \) is repair manpower cost.
- \( \theta \) is total number of repairable units failing over system or equipment life.
- \( F_{rs} \) is repairable shrinkage factor due to damage, loss, etc. Its values are tabulated in reference 6 and vary from 0 to 0.1375.
- \( RC_{um} \) is unit repair cost with respect to manpower.

The total number of repairable units failing over system or equipment life is expressed by

\[ \theta = \lambda (T)(\alpha)(SL) \]  \hspace{1cm} (6.6)

where

- \( \lambda \) is item constant failure rate.
- \( T \) is annual operating hours.
- \( \alpha \) is number of repairable items.
- \( SL \) is system or equipment life (in reference 6, taken to be 10 years).

The unit repair cost with respect to manpower is given by

\[ RC_{um} = (x)(F_{mu})(y) \]  \hspace{1cm} (6.7)

where

- \( x \) is mean number of man-hours per repair action.
- \( F_{mu} \) is manpower use factor. Its values are tabulated in reference 6 and they vary from 1.04 to 3.
- \( y \) is hourly manpower cost including overhead.
Life Cycle Costing for Engineers

The maintenance material cost is an important element of the total maintenance cost. For example, according to Neibel [8], in the United States industrial sector, the cost of maintenance materials typically accounts for 40–50% of the total maintenance cost. Because the cost of excessive inventory and obsolete parts is an important factor in most maintenance stockrooms and storerooms, well-planned and efficiently operated stockrooms and storerooms can help to reduce the cost of materials.

The total cost of stock or stores at the time of repair can be calculated by using the following equation [8]:

\[
SC_i = ITC + C_i + (W_{it} - ITC) + (0.01)(ITC)(t) + (0.1)(ITC)
\]

\[
= ITC + C_i + \left[ \frac{(t)(ITC) + (10)(ITC)}{100} \right]
\]

(6.8)

where

- \( SC_i \) is total cost of stock or stores at the time of repair.
- \( C_i \) is inventory cost per item.
- \( ITC \) is present worth of the inventory item cost including procurement and delivery costs.
- \( W_{it} \) is inventory item worth after \( K \) periods.
- \( t \) is time, expressed in months, during which the stock item is in inventory.

Note that Equation (6.8) allows an inflation rate of 1% per month of procurement cost, while the item under consideration is in inventory, and 10% for the item’s total shelf life to take into consideration factors such as spoilage, obsolescence, theft, and deterioration.

Equations to calculate \( W_{it}, C_i, \) and \( ITC \), respectively, are presented next.

\[
W_{it} = (ITC)(1+j)^k
\]

(6.9)

\[
C_i = (S_b)(FSC)/(n)(y)
\]

(6.10)

\[
ITC = (1+UL+SL)(PC)(WT) - MSP
\]

(6.11)

where

- \( j \) is interest rate for a given period.
- \( K \) is total number of interest periods.
- \( S_b \) is size of a bin expressed in square feet.
- \( FSC \) is yearly floor space cost per square foot.
- \( n \) is mean number of items stored in a bin.
- \( y \) is reciprocal of total years that an item usually spends in inventory.
- \( UL \) is amount of losses generated by unused stock returned to inventory considered too small in terms of quantity for use in the future.
SL is total amount of losses due to scrap, chips, skeletons, and so on.
PC is procurement cost or price (i.e., the delivered price) of material per unit.
WT is weight or other unit of quantity of material used.
MSP is unit price of material salvaged.

The spare and repair parts cost is defined by

\[
SRC = ISRC + CC + DSRC + SSRC + OSRC
\]  

where

- SRC is spare and repair parts cost.
- ISRC is intermediate spare and repair parts cost.
- CC is total cost of consumables.
- DSRC is depot spare and repair parts cost.
- SSRC is supplier spare and repair parts cost.
- OSRC is organizational spare and repair parts cost.

### 6.6 Maintenance Cost Estimation Models

Over the years, many mathematical models have been developed to estimate various types of maintenance-related costs. Four of these models are presented next.

#### 6.6.1 Model I

This model is concerned with estimating equipment initial logistic support cost, which is expressed by [9]

\[
EILSC = ISRC + ITHC + IMC + TDPC + LPMC + ITTEC + PC + OTSEPC
\]  

where

- EILSC is equipment initial logistic support cost.
- ISRC is cost of initial spare and repair parts.
- ITHC is initial transportation and handling cost.
- IMC is cost of initial inventory management.
- TDPC is technical data preparation cost.
- LPMC is cost of logistic program management.
- ITTEC is initial training and training equipment cost.
- PC is provisioning cost, including preparation of procurement data for essential spares, test, and support equipment.
- OTSEPC is procurement cost of operational test and support equipment.
6.6.2 Model II

This model is concerned with estimating software maintenance cost. This cost is expressed by [10]

\[ SMC = \frac{3(m)(LC)}{\theta} \]  

(6.14)

where

- \( SMC \) is software maintenance cost.
- \( m \) is total number of instructions to be changed per month.
- \( LC \) is labor cost per man-month.
- \( \theta \) is difficulty constant. Its values for hard programs, easy programs, and programs of medium difficulty are 100, 500, and 250, respectively.

6.6.3 Model III

This model is concerned with estimating Doppler radar maintenance cost. This is expressed by [11]

\[ DRMC = \frac{(C_a)y}{1000} \]  

(6.15)

where

- \( DRMC \) is Doppler radar maintenance cost.
- \( C_a \) is Doppler radar annual maintenance cost.
- \( y \) is number of years in service.

The natural logarithm of \( C_a \) is given by

\[ \ln C_a = \theta_1 + \theta_2 \ln C_{fu} \]  

(6.16)

where

- \( \theta_1 = -1.269 \)
- \( \theta_2 = 0.696 \)
- \( C_{fu} \) is the first unit cost of the Doppler radar expressed in 1974 dollars (\( \times 10^3 \)).

6.6.4 Model IV

This model is concerned with estimating the fire control radar maintenance cost, which is expressed by [11]

\[ FCRMC = (MC_{ph})h_1 h_2/1000 \]  

(6.17)

where

- \( FCRMC \) is fire control radar maintenance cost.
- \( MC_{ph} \) is maintenance cost per flying hour per unit expressed in 1974 dollars (\( \times 10^3 \)).
- \( h_1 \) is total number of annual flying hours.
- \( h_2 \) is total number of years in service.
The natural logarithm of $MC_{ph}$ is expressed by

$$\ln MC_{ph} = \alpha_1 + \alpha_2 \ln P_{pw} \quad (6.18)$$

where

- $\alpha_1 = -2.086$
- $\alpha_2 = 0.611$

$P_{pw}$ is peak power expressed in kilowatts.

### 6.7 Maintenance Cost Data Collection

As various types of cost data are needed in maintenance costing, management decides the types of cost data the maintenance department should collect by considering their potential applications. Four types of maintenance cost-related data are collected [12]:

- **Labor costs** are usually obtained by using items such as timesheets, job tickets, and maintenance work orders.
- **Spare parts and supplies costs** are usually obtained from maintenance work orders.
- **Overhead costs** are usually obtained from the company accounting department.
- **Equipment costs** are usually obtained from either purchase orders or suppliers’ invoices.

### 6.8 Maintainability Investment Cost Elements

The main elements of maintainability investment cost are as follows [6]:

- repair parts;
- system test and evaluation;
- new operational facilities;
- system engineering management;
- data;
- training;
- prime equipment; and
- support equipment.

Additional information on these elements is available in reference 6.
6.9 Manufacturer Warranty and Reliability Improvement Warranty Costs

The cost of warranty to an equipment manufacturer can be quite significant. It can be estimated by using the following equation [13]:

\[ MWC = (C_{mu})(n)(\lambda) + C_{fw} \]  \hspace{1cm} (6.19)

where
MWC is manufacturer or contractor warranty cost.
\( C_{mu} \) is mean cost for the manufacturer or contractor to repair a unit sent back for warranty service.
\( n \) is operating hours of equipment under warranty during the warranty period.
\( \lambda \) is average constant failure rate per hour of equipment under warranty during the warranty period.
\( C_{fw} \) is manufacturer or contractor warranty fixed cost.

The manufacturer warranty and reliability improvement warranty cost is expressed by [14]

\[ MWRC = FC_m + C_{ia} + C_d + P + C_x \]  \hspace{1cm} (6.20)

where
MWRC is manufacturer warranty and reliability improvement warranty cost.
\( FC_m \) is fixed cost of the manufacturer associated with the warranty.
\( C_{ia} \) is cost associated with reliability improvement actions for attaining the achieved mean time between failures (i.e., reliability improvement warranty period average).
\( C_d \) is cost of damages associated with not meeting the specified turnaround time.
P is profit.
\( C_x \) is cost.

The cost, \( C_x \), is expressed by

\[ C_x = (C_{mr})(n)(T_w)(UR)/MTBF_a \]  \hspace{1cm} (6.21)

where
\( C_{mr} \) is manufacturer’s cost per unit repair.
\( n \) is number of systems or items to be delivered.
\( T_w \) is length of the warranty period.
\( UR \) is usage rate expressed in operating time per calendar time.
\( MTBF_a \) is achieved mean time between failures (i.e., reliability improvement warranty period average).
6.10 Usability Costing and Related Facts and Figures

A wide range of activities is generally employed in effectively developing usable engineering products. The cost of these activities depends on factors such as the scope of the product under consideration, functional range, the number of scenarios to be studied, the number of users to be studied, and the skill and experience of the usability specialists [15]. Some of the usability costing-related facts and figures include:

- An American Airlines study reported that catching a usability-related problem early in the design process can decrease the cost of correcting it by 60–90% [16].
- A study revealed that the total training time for new users of a standard personal computer was approximately 21 hours as opposed to around 11 hours for users of a user-friendly computer [17].
- A study reported that the annual cost of lost productivity to American businesses is around $100 billion because office workers “futz” with their machines an average of 5.1 hours per week [18].
- A study revealed that approximately 80% of software maintenance cost is due to unmet or unforeseen user requirements [19].
- A study reported that an Australian insurance company spent approximately $100,000 (Australian) on a usability-related project concerned with redesigning its application forms to reduce customer errors and saved $536,023 (Australian) annually [20].

Additional information on usability-related facts and figures is available in Dhillon [21].

6.11 Principal Costs of Ignoring Product Usability and Product Usability Cost Estimation

The principal costs of ignoring engineering product usability are as follows [22]:

- **User error cost** is concerned with the users of engineering products making errors. In turn, these errors result in reduction in their productivity.
- **Poor productivity cost** consists of the additional time spent by engineering product users with products that are difficult to use.
- **Training cost** deals with the training of users when the product is first introduced. It increases significantly when products are difficult to use.
- **Customer support cost** involves a customer hotline telephone service, usually provided by product manufacturers for people having difficulties using the product. Past experiences indicate that products that are difficult to use generate greater customer or user requests for help. In turn, more people are required to handle users or customers, thus resulting in greater customer support cost.

- **Poor sale cost** involves dissatisfied customers or users not purchasing the product in the future, even when they are made aware of improvements in product usability. Past experiences indicate that a dissatisfied customer or user influences roughly 10 others to avoid buying the product in question [22].

- **Tarnished corporate image cost** is concerned with users or customers buying not only the current or improved usability version of the product in question, but also other products manufactured by the same firm.

The product usability cost can be estimated by using the following equation when usability cost data are available for similar products of different capacities [23]:

\[
DPC_u = SPC_u \left( \frac{CP_d}{CP_o} \right)^\theta
\]

(6.22)

where

- \(DPC_u\) is desired product usability engineering cost.
- \(SPC_u\) is known usability engineering cost of a similar item, product, or piece of equipment of known capacity \(CP_o\).
- \(CP_d\) is desired product capacity.
- \(\theta\) is cost-capacity factor. The value of this factor varies for different products or items. In circumstances when no data for \(\theta\) are available, it is considered quite reasonable to assume its value to be 0.6.

**Example 6.3**

Assume that the usability engineering cost of an 80 GB computer system is $300. Calculate the cost of usability engineering of a similar 100 GB computer system if the value of the cost-capacity factor is 0.8.

By substituting the specified data values into Equation (6.23), we get

\[
DPC_u = (300) \left( \frac{100}{80} \right)^{0.8}
\]

\[= \$358.63\]

Thus, the cost of usability engineering of the similar 100 GB computer system is $358.63.
Problems

1. What are the principal reasons for maintenance costing?
2. Discuss at least seven factors that influence maintenance cost.
3. Assume that annual preventive and corrective rates of an engineering system are 7 and 3, respectively. Each preventive and corrective action costs $400 and $1,200, respectively. Calculate the present value of the system maintenance cost, if the expected system life and annual interest rate are 12 years and 3%, respectively.
4. Discuss the collection of three types of maintenance cost-related data.
5. What are the principal elements of maintainability investment cost?
6. Discuss equipment warranty cost.
7. What is the equipment usability cost?
8. List at least five usability costing-related facts and figures.
9. Discuss the costs of ignoring engineering product usability.
10. Assume that an engineering system is scheduled to operate for 3,000 hours annually and its mean time between failures and mean time to repair are 800 hours and 4 hours, respectively. Calculate the system annual corrective maintenance labor cost, if the hourly corrective maintenance labor cost is $40.

References

7

Computer System Life Cycle Costing

7.1 Introduction

Today computers play an important role in our daily lives. Over the years, their applications have increased quite dramatically, ranging from personal use to controlling nuclear reactors and space systems. The computer industry has become an important component of the global economy; a vast sum of money is spent to produce, operate, and maintain computers each year. For example, in fiscal year 1980, the U.S. government spent over $57 billion on computer systems [1].

Computer systems are made up of both hardware and software components and the percentage of overall computer system cost spent on hardware has changed quite remarkably over the years. For example, in 1955, the hardware component accounted for 80% of total computer system cost; however, in 1985, the hardware component cost decreased to just 10% [2]. This means that, nowadays, software cost is a very important element of total computer system cost—more specifically, the computer system life cycle cost.

Over the years, many models and procedures have been developed to estimate directly or indirectly computer system life cycle cost. This chapter presents various important aspects of computer system life cycle costing.

7.2 Computer System Life Cycle Cost Models

A number of mathematical models are used to estimate life cycle cost of a computer system. Two such models are presented next [3,4].

*Model I* divides the life cycle cost of a computer system into two main components: procurement cost and ownership cost. Thus, the life cycle cost of a computer system is expressed by

\[ LCC_{CS1} = C_p + C_0 \]  

(7.1)

where

- \( LCC_{CS1} \) is computer system life cycle cost.
- \( C_p \) is computer system procurement cost.
- \( C_0 \) is computer system ownership cost.
The procurement cost includes the cost of items such as system hardware, software license fees, installation, training, and documentation. Similarly, the ownership cost includes the cost of items such as preventive maintenance, computer downtime, supplies, and corrective maintenance.

*Model II* is a more detailed model to estimate the life cycle cost of a computer system. However, the model assumes that the cost of corrective maintenance is the only ownership cost of the computer system. Thus, the life cycle cost of the computer system is defined by

\[
\text{LCC}_{CS2} = C_{p2} + \sum_{j=1}^{n} \left( C_{mj} \right) \frac{\alpha_j}{(1+i)^j}
\]  

(7.2)

where

- \( \text{LCC}_{CS2} \) is the life cycle cost of the computer system.
- \( C_{p2} \) is the procurement cost of the computer system.
- \( n \) is the computer system expected life expressed in years.
- \( C_{mj} \) is the corrective maintenance cost of a single maintenance activity during year \( j \).
- \( \alpha_j \) is the expected number of times that the computer system will fail during year \( j \).
- \( i \) is the discount rate.

For the same number of computer system failures occurring in each year, Equation (7.2) simplifies to

\[
\text{LCC}_{CS2} = C_{p2} + \alpha \sum_{j=1}^{n} C_{mj} / (1+i)^j
\]  

(7.3)

where \( \alpha \) is the expected number of computer system failures per year.

**Example 7.1**

Assume that the procurement cost and expected useful life of a computer system are $4,000 and 5 years, respectively. The computer system’s expected number of failures per million hours is 100 and its only ownership cost is the cost of corrective maintenance. Calculate the life cycle cost of the computer system, if the cost of each corrective maintenance call is $200 and the yearly discount or interest rate is 4%.

The expected number of failures of the computer system per year is given by

\[
n = \frac{(100)(8,760)}{1,000,000} = 0.876 \text{ failures/year}
\]
Using the preceding calculated value and the given data in Equation (7.3), we get

\[
LCC_{CS2} = 4,000 + (0.876)(200) \sum_{j=1}^{5} (1+0.04)^{-j}
\]

\[
= 4,779.96
\]

Thus, the life cycle cost of the computer system is $4,779.96.

### 7.3 Computer System Maintenance Cost

The computer system maintenance cost is an important component of computer system life cycle cost. This section presents two mathematical models to estimate, directly or indirectly, computer system maintenance cost.

**Model I** is concerned with estimating the maintenance cost of computer system hardware, which is expressed by [3,4]

\[
C_{sm} = C_{pm} + C_{cm} + C_i
\]  

(7.4)

where

- \( C_{sm} \) is monthly maintenance cost of the computer system hardware.
- \( C_{pm} \) is preventive maintenance cost of the computer system hardware.
- \( C_{cm} \) is corrective maintenance cost of the computer system hardware.
- \( C_i \) is inventory cost.

The preventive maintenance cost of the computer system hardware is expressed by

\[
C_{pm} = (OH) \theta [SPMT_i + TT_i] / SPM_i
\]  

(7.5)

where

- \( OH \) is equipment operating hours per month.
- \( \theta \) is hourly rate of the customer engineer. This also includes the spare parts usage rate.
- \( SPMT_i \) is customer engineer’s scheduled preventive maintenance time.
- \( TT_i \) is customer engineer’s travel time to perform preventive maintenance.
- \( SPM_i \) is scheduled preventive maintenance interval.

The customer engineer’s hourly rate, \( \theta \), is expressed by

\[
\theta = \frac{PR (1+OR)}{\alpha} + C_r
\]

(7.6)
where

- \( PR \) is hourly pay rate of the customer engineer.
- \( OR \) is overhead rate.
- \( C_p \) is cost of parts per hour.
- \( \alpha \) is fraction of time that the customer engineer spends on the maintenance activity. Note that the customer engineer spends the remaining fraction of time on items such as paperwork, training, and waiting.

The corrective maintenance cost of the computer system hardware is defined by

\[
C_{cm} = \theta (OH) \left[ TT_{ecm} + \frac{MTTR}{MTBF} \right]
\]

(7.7)

where

- \( TT_{ecm} \) is customer engineer’s travel time for performing corrective maintenance.
- \( MTTR \) is mean time to repair.
- \( MTBF \) is mean time between failures.

The inventory cost, \( C_i \), is expressed by

\[
C_i = (V_{ip}) (R_i)
\]

(7.8)

where

- \( V_{ip} \) is value of the maintenance spare parts inventory.
- \( R_i \) is monthly inventory cost rate, which includes items such as handling cost, interest charges for spares, and depreciation.

Model II is concerned with estimating the annual labor cost of servicing a computer system. This cost depends on many factors, including average cost of labor, mean time to preventive maintenance, preventive maintenance time interval, mean time between failures, and mean time to repair.

The annual labor cost is defined by

\[
C_a = (LC_h)(8760) \left[ \frac{(T_{apm} + TT_{pm})}{T_{bpm}} + \frac{(TT_r + MTTR)}{MTBF} \right]
\]

(7.9)

where

- \( LC_h \) is labor cost per hour.
- \( T_{apm} \) is average time taken to perform preventive maintenance.
- \( TT_{pm} \) is travel time associated with a preventive maintenance call.
- \( T_{bpm} \) is mean time between preventive maintenance services.
- \( TT_r \) is travel time associated with a repair or corrective maintenance call.
- \( MTTR \) is mean time to repair.
- \( MTBF \) is mean time between failures.
Example 7.2
Assume the following data values concerning servicing a computer system:

\[ L_{Ch} = \$50 \]
\[ T_{apm} = 4 \text{ hours} \]
\[ TT_{pm} = 0.5 \text{ hour} \]
\[ T_{bpm} = 2,500 \text{ hours} \]
\[ T_{Tr} = 1 \text{ hour} \]
\[ MTTR = 2 \text{ hours} \]
\[ MTBF = 3,000 \text{ hours} \]

Calculate the annual labor cost for servicing the computer system by using Equation (7.9).

By substituting the given data values into Equation (7.9), we get

\[ C_a = (L_{Ch}) \left( \frac{(4 + 0.5)}{2,500} + \frac{(1 + 2)}{3,000} \right) \]

\[ = \$1,226.4 \]

Thus, the annual labor cost for servicing the computer system is $1,226.40.

7.4 Software Costing and Related Difficulties

Over the years, software cost has increased to a very high level from a rather low percentage of the total computer system cost. For example, according to a U.S. Air Force study conducted in 1972, cost of software in 1955 accounted for less than 20% of total computer system cost; however, its projection for 1985 was around 80% of the total amount [3]. Furthermore, in July 1976, Newsweek magazine reported that the ratios of computer system hardware cost to software cost were 1:4 and 4:1 in 1976 and the 1950s, respectively.

Needless to say, today software cost has become a very important element of the computer system life cycle cost. Over time, many methods and procedures have been developed to estimate software cost.

Some of the difficulties faced in estimating software cost include [5]:

- poor understanding of the effects of management and technical-related constraints;
- poor understanding of the software development and maintenance processes;
- unavailability of adequate historic data to make appropriate checks;
unavailability of adequate historic data for calibration applications
(A calibration may be described as a process through which a model
is fitted to a given cost estimating condition.); and
project-to-project comparison inhibition because of firm belief in a
project’s uniqueness.

7.5 Software Life Cycle Cost Influencing Factors and Model

Many factors influence software life cycle cost. They may be grouped under
five distinct attributes [6]:

- **Group I: computer attributes.** Some examples of these attributes are
turnaround time, speed, and storage constraints.

- **Group II: project attributes.** Some examples of these attributes are
schedule constraints, use of software tools, and modern program-
ing practices [7].

- **Group III: size attributes.** Some examples of these attributes are
numbers of inputs, outputs, data elements, and instructions.

- **Group IV: product attributes.** Some examples of these attributes are
required software reliability, the choice of programming language,
and software product complexity.

- **Group V: personnel attributes.** These attributes affect software cost
much more than any other groups of attributes. Some examples of
personnel attributes are teamwork; experience with respect to items
such as programming language, applications, and virtual machines;
and personnel and team capabilities.

The life cycle cost of software is composed of seven distinct elements, as
shown in Figure 7.1. This is expressed mathematically by [8]

\[ LCC_{se} = SDC + SAC + CC + SOSC + SIC + STIC + SDOC \]  

(7.10)

where
- \( LCC_{se} \) is software life cycle cost.
- \( SDC \) is software design cost.
- \( SAC \) is software analysis cost.
- \( CC \) is software code and checkout cost.
- \( SOSC \) is software operating and support cost.
- \( SIC \) is software installation cost.
- \( STIC \) is software test and integration cost.
- \( SDOC \) is software documentation cost.
Table 7.1 presents the main elements of costs of software design, analysis, operating and support, code and checkout, test and integration, installation, and documentation [8].

7.6 Software Cost Estimation Methods and Models

Over the years, many methods and models have been developed to estimate software cost. Some of these methods and models are presented next.

7.6.1 Software Cost Estimation Methods

Many methods have been used to estimate software costs, including [3,9]:

- algorithmic models;
- top-down estimating;
- bottom-up estimating;
- analogy; and
- expert opinion.

The algorithmic models are described later in detail, and additional information on the remaining four methods is available in Dhillon [3] and Boehm [9].

The algorithmic models may be described as the models that provide at least one mathematical algorithm to generate a computer software cost estimate as a
7.6.1.1 Tabular Models

Generally, these models are quite straightforward to comprehend and implement. They are composed of tables relating cost driver variables’ values to portions of the software development effort or to multipliers employed to adjust the effort estimate. Three examples are the Black et al. [10], Aron [11], and Wolverton [12] models.

7.6.1.2 Composite Models

These models incorporate an amalgamation of four types of functions (i.e., linear, tabular, analytic, and multiplicative) for determining software effort function of several variables. These variables are considered very important cost drivers. The five common types of algorithmic models are presented next [9].

TABLE 7.1
Subelements of Software Life Cycle Cost Elements

<table>
<thead>
<tr>
<th>No.</th>
<th>Software Life Cycle Cost Element</th>
<th>Subelements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design cost</td>
<td>Cost of flow charts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data structure cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of test procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of input and output parameters</td>
</tr>
<tr>
<td>2</td>
<td>Analysis cost</td>
<td>Cost of system requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of program requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of design requirements and specifications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of interface requirements</td>
</tr>
<tr>
<td>3</td>
<td>Operating and support cost</td>
<td>Cost of modifications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of test revisions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of documentation revisions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of environments</td>
</tr>
<tr>
<td>4</td>
<td>Code and checkout cost</td>
<td>Cost of desk checks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of coded instructions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of compiling programs</td>
</tr>
<tr>
<td>5</td>
<td>Test and integration cost</td>
<td>Cost of program test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of system integration</td>
</tr>
<tr>
<td>6</td>
<td>Installation cost</td>
<td>Validation cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Verification cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Certification cost</td>
</tr>
<tr>
<td>7</td>
<td>Documentation cost</td>
<td>Cost of listings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of user manual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of maintenance manual</td>
</tr>
</tbody>
</table>
as a function of cost driver variables. Past experiences indicate that composite models are relatively more difficult to learn and use, in addition to requiring more data and effort.

### 7.6.1.3 Analytic Models

These models take the following form [3]:

\[
ET = f(x_1, x_2, \ldots, x_n)
\]

(7.11)

where

- \( ET \) is effort.
- \( f \) is a function (it is to be noted that this function is neither linear nor multiplicative).
- \( x_j \) is cost driver variable \( j \) for \( j = 1, 2, 3, \ldots, n \).
- \( n \) is total number of cost driver variables.

Two good examples of the analytic models are the Putnam [13] and Halstead [14] models.

### 7.6.1.4 Linear Models

These models take the following form [3]:

\[
ET = N_0 + \sum_{j=1}^{K} N_j x_j
\]

(7.12)

where

- \( ET \) is effort.
- \( K \) is total number of cost driver variables.
- \( N_j \) is coefficient chosen to best fit the observed data points for \( j = 0, 1, 2, 3, \ldots, K \).
- \( x_j \) is cost driver variable \( j \) for \( j = 1, 2, 3, \ldots, K \).

An important reference to the earliest use of the linear model is the System Development Corporation software cost-estimation study performed in the mid-1960s [15]. Finally, it was concluded that there are many nonlinear interactions in the software development process for linear models to perform very effectively.

### 7.6.1.5 Multiplicative Models

These models take the following form [3]:

\[
ET = M_0 \prod_{j=1}^{n} M_j^{x_j}
\]

(7.13)
where

\( ET \) is effort.

\( n \) is total number of cost driver variables.

\( M_j \) is coefficient chosen to best fit the observed data for \( j = 0, 1, 2, 3, \ldots, n \).

\( x_j \) is cost driver variable \( j \) for \( j = 1, 2, 3, \ldots, n \).

Past experiences indicate that multiplicative models work fairly well for reasonable, independently selected variables. Additional information on multiplicative models is available in Walston [15] and Herd et al. [16].

### 7.6.2 Software Cost Estimation Models

As mentioned earlier, many types of models can be used to estimate software cost (see references 3, 5, 9, and 17). Some of these models used directly or indirectly to estimate software cost are presented next.

**Model I** is concerned with estimating the software development cost, which is expressed by [16,18]

\[
SDC = SPC + SSC
\]  

(7.14)

where

\( SDC \) is software development cost.

\( SPC \) is software primary development cost.

\( SSC \) is software secondary development cost.

The software primary development cost is defined by

\[
SPC = (ALR)(MR)
\]  

(7.15)

where

\( ALR \) is average labor rate of the software development manpower expressed in dollars per man-month. It includes items such as administration cost, general cost, and overhead cost.

\( MR \) is manpower required for software development expressed in man-months. This includes activities such as analysis, design, code, test, debug, and checkout.

Similarly, the software secondary development cost is expressed by

\[
SSC = \sum_{i=1}^{m} C_i = \lambda (SPC) = \lambda (ALR)(MR)
\]  

(7.16)
where

\( m \) is total number of secondary resources.
\( C_i \) is cost associated with secondary resource \( i \) for \( i = 1, 2, 3, \ldots, m \).
\( \lambda \) is ratio of software secondary development cost to software primary development cost.

*Model II* is concerned with estimating the duration of a software project. The model predicts the minimum project duration under the assumption that the total hardware will be available during the project life. Thus, the minimum project duration is expressed by [19]

\[
D_{\text{min}} = \frac{D_p}{S_a}
\]  

(7.17)

where

\( D_{\text{min}} \) is minimum project duration.
\( D_p \) is total programmer-months.
\( S_a \) is average staff size allocated to the software project under consideration.

Additional information on the model is available in Schneider [19].

*Model III* is concerned with estimating the software marketing cost, which is expressed by [20]

\[
C_{\text{sm}} = C_{ho} + C_{fs}
\]  

(7.18)

where

\( C_{\text{sm}} \) is annual software marketing cost.
\( C_{ho} \) is cost associated with the home office.
\( C_{fs} \) is field sales-related cost.

The field sales-related cost is given by

\[
C_{fs} = [\theta (BS) + \theta (SAS) \alpha](1 + r_o) + r_c \text{ (APS)}
\]  

(7.19)

where

\( \theta \) is total number of people involved in sales.
\( BS \) is annual base salary of a salesperson.
\( SAS \) is annual salary of a system analyst.
\( \alpha \) is total number of system analysts employed per salesperson.
\( r_o \) is overhead rate.
\( r_c \) is commission rate.
\( APS \) is annual product sales.

*Model IV* is concerned with estimating the software quality cost, which is expressed by [21]

\[
SQC = PC + AC + IFC + EFC
\]  

(7.20)
Life Cycle Costing for Engineers

where

- \(\text{SQC}\) is software quality cost.
- \(\text{PC}\) is prevention cost associated with activities performed to prevent the occurrence of software errors. Some examples of these activities are developing a software quality infrastructure, improving and updating that infrastructure, and performing the regular activities necessary for its successful operation.
- \(\text{AC}\) is appraisal cost associated with activities pertaining to the detection of software errors in software projects under consideration. Some examples of the appraisal cost components are the cost of software testing, cost of reviews, and cost of assuring quality of external participants (e.g., subcontractors).
- \(\text{IFC}\) is internal failure cost associated with correcting software errors discovered through testing, design reviews, and acceptance tests prior to the installation of the software under consideration at customer sites.
- \(\text{EFC}\) is external failure cost associated with correcting software failures discovered by customers after the installation of software at their sites.

*Model V* is concerned with estimating software project effort, in programmer-months, in situations when very little information about the project under consideration is available, except its expected delivery instructions. The software project effort is expressed by [19]

\[
\text{SPE} = (1.7)(I_d)(S_{cf})(L_{af})
\]  

(7.21)

where

- \(\text{SPE}\) is software project effort expressed in programmer-months.
- \(I_d\) is delivered instructions expressed in thousands.
- \(S_{cf}\) is software complexity factor. Its values for trivial, moderately complex, and very complex software are 1, 5, and 10, respectively.
- \(L_{af}\) is labor estimate adjustment factor expressed in decimal fraction. Its recommended values for rather poorly managed projects and under best conditions are 2.9 and 0.435, respectively.

*Model VI* was developed by the U.S. Naval Air Development Center and is concerned with estimating the effort to develop software [22]. This effort is expressed by [17,22]

\[
\text{SDE} = 2.8x + 1.3y + 33z + 10K + L - 17M - 188
\]  

(7.22)

where

- \(\text{SDE}\) is total number of man-months needed for the software development.
- \(x\) is delivered program’s machine language instructions expressed in thousands.
- \(y\) is contractor man-miles traveled.
- \(z\) is total number of document types produced or generated.
$K$ is total number of independent consoles in the delivered system.
$L$ is number of new instructions in percentages.
$M$ is average programmer experience with the system under consideration, expressed in years.

Problems

1. Write an essay on computer system life cycle costing.
2. Assume that the acquisition cost and expected useful life of a computer system are $5,000 and 6 years, respectively. The computer system’s expected number of failures per million hours is 80 and its only ownership cost is the cost of corrective maintenance. Calculate the life cycle cost of the computer system, if the cost of each corrective maintenance call is $150 and the annual discount or interest rate is 6%.
3. Discuss the major difficulties faced in estimating software cost.
4. Discuss the factors that influence software life cycle cost.
5. What is the difference between computer hardware and software costing?
6. Write an equation that can be used to estimate software life cycle cost.
7. Discuss software cost estimation methods.
8. Compare tabular models with linear models with respect to software costing.
9. Discuss a mathematical model that can be used to estimate computer system hardware maintenance cost.
10. What is the main difference between Equation (7.2) and Equation (7.3)?

References

8

Transportation System Life Cycle Costing

8.1 Introduction

Each year a vast amount of money is spent to develop, manufacture, and operate transportation systems such as motor vehicles, trains, aircraft, and ships throughout the world. This amount has become an important element of the global economy. Saving a small percentage of this amount can result in a large sum of money.

The concept of life cycle costing is increasingly being applied to make various types of decisions concerning transportation systems, particularly at their design and procurement stages. The main reason for the increasing use of the life cycle costing concept during a transportation systems’ design and procurement stages is that past experiences indicate that many transportation systems’ ownership costs (i.e., logistics and operating cost) often exceed their procurement costs. This is also the case for many other engineering products and systems. In fact, according to Ryan [1], the ownership costs of certain engineering products and systems can vary from 10 to 100 times their acquisition costs.

Over the years, a large number of publications have appeared on various aspects of transportation system life cycle costing. This chapter presents various important aspects of aircraft, ship, urban rail, and motor vehicle life cycle costing.

8.2 Aircraft Life Cycle Cost

Although the life cycle cost breakdown structure of an aircraft can vary from one organization to another and from one type of aircraft to another, it can be broken down into four parts as follows:

\[
LCC_a = C_1 + C_2 + C_3 + C_4
\]

(8.1)

where

- \( LCC_a \) is aircraft life cycle cost.
- \( C_1 \) is aircraft research, development, test, and evaluation cost.
- \( C_2 \) is aircraft production cost.
- \( C_3 \) is aircraft initial support costs associated with items such as support equipment, spares, data, special equipment, and contractual training.
$C_4$ is aircraft operations and support cost associated with items such as base-level maintenance, training, and operations personnel and depot-level engine and component repair.

Usually, the life cycle cost of a typical fighter aircraft is broken into three categories [1]:

$$LCC_{fa} = DC_{fa} + PC_{fa} + OSC_{fa}$$  \hspace{1cm} (8.2)

where
- $LCC_{fa}$ is life cycle cost of a typical fighter aircraft.
- $DC_{fa}$ is fighter aircraft development cost.
- $PC_{fa}$ is fighter aircraft acquisition cost.
- $OSC_{fa}$ is fighter aircraft operations and support cost.

According to Huie and Harris [2], for a typical fighter aircraft, the operations and support cost, acquisition cost, and development cost over its life span of 15 years usually account for approximately 55, 35, and 10% of the life cycle cost, respectively.

The four main components of fighter aircraft development cost are design and development cost, test and evaluation cost, flight test support cost (e.g., cost of spares, ground support equipment, and personnel), and cost of data (e.g., test and stress reports). Normally, activities such as design, manufacturing, and testing account for roughly 90% of the development cost. The factors that drive the cost of the development include mission capabilities, physical characteristics such as weight, size, reliability, and maintainability characteristics (e.g., mean time between failures and mean time to repair).

The six main components of the fighter aircraft acquisition cost are shown in Figure 8.1 [2,3]. Two of these components (i.e., flyaway cost and cost of initial support) account for an extremely large percentage of the acquisition cost. The flyaway cost includes the cost of the airframe, engine, and avionics, and the cost of initial support includes the cost of spares, ground support equipment, inventory entry and management, and training and training equipment.

Some of the main drivers of the acquisition cost are reliability and maintainability characteristics, maintenance concept, mission capabilities, and training system requirements.

The fighter aircraft operations and support cost is composed of nine main components:

- cost of fuel;
- cost of personnel;
- cost of depot maintenance;
- cost of facilities;
- cost of base maintenance material;
- cost of modifications;
The five cost components that account for approximately 85% of the operations and support cost are fuel cost, depot maintenance cost, personnel cost, base maintenance material cost, and replenishing spares cost.

The seven factors that drive the fighter aircraft operations and support cost are shown in Figure 8.2 [3].
8.3 Aircraft Turbine Engine Life Cycle Cost

In the overall cost of an aircraft, the turbine engine is an important subsystem. The engine life cycle cost is expressed by [4,5]

\[
LCC_{ae} = TEDC + TEPIC + TEPQC + TEBMC + TEDMC
\]

(8.3)

where

- \( LCC_{ae} \) is aircraft turbine engine life cycle cost.
- \( TEDC \) is turbine engine development cost.
- \( TEPIC \) is turbine engine part improvement cost.
- \( TEPQC \) is turbine engine production quantity cost.
- \( TEBMC \) is turbine engine base maintenance cost.
- \( TEDMC \) is turbine engine depot maintenance cost.

Equations to estimate the five right-hand-side elements of Equation (8.3) are given in Jones [4] and Nelson [5].

8.4 Aircraft Cost Drivers

There are many aircraft cost drivers. In general, they may be grouped under the following three areas [2]:

- design;
- manufacturing; and
- operations and support.

The design cost drivers may be divided into three categories: reliability and maintainability requirements, performance requirements, and specifications. Two important elements of the reliability and maintainability requirements are mean time between failures (MTBF) and mean time to repair (MTTR).

Similarly, the four elements of the performance requirements are speed, payloads, range, and mission role. Finally, the elements of the specifications include corrosion control and fatigue life. Four main categories of the typical manufacturing cost drivers are shown in Figure 8.3 [2,3].

The elements of the material category include steel, aluminum, titanium, and composite. Some of the elements of the manufacturing process category are forgings, castings, machined parts, and sheet metal. The two main elements of the structure category are wing and body. The wing includes components such as the number of hard points, wet versus dry, and complexity of control surfaces. Similarly, the body includes components such as landing gear attachment and wing attachment.
The subsystems category has two main elements: flight control and landing gear. The flight control includes items such as the number of redundancies and mechanical versus fly-by-wire. Similarly, the landing gear includes items such as the number of wheels and brakes.

8.4.1 Helicopter Maintenance Cost Drivers

Many maintenance cost drivers are associated with helicopters. For example, maintenance cost drivers for military helicopters include the rotor system, power plants, transmissions, inspections, and others [3]. Generally, the breakdown percentages of direct maintenance cost (parts and labor) for these cost drivers are roughly 29, 27, 12, 9, and 23%, respectively. The breakdown percentages within the rotor system are blades (80%) and hub (20%).

Furthermore, note that the major contributor to the rotor hub operation and support cost is the seal leak, which results in lubricant loss and fluid. Similarly, two major contributors to the rotor blade operation and support cost are foreign object damage and inability to repair damaged blades.

8.4.2 Aircraft Airframe Maintenance Cost Drivers

According to a study performed in the early 1970s, the top nine airframe maintenance cost components were as follows [3]:

- brakes;
- tires;
• nose landing gear wheel and tire;
• flight control power control units;
• constant speed drive;
• motor-driven hydraulic pump;
• engine-driven hydraulic pump;
• auxiliary power unit; and
• starter.

8.4.3 Combat Aircraft Hydraulic and Fuel Systems Cost Drivers

The following are cost drivers of a combat aircraft hydraulic system [3,6]:

• valves (9%);
• pumps (26%);
• filters (12%);
• reservoirs (20%);
• accumulators (7%);
• plumbing (12%); and
• other (14%).

The cost drivers of a combat aircraft fuel system are valves (33%), pumps (27%), filters (8%), measurement (17%), and other (15%) [3,6].

8.5 Cargo Ship Life Cycle Cost

Ships are an important mode of transportation; over 90% of the world’s cargo is transported by merchant ships. The life cycle cost of a cargo ship is expressed by [7]

\[ LCC_{CS} = BC + OC + AC + OPC \]  (8.4)

where

- \( LCC_{CS} \) is cargo ship life cycle cost.
- \( BC \) is cargo ship building cost, including the cost of items such as machinery, outfitting, and hull.
- \( OC \) is the cargo ship owner’s cost, including items such as naval architect’s fee, attorney’s fee, and consulting fees.
- \( AC \) is cargo ship accommodation cost, including the cost of items such as steel, hull engineering, and outfitting.
OPC is cargo ship operating cost, including the cost of items such as fuel, maintenance and repair, cargo handling, part changes, wages, inventory, protection and indemnity insurance, hull and machinery insurance, and subsistence.

Additional information on cargo ship life cycle cost is available in Earles [7].

8.6 Operating and Support Costs for Ships

Over the years, many formulas have been developed to estimate various types of ship operating and support costs. Some of these formulas that have been developed for the U.S. Navy are presented next [7,8].

8.6.1 Formula I

This formula is concerned with estimating the cost of repair parts:

\[ C_{rp} = A + (B)(LD) \]  (8.5)

where

- \( C_{rp} \) is cost of repair parts expressed per steaming hour (i.e., underway and not underway) in 1976 dollars.
- \( A = 28.083 \)
- \( B = 0.00263 \)
- \( LD \) is full load displacement expressed in tons.

8.6.2 Formula II

This formula is concerned with estimating the cost of conventional fuel and is expressed by

\[ C_{cf} = D + (E)(HP) - (F)x \]  (8.6)

where

- \( C_{cf} \) is cost of conventional fuel.
- \( D = 166.021 \)
- \( E = 0.001974 \)
- \( HP \) is total shaft horsepower.
- \( F = 490.220 \)
- \( x \) is a dummy variable whose value is either 1 (when the ship is nuclear powered) or 0 (when the ship is not nuclear powered).

8.6.3 Formula III

This formula is concerned with estimating the ship overhaul cost, which is expressed by

\[ C_{Sho} = (MD_r)(N) + (0.25)(MD_r)(N) \]  (8.7)
where

\[ C_{Sho} \] is ship overhaul cost.
\[ MD_r \] is repair man-days per overhaul.
\( N = $150 \) (in 1976 dollars)

Note that the right-hand side of Equation (8.7) is composed of two components: labor cost \([MD_r \cdot (N)]\) and material cost \([0.25 \cdot (MD_r \cdot (N))]\).

### 8.6.4 Formula IV

This formula is concerned with estimating ship supplies’ cost. This is expressed by

\[
C_{SS} = G + (H) \cdot (\alpha) + (I) \cdot x
\]  
(8.8)

where

\( C_{SS} \) is ship supplies’ cost.
\( G = 44,797.515 \)
\( H = 248.260 \)
\( \alpha \) is ship crew size (i.e., officers + enlisted individuals).
\( I = 478,830 \)
\( x \) is a dummy variable whose value is either 1 (i.e., when the ship is nuclear powered) or 0 (i.e., when the ship is not nuclear powered).

Note that Equation (8.8) provides the annual cost of health, safety, and welfare supplies expressed in 1976 dollars.

### 8.7 Urban Rail Life Cycle Cost

Urban rail is an important means of transportation around the globe. Each day it transports millions of passengers and millions of dollars worth of goods from one place to another. The urban rail life cycle cost is defined by [7]

\[
LCC_{ur} = SCC + SOC
\]  
(8.9)

where

\( LCC_{ur} \) is life cycle cost.
\( SCC \) is capital cost, including the cost of items such as vehicles, track and track work, power substations and distribution, stations, and yard and maintenance facilities.
\( SOC \) is operating cost, including the cost of items such as power, transportation-associated manpower, and maintenance of tracks, vehicles, and equipment.

Additional information on this topic is available in references 3, 7, and 9.
8.8 Car Life Cycle Cost

Each day, a vast sum of money is spent to procure and operate various types of cars throughout the world. The life cycle cost of a car is defined by [3,10]

\[ LCC_c = C_a + \sum_{j=1}^{n} OC_j + SMC_j + USMC_j + C_d \]  

(8.10)

where

- \( LCC_c \) is life cycle cost of the car.
- \( C_a \) is acquisition cost.
- \( n \) is expected life of the car expressed in years.
- \( OC_j \) is operating cost (i.e., for gas, oil, tires, etc.) for year \( j \) for \( j = 1, 2, 3, \ldots, n \).
- \( SMC_j \) is scheduled maintenance cost (i.e., for tune-up, lubrication, etc.) for year \( j \) for \( j = 1, 2, 3, \ldots, n \).
- \( USMC_j \) is unscheduled maintenance or repair cost (dependent on car failure rate) for year \( j \) for \( j = 1, 2, 3, \ldots, n \).
- \( C_d \) is car disposal plus any other cost.

Additional information on car life cycle costing is available in references 3, 7, and 10.

**Example 8.1**

Assume that the acquisition cost of a car is $23,000. Annual scheduled and unscheduled maintenance costs are $200 and $400, respectively. Furthermore, the annual operating cost of the car is $1,500 and its life expectancy is 7 years. Calculate the car life cycle cost, if its disposal cost and the annual interest rate are $2,000 and 4%, respectively.

By using an equation given in Chapter 2 and in reference 3 and the given data, we get the following present values of the car operating cost, scheduled maintenance cost, and unscheduled maintenance cost, respectively:

\[ OC_p = 1500 \left[ \frac{1-(1+0.04)^{-7}}{0.04} \right] = $9,003.1 \]

\[ SMC_p = 200 \left[ \frac{1-(1+0.04)^{-7}}{0.04} \right] = $1,200.4 \]

and

\[ USMC_p = 400 \left[ \frac{1-(1+0.04)^{-7}}{0.04} \right] = $2400.8 \]

where

- \( OC_p \) is present value of operating cost.
- \( SMC_p \) is present value of scheduled maintenance cost.
- \( USMC_p \) is present value of unscheduled maintenance cost.
Using an equation given in Chapter 2 and in reference 3 and the specified data values, we get the following present value of the car disposal cost:

\[ C_{dp} = \frac{2,000}{(1+0.04)^7} = \$1,519.8 \]

where \( C_{dp} \) is present value of the car disposal cost.

Using all of the preceding calculated values, the given data value, and Equation (8.10), we get the following value for the car life cycle cost:

\[ LCC_c = \$23,000 + \$9,003.1 + \$1,200.4 + 2,400.8 + \$1,519.8 \]
\[ = \$37,124.1 \]

Thus, the car life cycle cost is \$37,124.10.

8.9 City Bus Life Cycle Cost Estimation Model

A bus is an important means of transport in cities throughout the world. This model is concerned with estimating city bus cost over the life span of the vehicle. Thus, the city bus life cycle cost is expressed by [3,11]

\[ LCC_{cb} = VAC + TC + IOC + WC + LC + FC + MCC + RC + GOC + OHC + CIC + TC \]  

(8.11)

where

\( LCC_{cb} \) is city bus life cycle cost.
\( VAC \) is vehicle acquisition cost.
\( TC \) is tire cost.
\( IOC \) is cost of intermediate overhauls.
\( WC \) is cost of wages.
\( LC \) is lubricant cost.
\( FC \) is fuel cost.
\( MCC \) is cost of maintenance and checkup.
\( RC \) is repair cost.
\( GOC \) is cost of general overhauls.
\( OHC \) is cost of overhead.
\( CIC \) is cost of compulsory insurance.
\( TC \) is taxes.

Additional information on the model is available in Zalud and Lanc [11].
Problems

1. Write an essay on transportation system life cycle costing.
2. What are the main components of fighter aircraft development cost?
3. What are the driving factors of fighter aircraft operation and support cost?
4. What are the main components of the fighter aircraft procurement cost?
5. Mathematically, define the life cycle cost of an aircraft turbine engine.
6. Discuss helicopter maintenance cost drivers.
7. What are the aircraft airframe maintenance cost drivers?
8. Mathematically, define the life cycle cost of a cargo ship.
9. Write formulas to estimate ship overhaul cost and conventional fuel cost.
10. Assume that the procurement cost of a car is $30,000. The annual scheduled and unscheduled maintenance costs are $300 and $500, respectively. Furthermore, the annual operating cost of the car is $1,000 and its life expectancy is 8 years. Calculate the car life cycle cost, if its disposal cost and the annual interest rate are $1,500 and 6%, respectively.

References

(NATO) Advisory Group for Aerospace Research and Development (AGARD) conference proceedings no. 289, 6.1–6.10.


9

Civil Engineering Structures and Energy Systems Life Cycle Costing

9.1 Introduction

In recent years, energy conservation has received considerable attention because the escalation of fuel prices has made energy costs an important consideration in the procurement of a wide range of items or systems. In the development and construction of many civil engineering systems and buildings, cost has become an increasingly important issue because past experience indicates that operating and maintenance costs over the long life of a system or building far exceed initial costs. Thus, operating and maintenance costs must be factored into the decision process concerning procurement and construction of civil engineering systems and buildings because it may be more cost effective to take on a higher initial cost in order to obtain lower ownership costs of these items.

The concept of life cycle costing has frequently been used in making procurement and construction decisions concerning energy and civil engineering systems. Over the years, a large number of publications on both these areas have appeared. This chapter presents various important aspects of civil engineering and energy systems life cycle costing.

9.2 Building Life Cycle Cost

In the past, decisions in the building industrial sector during the design phase were made basically by comparing initial capital costs. The main reason for using this approach was its simplicity. Various studies conducted over the years indicate that a building’s long-term costs can far outweigh initial capital costs [1,2].

Thus, estimating the life cycle cost of a building at the initial design stage is very important, because past experiences indicate that the earliest decisions tend to establish boundaries to a certain degree for the later ones. According to Khanduri, Bedard, and Alkass [2], around 75–95% of the total life cycle costs of a typical building are locked in by the time its working drawings are prepared. Furthermore, if an estimate of the total life cycle cost is available at an
early design stage of a building project, then it is relatively easy to take appro- 
priate cost reduction measures. However, once the project goes into construc- 
tion, chances to influence the total project cost are reduced quite significantly. 

Building life cycle cost is defined by [2]

\[
LCC_b = CC + OC + RMC + DC
\]  

(9.1)

where

\(LCC_b\) is life cycle cost of a building.

CC is capital cost, which is composed of land and construction costs.

OC is operation cost associated with items such as energy, insurance, 
and wages.

RMC is repair and maintenance cost.

DC is demolition cost.

9.3 Steel Structure Life Cycle Cost

Life cycle cost of a steel structure is the total cost during its life span. Mathematically, it is expressed as follows [3,4]:

\[
LCC_{St} = IC + MC + INC + RC + OC + FC + DC
\]  

(9.2)

where

\(LCC_{St}\) is life cycle cost of a steel structure.

IC is initial cost. This includes cost of planning and design; erection cost; 
cost of preparing the project site, including the cost of the founda-
tion; storage, handling, and receiving costs associated with fabricated 
pieces and rolled sections; material cost of structural members such 
as columns, bracings, and beams; fabrication cost, including the mate-
rial costs of connection elements or components; cost associated with 
operation of machinery and tools at the construction site; and cost 
associated with transporting rolled sections to the fabrication shop 
and transporting the fabricated pieces to the construction site [4].

MC is maintenance cost associated with items such as painting of exposed 
parts of the steel structure.

INC is inspection cost associated with preventing potentially severe dam-
age to the structure.

RC is repair cost.

OC is operating cost associated with the proper use of the structure for 
items such as electricity and heating.

FC is probable failure cost. This cost is based on an acceptable probability 
of failure.

DC is demolishing or dismantling cost.
Past experience indicates that the following main factors influence the life cycle cost of a steel structure [3]:

- structure maintenance policy;
- structure usage;
- cost of the rolled sections used in initial structure construction;
- project site’s geographic location;
- expected life of the structure;
- total number of different section types employed in the structure under consideration;
- total number of connections;
- structure importance;
- perimeter of rolled sections in the complete structure;
- currency discount rate; and
- total weight of all rolled sections used in the entire structure.

### 9.4 Bridge and Waste Treatment Facilities Life Cycle Costs

Life cycle cost analysis is a powerful tool that allows bridge owners or managers to consider the potential consequences of their decisions in present day monetary terms. The life cycle cost of a bridge is expressed by [5,6]

\[
LCC_{br} = CONC + INSC + DESC + FAIC + RAMC
\]

(9.3)

where

- \(LCC_{br}\) is bridge life cycle cost.
- \(CONC\) is construction cost.
- \(INSC\) is inspection cost.
- \(DESC\) is design cost.
- \(FAIC\) is failure cost.
- \(RAMC\) is repair and maintenance cost.

The life cycle cost of waste treatment facilities is defined by [7]

\[
LCC_w = CONC + EDIC + OPC + DDC + SRC + WTDC + FEC
\]

(9.4)

where

- \(LCC_w\) is waste treatment facilities life cycle cost.
- \(CONC\) is construction cost, which contains the cost of items such as building construction, process equipment, construction management, improvements to land, and site work.
EDIC is engineering, design, and inspection cost.
OPC is operating cost, including the cost of items such as materials, staff, maintenance, peripheral equipment, and utilities.
DDC is decontamination and decommissioning cost. It includes the cost of decontamination and decommissioning (DAD) as well as the cost associated with managing the wastes generated during DAD.
SRC is start-up and readiness review cost and includes the cost of items such as training of personnel, operation and maintenance manuals, initial system testing, and preparation for and performance of contractor readiness reviews.
WTDC is waste transport and disposal cost.
FEC is front-end cost. Usually, this cost includes mostly the cost of activities that are not directly related to producing a new facility but rather are related to regulation. The other important components of the front-end cost are project management cost and cost of preliminary studies such as establishing project definition and developing functional and operational requirements.

9.5 Building Energy Cost Estimation

Over the years, a number of formulas have been developed to estimate the cost of various items concerned with building energy. Some of these formulas are presented next [8,9].

9.5.1 Formula 1

This formula is concerned with estimating annual lighting cost and is expressed by [8]

\[
LC_a = \frac{(BS)(OT)(EC)}{1000}
\]  (9.5)

where
\( LC_a \) is annual lighting cost.
\( BS \) is light bulb size.
\( OT \) is light bulb operating period.
\( EC \) is electricity cost expressed in dollars per kilowatt hour.

Example 9.1

Assume that a 100 W incandescent light bulb is operated for 9 hours per day for 365 days. Calculate the cost to operate the bulb during the specified period if the electricity cost is $0.4 per kilowatt hour.
By substituting the specified data values into Equation (9.5), we get

\[
LCA = \frac{(100)(9 \times 365)(0.4)}{1000} = $131.4
\]

Thus, the total cost to operate the bulb during the given period will be $131.40.

### 9.5.2 Formula II

This formula is concerned with estimating annual water heating cost and is expressed as follows [8]:

\[
WHC_a = \left(\frac{BTU_a \cdot FC}{ER \cdot Btu_p}\right) \tag{9.6}
\]

where

- \(WHC_a\) is annual water heating cost.
- \(BTU_a\) is annual British thermal units.
- \(FC\) is cost per fuel unit.
- \(ER\) is efficiency (i.e., the ratio of energy output to energy input).
- \(Btu_p\) is British thermal unit per fuel unit.

**Example 9.2**

Assume that, for a certain manufacturing process, 1,200 gallons of water per hour are needed and water temperature is at 170°F supplied at 60°F for 8 hours per day for 280 days per year. Furthermore, to heat the water, natural gas is burned at 70% efficiency level and its cost is $5 per 1,000 cubic feet (CF). Calculate the annual water heating cost.

By inserting the given data values into Equation (9.6), we get

\[
WHC_a = \left(\frac{(1200)(8.34)(170-60)(8)(280)}{(0.7)(1000 \cdot BTU/CF)} \times \frac{5}{1000 \cdot CF}\right)
\]

\[
= $17,614.08
\]

Thus, the total annual water heating cost will be $17,614.08.

### 9.5.3 Formula III

This formula is concerned with estimating air filter energy cost. The energy cost, \(C_e\), over the useful life of the filter is expressed by [9,10]

\[
C_e = (C_p \cdot A_q)(FL)(R_f)(K)/(MB_e)(10,000) \tag{9.7}
\]
where

- $C_p$ is power cost expressed in dollars per kilowatt hour.
- $A_q$ is quantity of air to be filtered expressed in cubic feet per minute.
- $FL$ is useful life of the air filter expressed in hours.
- $R_f$ is filter final resistance expressed in inch water gauge.
- $K$ is the constant with value 1.173.
- $MB_e$ is motor and blower efficiency.

**9.5.4 Formula IV**

This formula is concerned with estimating the cost of heat exchangers, and is expressed by [9,11]

$$C_{he} = \theta (SA)^n$$

(9.8)

where

- $C_{he}$ is procurement cost, free-on-board (F.O.B) factory.
- $SA$ is heat exchanger surface area expressed in square feet.
- $\theta$ and $n$ are constants (their tabulated values are available in references 9 and 11).

**9.5.5 Formula V**

This formula is concerned with estimating operational equipment energy consumption cost and is expressed by [12]

$$C_{oe} = (P_a)(EPC)(OH)(OE)$$

(9.9)

where

- $C_{oe}$ is total energy consumption cost of operational equipment.
- $P_a$ is average electrical power rating.
- $EPC$ is electrical power cost.
- $OH$ is total number of annual operating hours.
- $OE$ is total number of pieces of operational equipment.

**9.6 Appliance Life Cycle Costing**

There are many different types of appliances—for example, refrigerators, ranges and ovens, freezers, gas dryers, washing machines, electric dryers, and room air conditioners. Their life cycle costs can be estimated by using the following equation [9,13]:

$$LCC_a = AQC + \sum_{i=1}^{K} ECI \left[ \frac{FC(1 + fr)^i}{(1 + dr)^i} \right]$$

(9.10)
where

$LCC_a$ is appliance life cycle cost.

$AQC$ is appliance acquisition cost expressed in dollars.

$K$ is appliance useful life expressed in years.

$EC_i$ is energy consumption of year $i$ expressed in British thermal units (BTUs).

$FC$ is annual fuel cost expressed in constant dollars per million BTUs.

$fr$ is annual fuel escalation rate (%) expressed in constant dollars.

$dr$ is discount rate (%) expressed in constant dollars.

In the case of yearly constant energy consumption, $EC$, and the fuel escalation rate, $fr$, over appliance useful life, Equation (9.10) simplifies to

$$LCCA = AQC + (EC)(FC)K + \sum_{i=1}^{K} \frac{(1+fr)^i}{(1+dr)^i}$$

(9.11)

Past experience indicates that acquisition cost for items such as refrigerators, electric ranges, and room air conditioners accounts for roughly 41, 38, and 59% of their life cycle costs, respectively [12].

### 9.7 Energy System Life Cycle Cost Estimation Model

This model was developed by the Center for Building Technology of the National Bureau of Standards for the U.S. Department of Energy [13]. The model takes into consideration all relevant costs over time of a building facility’s design, materials, operation, systems, and components. More specifically, it includes items such as initial investment cost, operation and maintenance cost, future replacement cost, and salvage and resale value.

Thus, the energy system life cycle cost is expressed by [12,13]

$$LCC_{es} = EC_{pv} + IC_{pv} + SV_{pv} + NFOMC_{pv} + NRC_{pv} + RC_{pv}$$

(9.12)

where

$LCC_{es}$ is present value of the energy system life cycle cost.

$EC_{pv}$ is present value of the energy cost.

$IC_{pv}$ is present value of the investment cost.

$SV_{pv}$ is present value of salvage.

$NFOMC_{pv}$ is present value of the annually recurring nonfuel operation and maintenance cost.

$NRC_{pv}$ is present value of the nonrecurring nonfuel operation and maintenance cost.

Additional information on this model is available in references 12 and 13.
9.8 Motor, Pump, and Circuit-Breaker Life Cycle Costs

This section presents mathematical models to estimate life cycle cost of a motor, a pump, and a circuit breaker.

9.8.1 Motor Life Cycle Cost Estimation Model

This model is concerned with estimating the life cycle cost of an electric motor, which is expressed by [9,14]

$$LCC_m = C_{ma} + C_{mo}$$  \hspace{1cm} (9.13)

where

- $LCC_m$ is motor life cycle cost.
- $C_{ma}$ is motor acquisition cost.
- $C_{mo}$ is motor operating cost.

Note that in Equation (9.13), the motor maintenance cost is assumed negligible. Using Dhillon [9], the present value of the motor operating cost, $C_{moy}$ for year $j$ may be expressed as follows:

$$PV_j = C_{moy} \left[ \frac{1}{1+i} \right]^j$$  \hspace{1cm} (9.14)

where

- $PV_j$ is present value of the motor operating cost, $C_{moy}$ for year $j$.
- $i$ is interest rate.

If the motor operational life is $m$ years, then the present value of the motor total operating cost is expressed by

$$C_{mot} = C_{moy1} \left( \frac{1}{1+i} \right) + C_{moy2} \left( \frac{1}{1+i} \right)^2 + C_{moy3} \left( \frac{1}{1+i} \right)^3 + \cdots + C_{moym} \left( \frac{1}{1+i} \right)^m$$  \hspace{1cm} (9.15)

where

- $C_{moy}$ is present value of the total operating cost of the motor.
- $C_{moyj}$ is motor operating cost in year $j$ for $j = 1, 2, 3, \ldots, m$.

The yearly operating cost of the motor can be calculated by using the following equation [8,14]:

$$C_{mo} = \frac{(OH)(0.746)(MS)(C_m)}{EFF}$$  \hspace{1cm} (9.16)
where
\( C_{mo} \) is motor operating cost per year expressed in dollars.
\( OH \) is annual motor operating hours.
\( MS \) is motor size expressed in horsepower.
\( C_e \) is cost of electricity expressed in dollars per kilowatt hour.
\( EFF \) is motor efficiency.

**Example 9.3**

Assume that a 30-horsepower electric motor is operated for 3,000 hours annually. The cost of electrical energy is $0.2 per kilowatt hour. Calculate the annual cost to operate the motor if motor efficiency is 95%.

By substituting the given data values into Equation (9.16), we get
\[
C_{mo} = \frac{(3000)(0.746)(30)(0.2)}{0.95}
\]
\[= 14,137.74\]

Thus, the annual cost to operate the motor will be $14,137.74.

### 9.8.2 Pump Life Cycle Cost Estimation Model

This model is concerned with estimating the life cycle cost of a pump, which is expressed by [15,16]

\[
LCC_p = IC + EC + IAC + DC + DTC + OC + MRC + ENC
\]  (9.17)

where
- \( LCC_p \) is pump life cycle cost.
- \( IC \) is pump initial cost, including the cost of items such as pump, pipe, system, and auxiliary.
- \( EC \) is pump energy cost associated with various aspects of pump system operation.
- \( IAC \) is pump installation and commissioning cost, including the cost of training.
- \( DC \) is pump decommissioning or disposal cost, which also includes the cost associated with restoration of the local environment and disposal of auxiliary services.
- \( DTC \) is pump downtime cost associated with the production losses.
- \( OC \) is pump operation cost, which is basically the labor cost of normal pump system supervision.
- \( MRC \) is pump maintenance and repair cost.
- \( ENC \) is pump environmental cost associated with contamination from pumped liquid.

Each of these eight costs is described in detail in reference 16.
The pump energy cost, $EC$, may be calculated by using the following formula [8]:

$$EC = \frac{(PS)(PHS)(AOP)(C_e)}{(5300)\theta_p \theta_m}$$  \hspace{1cm} (9.18)

where

- $PS$ is pump size expressed in gallons per minute (GPM).
- $PHS$ is pump head size expressed in feet.
- $AOP$ is pump annual operational period expressed in hours.
- $C_e$ is cost of electricity expressed in dollars per kilowatt hour.
- $\theta_p$ is pump efficiency.
- $\theta_m$ is motor efficiency.

**Example 9.4**

Assume that an 800 GPM pump with a total head size of 10 feet is operated for 1,500 hours per year. The pump and motor efficiency are 70 and 90%, respectively. Calculate the annual cost to operate the pump if the cost of electricity is $0.3 per kilowatt hour.

By substituting the specified data values into Equation (9.18), we get

$$EC = \frac{(800)(10)(1500)(0.3)}{(5300)(0.7)(0.9)}$$

$$= $1,078.17$$

Thus, the annual cost to operate the pump will be $1,078.17.

**9.8.3 Circuit-Breaker Life Cycle Cost Estimation Model**

This model is concerned with estimating the life cycle cost of a high-voltage circuit breaker. This cost is expressed by [9,17]

$$LCC_{cb} = CFC + CMC + UC$$  \hspace{1cm} (9.19)

where

- $LCC_{cb}$ is life cycle cost of the high-voltage circuit breaker.
- $CFC$ is high-voltage circuit breaker fixed cost.
- $CMC$ is high-voltage circuit breaker maintenance cost.
- $UC$ is cost associated with the unavailability of power transmission and distribution systems.

**Problems**

1. Write an essay on building life cycle costing.
2. Write an equation for estimating life cycle cost of a building.
3. Write an equation that can be used to estimate life cost of a steel structure.
4. Write at least 10 factors that influence the life cycle cost of a steel structure.
5. Write an equation that can be used to estimate life cycle cost of a bridge.
6. Assume that a 60 W incandescent light bulb is operated for 6 hours per day for 365 days. Calculate the cost to operate the bulb during the specified period if the electricity cost is $0.3 per kilowatt hour.
7. Write formulas for estimating the cost of (1) heat exchangers, and (2) filter energy.
8. Assume that for a certain manufacturing process, 1,000 gallons of water per hour is required and water temperature is at 150°F supplied at 70°F for 6 hours per day for 250 days per year. Furthermore, to heat the water, natural gas is burned at 60% efficiency level and its cost is $6 per 1,000 CF. Calculate the annual water heating cost.
9. Write an equation that can be used to estimate life cycle costs of refrigerators and washing machines.
10. Assume that a 20-horsepower electric motor is operated for 2,000 hours annually. The cost of electrical energy is $0.3 per kilowatt hour. Calculate the annual cost to operate the motor if the motor efficiency is 90%.

References


10

Miscellaneous Cost Estimation Models

10.1 Introduction

Over the years, a large number of cost estimation models have been developed in diverse areas ranging from software engineering to telecommunication engineering. A cost estimation model may be described simply as an approach, based on programmatic and technical parameters, to calculating costs under consideration. More specifically, some of the possible dimensions of a cost estimation model include the elements of cost, time, and cost breakdown structure.

Many desirable features are associated with a cost estimation model; in designing such a model, the main factors that should be considered are feasibility of data requirements; operation ease; cost to develop, operate, and alter; capability for sensitivity analyses; speed to set up, operate, and change; inclusiveness and authoritativeness; and tolerance of input errors [1,2].

There are various types of cost estimation models: capital cost estimation models, operation and maintenance cost estimation models, life cycle cost estimation models, and so on. This chapter presents a number of models that were not covered in previous chapters. They can also be used to estimate various types of costs for performing life cycle cost analysis directly or indirectly.

10.2 Plant Cost Estimation Model

This model was developed by Cran to estimate plant cost in the chemical industry [3]. The total plant cost is expressed by [3,4]

\[ TPC = C_d + C_i \]

\[ = C_d + (C_d)(C_f) \]  

(10.1)

where

TPC is total plant cost expressed in dollars.

C_d is direct cost expressed in dollars.

C_i is indirect cost expressed in dollars.

C_f is indirect cost factor.
The direct cost, $C_d$, is defined by

$$C_d = (C_{is})(C_{di}) + (C_r)(C_{dp})$$  \hspace{1cm} (10.2)

where

- $C_{is}$ is cost of instruments.
- $C_{di}$ is direct cost factor associated with instruments.
- $C_r$ is cost of equipment.
- $C_{dp}$ is direct cost factor associated with the plant.

The following are the mean values for plant direct cost and instrument direct cost factors:

- 2.16 (for $C_{dp}$)
- 2.50 (for $C_{di}$)

The value of the indirect cost factor, $C_{if}$, can be estimated by using the following equation:

$$C_{if} = 1.36 - (0.073) \ln C_d$$  \hspace{1cm} (10.3)

Additional information on the model is available in Cran [3] and Ward [4].

### 10.3 Reliability Acquisition Cost Estimation Model

This model can be used to estimate reliability acquisition cost when state-of-the-art system acquisition cost and reliability improvement ratio compared to state of the art are known. The reliability acquisition cost is expressed by [5]

$$C_{ra} = (0.2)(AC_{sa}) \ln \alpha$$  \hspace{1cm} (10.4)

where

- $C_{ra}$ is reliability acquisition cost.
- $AC_{sa}$ is state-of-the-art system acquisition cost.
- $\alpha$ is reliability improvement ratio compared to state of the art.

Additional information on the model is available in Winlund [5].
10.4 Development Cost Estimation Model

This model is concerned with estimating development cost by considering the reliability factor. Thus, the development cost is expressed by [6, 7]

\[ DC_r = C_{ir} + C_{dr} \]  \hspace{1cm} (10.5)

where

- \( DC_r \) is development cost, considering the reliability.
- \( C_{ir} \) is basic cost, independent of reliability.
- \( C_{dr} \) is cost, dependent on reliability (i.e., reliability-related cost).

The cost dependent on reliability, \( C_{dr} \), is defined by

\[ C_{dr} = C_s \left[ \frac{MTBF_i}{MTBF_s} \right]^\theta \]  \hspace{1cm} (10.6)

where

- \( C_s \) is “standard” cost to develop item, equipment, or system having “standard” or current reliability.
- \( MTBF_i \) is item, equipment, or system mean time between failures with improved design.
- \( MTBF_s \) is item, equipment, or system mean time between failures with standard design.
- \( \theta \) is a constant whose value is to be estimated from empirical studies.

Let us now assume that the reliability of the standard design, \( R_s(t) \), and the reliability of the improved design, \( R_i(t) \), are respectively expressed by [8]

\[ R_s(t) = e^{-\frac{t}{MTBF_s}} \]  \hspace{1cm} (10.7)

and

\[ R_i(t) = e^{-\frac{t}{MTBF_i}} \]  \hspace{1cm} (10.8)

where

- \( t \) is time.
- \( R_s(t) \) is standard design reliability at time \( t \).
- \( R_i(t) \) is improved design reliability at time \( t \).
By taking natural logarithms of Equation (10.7) and (10.8) and then rearranging them, we get, respectively,

\[
MTBF_s = -\left[ \frac{t}{\ln R_s(t)} \right] \tag{10.9}
\]

and

\[
MTBF_i = -\left[ \frac{t}{\ln R_i(t)} \right] \tag{10.10}
\]

By substituting Equations (10.9) and (10.10) into Equation (10.6) and then substituting the resulting equation into Equation (10.5), we get

\[
DC_{C_r} = C_{r_1} + C_s \left[ \frac{\ln R_s(t)}{\ln R_i(t)} \right]^\theta \tag{10.11}
\]

Note that the preceding equation makes use of time-dependent reliabilities of standard and improved item, equipment, or system designs instead of mean time between failures (i.e., \(MTBF_s\) and \(MTBF_i\)) as in the case of Equation (10.6). Additional information on the model is available in Hevesh [6] and Carhart and Herd [7].

### 10.5 Program Error Cost Estimation Model

This model is concerned with estimating the cost of program errors in a program and is expressed by [8]

\[
PEC = \sum_{j=1}^{m} (C_{o_j} + C_{c_j}) \tag{10.12}
\]

where

- \(PEC\) is total cost of errors in a program.
- \(m\) is total number of errors in a program.
- \(C_{o_j}\) is cost associated with the occurrence of error \(j\).
- \(C_{c_j}\) is cost associated with correcting error \(j\).

Note that the cost elements associated with the error occurrence cost are lost equipment time cost, wasted manpower hours cost, etc. Similarly, the cost of correcting the error includes components such as equipment cost, supply cost, and manpower cost. Additional information on the model is available in Sontz [8].
10.6 Cooling Tower Cost Estimation Model

This model is concerned with estimating cooling tower cost using operating data. This cost is expressed by [9]

\[
C_t = \frac{L}{(Z)(X) - 586 + (39.2)(R)}
\]  
(10.13)

\[
Z = \frac{279}{(0.0335)(85 - T_{wb})^{1.143} + 1}
\]  
(10.14)

\[
R = T_{hw} - T_{cw}
\]  
(10.15)

\[
X = T_{cw} - T_{wb}
\]  
(10.16)

where

- \(C_t\) is cost of a cooling tower expressed in dollars.
- \(L\) is total heat load expressed in BTUs per hour.
- \(X\) is the temperature approach.
- \(R\) is cooling range.
- \(T_{wb}\) is wet bulb temperature expressed in degrees Fahrenheit.
- \(T_{hw}\) is hot water temperature expressed in degrees Fahrenheit.
- \(T_{cw}\) is cooled water temperature expressed in degrees Fahrenheit.

Additional information on the model is available in Zanker [9].

**Example 10.1**

Calculate the cost of a cooling tower, if the following data values are given:

- \(T_{hw} = 120^\circ\text{F}\);
- \(T_{cw} = 80^\circ\text{F}\);
- \(T_{wb} = 60^\circ\text{F}\); and
- \(L = 300\text{ million BTUs per hour.}\)

By substituting the given data values into Equations (10.13)–(10.16), we get

\[
R = 120 - 80 = 40^\circ\text{F}
\]

\[
X = 80 - 60 = 20^\circ\text{F}
\]

\[
Z = \frac{279}{(0.0335)(85 - 60)^{1.143} + 1} = 119.89
\]

\[
C_t = \frac{300,000,000}{(119.89)(20) - 586 + (39.2)(40)} = \$88,760.64
\]

Thus, the cooling tower cost is \$88,760.64.
10.7 Storage Tank Cost Estimation Model

This model is concerned with estimating the cost of storage tanks and is expressed by [10]

\[ C_{st} = C_b (\lambda) \]  

(10.17)

where

- \( C_{st} \) is cost of a storage tank.
- \( C_b \) is base cost, in carbon steel, expressed in dollars.
- \( \lambda \) is the material-of-construction factor.

The base cost in carbon steel for field-erected tanks (cone roofs and flat bottoms) is expressed by

\[ C_b = \exp \left[ \theta_1 - \theta_2 \ln V + \theta_3 (\ln V)^2 \right] \]  

(10.18)

where

- \( C_b \) is base cost in carbon steel for field-erected tanks.
- \( \theta_j \) is the \( j \)th constant for \( j = 1 \) (\( \theta_1 = 9.369 \)), \( j = 2 \) (\( \theta_2 = 0.1045 \)), and \( j = 3 \) (\( \theta_3 = 0.045355 \)).
- \( V \) is tank volume in cubic meters (80 m\(^3\) \( \leq V \leq 45,000 \text{ m}^3 \)).

Similarly, the base cost in carbon steel for shop-fabricated tanks (cone roofs and flat bottoms) is expressed by

\[ C_b = \exp \left[ \alpha_1 + \alpha_2 \ln V - \alpha_3 (\ln V)^2 \right] \]  

(10.19)

where

- \( C_b \) is base cost in carbon steel for shop-fabricated tanks.
- \( \alpha_j \) is the \( j \)th constant for \( j = 1 \) (\( \alpha_1 = 7.994 \)), \( j = 2 \) (\( \alpha_2 = 0.6637 \)), and \( j = 3 \) (\( \alpha_3 = 0.063088 \)).
- \( V \) is tank volume in cubic meters (5 m\(^3\) \( \leq V \leq 80 \text{ m}^3 \)).

The values of \( \lambda \) for construction materials such as stainless steel 304, stainless steel 316, stainless steel 347, aluminum, copper, nickel, titanium, and monel are 2.4, 2.7, 3, 2.7, 2.3, 3.5, 11.0, and 3.3, respectively. Additional information on the model is available in Corripio, Chrien, and Evans [10].

10.8 Pressure Vessel Cost Estimation Model

This model is concerned with estimating the cost of pressure vessels. The total cost is expressed by [11]

\[ PVC = (\theta)C_v + C_p \]  

(10.20)
where

- PVC is total cost of a pressure vessel expressed in dollars.
- \( \theta \) is construction material cost factor.
- \( C_u \) is base vessel cost in carbon steel expressed in dollars.
- \( C_p \) is cost of platform and ladders expressed in dollars.

For horizontal vessels, \( C_u \) and \( C_p \) are expressed by Equations (10.21) and (10.22), respectively:

\[
C_u = \exp \left[ L_1 - L_2 \ln W + L_3 (\ln W)^2 \right] \tag{10.21}
\]

where

- \( L_j \) is the \( j \)th constant for \( j = 1 \) \( (L_1 = 8.114) \), \( j = 2 \) \( (L_2 = 0.16449) \), and \( j = 3 \) \( (L_3 = 0.04333) \).
- \( W \) is carbon steel shell weight in kilograms \( (369 \text{ kg} \leq W \leq 415,000 \text{ kg}) \).

\[
C_p = M_1 (D^{M_2}) \tag{10.22}
\]

where

- \( M_j \) is the \( j \)th constant for \( j = 1 \) \( (M_1 = 1288.3) \) and \( j = 2 \) \( (M_2 = 0.20294) \).
- \( D \) is inside diameter of platform and ladders in meters \( (0.92 \text{ m} \leq D \leq 3.66 \text{ m}) \).

Similarly, for vertical vessels, \( C_u \) and \( C_p \) are expressed by Equations (10.23) and (10.24), respectively:

\[
C_u = \exp \left[ N_1 - N_2 \ln W + N_3 (\ln W)^2 \right] \tag{10.23}
\]

where

- \( N_j \) is the \( j \)th constant for \( j = 1 \) \( (N_1 = 8.6) \), \( j = 2 \) \( (N_2 = 0.21651) \), and \( j = 3 \) \( (N_3 = 0.04576) \).
- \( W \) is carbon steel shell weight in kilograms \( (2210 \text{ kg} \leq W \leq 103,000 \text{ kg}) \).

\[
C_p = n_1 D^{n_2} (TL)^{n_3} \tag{10.24}
\]

where

- \( n_j \) is the \( j \)th constant for \( j = 1 \) \( (n_1 = 1017) \), \( j = 2 \) \( (n_2 = 0.73960) \), and \( j = 3 \) \( (n_3 = 0.70684) \).
- \( D \) is inside diameter of platform and ladders in meters \( (1.83 \text{ m} \leq D \leq 3.05 \text{ m}) \).

The values of \( \theta \) for construction materials such as stainless steel 316, stainless steel 304, titanium, nickel 200, monel 400, incoloy 825, and inconel 600 are 2.1, 1.7, 7.7, 5.4, 3.6, 3.7, and 3.9, respectively. Additional information on the model is available in Mulet, Corripio, and Evans. [11].
10.9 New Aircraft System Spares Cost Estimation Model

This model is concerned with estimating spares cost for the new aircraft system. The model uses the spares cost for an existing aircraft system and adjusts it by a comparison factor reflecting the differences in system cost, reliability, hardware complexity, and repairability. The new aircraft system’s spares cost is defined by [12]

\[ C_{na} = \gamma C_{ea} \]  

(10.25)

where

\( C_{na} \) is new aircraft system spares cost.
\( \gamma \) is the comparison factor expressed in terms of operational and support parameters.
\( C_{ea} \) is existing aircraft system spares cost.

The comparison factor, \( \theta \), is expressed by

\[ \theta = \beta q \left( \frac{MI_n}{MI_e} \right) \]  

(10.26)

where

\( q \) is quantifier of the cost impact associated with a shift in the classification of spares from “base repaired” to “depot repaired” or vice versa between the two aircraft systems under consideration. Note that the value of this quantifier is equal to unity when the change in the ratio of the two classifications is zero.
\( MI_n \) is new aircraft system’s calculated (estimated) maintenance index expressed as maintenance man-hours per flying hour.
\( MI_e \) is existing aircraft system’s established maintenance index expressed as maintenance man-hours per flying hour.

The symbol \( \beta \) in Equation (10.26) is expressed by

\[ \beta = f_1 \left( \frac{C_{n1}}{C_{e1}} \right) + f_2 \left( \frac{C_{n2}}{C_{e2}} \right) + f_3 \left( \frac{C_{n3}}{C_{e3}} \right) \]  

(10.27)

where

\( C_{nj} \) is \( j \)th segment of the “fly-away” cost for the new aircraft system for \( j = 1 \) (airframe), \( j = 2 \) (propulsion), and \( j = 3 \) (equipment).
\( C_{ej} \) is \( j \)th segment of the “fly-away” cost for the existing aircraft system for \( j = 1 \) (airframe), \( j = 2 \) (propulsion), and \( j = 3 \) (equipment).
Miscellaneous Cost Estimation Models

\( f_j \) is the jth fraction of the total investment spares “lay-in” value calculated for existing systems for \( j = 1 \) (airframe related), \( j = 2 \) (propulsion related), and \( j = 3 \) (equipment related).

Additional information on the model is available in Tyszkiewicz [12].

10.10 Satellite Procurement Cost Estimation Model

This model is concerned with estimating the procurement cost of satellites in 1974 dollars. The satellite procurement cost is expressed by [2,13]

\[
C_s = \left[ \lambda_1 W_s^{-\lambda_2} \right] W_s
\]

(10.28)

where

- \( C_s \) is satellite procurement cost.
- \( \lambda_j \) is the jth constant for \( j = 1 \) (\( \lambda_1 = 1,970,300 \)) and \( j = 2 \) (\( \lambda_2 = 0.592 \)).
- \( W_s \) is the satellite’s total weight.

Additional information on the model is available in Hadfield [13].

10.11 Single-Satellite System Launch Cost Estimation Model

This model is concerned with estimating the total launch cost of a single-satellite system (circular orbits). The launch cost is defined by [13]

\[
LC_s = \beta_1 (W_s)^{\beta_2} \left[ \frac{OA}{\beta_3} + f_p + 1 \right]
\]

(10.29)

where

- \( LC_s \) is launch cost of a single-satellite system, expressed in millions of 1974 dollars.
- \( \beta_j \) is the jth constant for \( j = 1 \) (\( \beta_1 = 0.026 \)), \( j = 2 \) (\( \beta_2 = 2/3 \)), and \( j = 3 \) (\( \beta_3 = 8,000 \)).
- \( W_s \) is total satellite weight expressed in pounds.
- \( OA \) is orbit altitude or apogee expressed in statute miles.
- \( f_p \) is a factor measuring the satellite payload sophistication.

Additional information on the model is available in Hadfield [13].
10.12 Tank Gun System Life Cycle Cost Estimation Model

This model is concerned with estimating tank gun life cycle cost by decomposing it into three major components: research and development cost, investment cost, and operating and support cost. The life cycle cost is expressed by \[ LCC_{tg} = RDC_{tg} + IC_{tg} + OS_{tg} \] (10.30)

where
- \( LCC_{tg} \) is tank gun system life cycle cost.
- \( RDC_{tg} \) is tank gun system research and development cost.
- \( IC_{tg} \) is tank gun system investment cost.
- \( OS_{tg} \) is tank gun system operating and support cost.

The tank gun system research and development cost, \( RDC_{tg} \), is expressed by
\[
RDC_{tg} = \sum_{j=1}^{10} RDC_{bjj}
\] (10.31)

where
- \( RDC_{bjj} \) is cost component \( j \) of the tank gun system research and development cost for
  - \( j = 1 \) (tooling cost)
  - \( j = 2 \) (facilities cost)
  - \( j = 3 \) (development engineering cost)
  - \( j = 4 \) (system project management cost)
  - \( j = 5 \) (prototype manufacturing cost)
  - \( j = 6 \) (system test and evaluation cost)
  - \( j = 7 \) (training cost)
  - \( j = 8 \) (productibility engineering and planning cost)
  - \( j = 9 \) (data cost)
  - \( j = 10 \) (other cost)

The tank gun system investment cost, \( IC_{tg} \), is expressed by
\[
IC_{tg} = \sum_{j=1}^{11} IC_{bjj}
\] (10.32)

where
- \( IC_{bjj} \) is cost component \( j \) of the tank gun system investment cost for
  - \( j = 1 \) (training cost)
  - \( j = 2 \) (production cost)
j = 3 (data cost)  
j = 4 (nonrecurring investment cost)  
j = 5 (system project management cost)  
j = 6 (initial spares and repair parts cost)  
j = 7 (engineering changes cost)  
j = 8 (transportation cost)  
j = 9 (system test evaluation cost)  
j = 10 (operational and site activation cost)  
j = 11 (other cost)  

The tank gun system operation and support cost, \( O_{Stg} \), is expressed by

\[
O_{Stg} = \sum_{j=1}^{11} O_{Stg}^j
\]  

(10.33)

where

\( O_{Stg}^j \) is the cost component \( j \) of the tank gun system operating and support cost for

\( j = 1 \) (consumption cost)  
\( j = 2 \) (modification material cost)  
\( j = 3 \) (military personnel cost)  
\( j = 4 \) (depot maintenance cost)  
\( j = 5 \) (other direct support operations cost)  
\( j = 6 \) (indirect support and operations cost)

Additional information on the model is available in Earles [1] and Dhillon [2].

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This model is concerned with estimating the life cycle cost of weather radar. This cost is expressed by [1]

\[
WRLCC = SDC + VC + AC + OMSC
\]  

(10.34)

where

\( WRLCC \) is weather radar life cycle cost.  
\( SDC \) is weather radar system definition cost.  
\( VC \) is weather radar validation cost.  
\( AC \) is weather radar acquisition cost.  
\( OMSC \) is weather radar operation, maintenance, and support cost.
The weather radar system definition cost, $SDC$, is expressed by

$$SDC = \sum_{i=1}^{2} SDC_i$$

(10.35)

where $SDC_i$ is the $i$th cost component of the weather radar system definition cost for $i = 1$ (program management cost) and $i = 2$ (cost for each bidder).

The weather radar system validation cost, $VC$, is expressed by

$$VC = \sum_{i=1}^{15} VC_i$$

(10.36)

where

$VC_i$ is the $i$th cost component of the weather radar validation cost for

- $i = 1$ (engineering design and development cost)
- $i = 2$ (fabrication and manufacturing development cost)
- $i = 3$ (validation hardware cost)
- $i = 4$ (software system design and development cost)
- $i = 5$ (logistics planning and support cost)
- $i = 6$ (development test and test support cost)
- $i = 7$ (validation test site preparation cost)
- $i = 8$ (documentation cost)
- $i = 9$ (manual development cost)
- $i = 10$ (support and test equipment cost)
- $i = 11$ (training development and equipment cost)
- $i = 12$ (government-furnished equipment and facilities cost)
- $i = 13$ (transportation of equipment to test site cost)
- $i = 14$ (program management cost)
- $i = 15$ (general and administration cost)

The weather radar acquisition cost, $AC$, is expressed by

$$AC = \sum_{i=1}^{18} AC_i$$

(10.37)

where

$AC_i$ is $i$th cost component of the weather radar acquisition cost for

- $i = 1$ (software and firmware-manufacturing-related cost)
- $i = 2$ (software and firmware-depot-related cost)
- $i = 3$ (software and firmware-on-site-related costs)
- $i = 4$ (initial training cost)
- $i = 5$ (vendor warranty for first year cost)
- $i = 6$ (test and support equipment cost)
- $i = 7$ (initial spares cost)
i = 8 (test and evaluation cost)
i = 9 (data and documentation cost)
i = 10 (site preparation cost)
i = 11 (system installation and checkout cost)
i = 12 (site decommissioning cost)
i = 13 (land acquisition cost)
i = 14 (government printing cost)
i = 15 (manual binding and delivery cost)
i = 16 (government-furnished equipment cost)
i = 17 (program management cost)
i = 18 (general and administration overhead cost)

The weather radar operation, maintenance, and support cost, OMSC, is expressed by

\[
OMSC = \sum_{i=1}^{13} OMSC_i
\]  

(10.38)

where

OMSC\(_i\) is the \(i\)th cost component of the weather radar operation, maintenance, and support cost for

- \(i = 1\) (operating personnel cost)
- \(i = 2\) (electric power cost)
- \(i = 3\) (communications facilities cost)
- \(i = 4\) (occupying and housekeeping cost)
- \(i = 5\) (consumables cost)
- \(i = 6\) (dedicated maintenance personnel cost)
- \(i = 7\) (other maintenance-preventive and corrective cost)
- \(i = 8\) (recurring spares cost)
- \(i = 9\) (logistics and logistics support cost)
- \(i = 10\) (other maintenance-test and support cost)
- \(i = 11\) (equipment rental and housekeeping cost)
- \(i = 12\) (maintenance by contractor cost)
- \(i = 13\) (recurring training cost)

Additional information on the model is available in Earles [1].

**Problems**

1. What is a cost estimation model?
2. Write an essay on cost estimation models.
3. Discuss the desirable features of a cost estimation model.
4. Define two main elements of a plant cost estimation model.
5. Define the following two models: (1) reliability acquisition cost estimation model, and (2) development cost estimation model.
6. Define program error cost estimation model.
7. If the following data values are known, estimate the cost of a cooling tower by using Equation (10.13):
   - $L = 400$ million BTUs per hour
   - $T_{kw} = 130^\circ F$
   - $T_{cw} = 90^\circ F$
   - $T_{wb} = 65^\circ F$
8. Define satellite acquisition cost estimation model.
9. Discuss the following two items: (1) weather radar life cycle cost and (2) tank gun system life cycle cost
10. Define the following two models: (1) storage tank cost estimation model and (2) pressure vessel cost estimation model.

References


11

Introduction to Engineering
Reliability and Maintainability

11.1 Introduction

Reliability may be described simply as the probability that an item or system will perform its mission satisfactorily for the desired period when used according to designed conditions. The history of the reliability field may be traced back to the early 1930s, when probability-related concepts were applied to various problems associated with electric power generation [1–4]. During World War II, Germans applied various basic reliability concepts to improve reliability of their rockets (i.e., V1 and V2 rockets). A detailed history of the reliability field is available in Dhillon [5]. Today, reliability is a well-established discipline and has branched out into many specialized areas [5,6].

Maintainability may be described as the aspects of equipment or an item that improve repairability and serviceability, increase cost effectiveness of maintenance, and ensure that the equipment or item satisfies the requirements for its intended application. The roots of the maintainability history may be traced back to 1901 in the Army Signal Corps contract for development of the Wright Brothers’ airplane, which stated that the aircraft “should be simple to operate and maintain.” However, in the modern context, the beginning of the maintainability discipline may be traced back to the period between World War II and the early 1950s [7,8]. During this period, the U.S. Department of Defense conducted various studies that indicated startling results concerning the state of reliability and maintainability of equipment used by the three services [8–10].

Needless to say, today reliability and maintainability are well-established disciplines and, over the years, a vast amount of literature on both the topics has appeared [11,12]. This chapter presents various fundamental aspects of reliability and maintainability considered useful for direct or indirect applications in life cycle costing.
11.2 Reliability and Maintainability Definitions

Some of the commonly used terms and definitions in the area of reliability and maintainability follow [13–16]:

- **Reliability** is the probability that an item will perform its assigned mission satisfactorily for the desired period when used according to specified conditions.
- **Maintainability** is the probability that a failed item will be restored to its satisfactory working state within a stated total downtime, when maintenance activity is started according to specified conditions.
- **Failure** is the inability of an item to perform its specified function within defined guidelines.
- **Downtime** is the time during which the item or product is not in a condition to perform its stated mission or function.
- **Availability** is the probability that an item or equipment will be available for service when required.
- **Redundancy** is the existence of more than one means for performing a stated function.
- **Useful life** is the length of time an item or piece of equipment functions within an acceptable level of failure rate.
- **Maintenance** is all scheduled and unscheduled actions necessary to keep an item or piece of equipment in a serviceable state or restoring it to serviceability. It includes items such as inspection, testing, repair, modification, and servicing.
- **Mission time** is the time during which the item or piece of equipment is carrying out its stated mission.

11.3 Bathtub Hazard Rate Curve

The curve shown in Figure 11.1 is widely used to describe failure rate of various types of engineering items. As shown in the figure, the bathtub hazard rate curve is divided into three regions: region I (burn-in period), region II (useful life period), and region III (wear-out period).

- During the burn-in period, hazard rate (i.e., time-dependent failure rate) decreases with time \( t \). Some of the main reasons for the occurrence of failures in this region are inadequate quality control, poor processes, substandard materials and workmanship, poor manufacturing methods, inadequate debugging, and human error.
During the useful life period (region II), the hazard rate remains constant with respect to time $t$. Some of the main reasons for the occurrence of failures in this region are higher random stress than expected, undetectable defects, human errors, low safety factors, abuse, and natural failures.

Finally, during the wear-out period (region III), the hazard rate increases with time $t$. The main causes for the occurrence of failures in this region include poor maintenance, wear due to aging, wrong overhaul practices, short designed-in life of the item under consideration, wear due to friction and corrosion, and creep.

### 11.4 General Reliability, Mean Time to Failure, and Hazard Rate Formulas

A number of general formulas are commonly used to perform reliability analysis. Three of these formulas are presented next.

#### 11.4.1 General Formula for Reliability

This general formula is expressed by [17]

$$ R(t) = e^{-\int_0^t \lambda(t) \, dt} \quad (11.1) $$
where

- \( R(t) \) is reliability at time \( t \).
- \( t \) is time.
- \( \lambda(t) \) is time-dependent failure rate (i.e., hazard rate).

**Example 11.1**

Assume that the hazard rate of an engineering system is given by

\[
\lambda(t) = \lambda \tag{11.2}
\]

where \( \lambda \) is engineering system constant failure rate. Obtain an expression for the engineering system reliability by using Equation (11.1).

Using Equation (11.2) in Equation (11.1) yields

\[
R(t) = e^{-\int_0^t \lambda \, dt} = e^{-\lambda t} \tag{11.3}
\]

Thus, Equation (11.3) is the expression for the engineering system reliability.

**11.4.2 General Formula for Mean Time to Failure**

This general formula can be expressed in the three different ways that follow [10]:

\[
MTTF = \int_0^\infty R(t) \, dt \tag{11.4}
\]

or

\[
MTTF = \lim_{s \to 0} R(s) \tag{11.5}
\]

or

\[
MTTF = \int_0^\infty t \, f(t) \, dt \tag{11.6}
\]

where

- \( f(t) \) is the failure or probability density function.
- \( s \) is the Laplace transform variable.
- \( R(s) \) is the Laplace transform of \( R(t) \).
- \( MTTF \) is mean time to failure.

**Example 11.2**

Assume that the reliability of a piece of engineering equipment is expressed by

\[
R(t) = e^{-\lambda t} \tag{11.7}
\]
where

\( t \) is time.

\( \lambda \) is engineering equipment failure rate.

Obtain an expression for the engineering equipment mean time to failure.

By substituting Equation (11.7) into Equation (11.4), we get

\[
MTTF = \int_{0}^{\infty} e^{-\lambda t} \, dt = \frac{1}{\lambda}
\]

Thus, Equation (11.8) is the expression for the engineering equipment mean time to failure.

### 11.4.3 General Formula for Hazard Rate

This general formula can be expressed in the following three ways [10]:

\[
\lambda(t) = \frac{f(t)}{1 - \int_{0}^{t} f(t) \, dt}
\]

or

\[
\lambda(t) = \frac{f(t)}{R(t)}
\]

or

\[
\lambda(t) = -\frac{1}{R(t)} \cdot \frac{dR(t)}{dt}
\]

**Example 11.3**

Using Equation (11.7), obtain a hazard rate expression for the engineering equipment. Comment on the resulting expression.

Using Equation (11.7) in Equation (11.11) yields

\[
\lambda(t) = -\frac{1}{e^{-\lambda t}} \cdot \frac{de^{-\lambda t}}{dt} = \lambda
\]

Thus, Equation (11.12) is the expression for the engineering equipment hazard rate. Note from this expression that the hazard rate is independent of time. Thus, it is simply referred to as the constant failure rate.
11.5 Common Reliability Networks

Engineering systems can form various types of configurations or networks in performing reliability analysis. Some of the commonly occurring of these networks are presented next.

11.5.1 Series Network

This is the simplest and probably the most commonly occurring reliability network in engineering systems. Its block diagram is shown in Figure 11.2. Each block in the figure denotes a unit or component. More specifically, the Figure 11.2 diagram represents a system composed of \( m \) units in series. If any one of the units fails, the system fails. In other words, all system units must work normally for the system to succeed.

If we let \( E_j \) denote the event that the \( j \)th unit in Figure 11.2 is successful, then the series system reliability is expressed by [5]

\[
R_s = P(E_1 E_2 E_3 \ldots E_m)
\]  

where
- \( R_s \) is the series system reliability.
- \( P(E_1 E_2 E_3 \ldots E_m) \) is probability of occurrence of events \( E_1, E_2, E_3, \ldots, \) and \( E_m \)

For independent units, Equation (11.13) becomes

\[
R_s = P(E_1) P(E_2) P(E_3) \ldots P(E_m)
\]  

(11.14)

where \( P(E_j) \) is probability of occurrence of event \( E_j \) for \( j = 1, 2, 3, \ldots, m \).

If we let \( R_j = P(E_j) \) for \( j = 1, 2, 3, \ldots, m \), Equation (11.14) becomes

\[
R_s = R_1 R_2 R_3 \ldots R_m
\]  

(11.15)

where \( R_j \) is the unit \( j \) reliability for \( j = 1, 2, 3, \ldots, m \).

For constant failure rate, \( \lambda_j \), of unit \( j \), using Equation (11.1), the reliability of the unit \( j \) is given by

\[
R_j(t) = e^{-\int_0^t \lambda_j \, dt}
\]

\[
= e^{-\lambda_j t}
\]  

(11.16)

where \( R_j(t) \) is reliability of unit \( j \) at time \( t \).

\[\text{FIGURE 11.2}\]
Block diagram of a series system containing \( m \) units.
Thus, by inserting Equation (11.16) into Equation (11.15), we obtain

\[ R_S(t) = e^{-\sum_{j=1}^{m} \lambda_j t} \]  \hspace{1cm} (11.17)

where \( R_S(t) \) is series system reliability at time \( t \).

By substituting Equation (11.17) into Equations (11.4) and (11.11), we get the following equations for the series system mean time to failure and hazard rate, respectively:

\[ MTTF_S = \int_{0}^{\infty} e^{-\sum_{j=1}^{m} \lambda_j t} \, dt \]  \hspace{1cm} (11.18)

and

\[ \lambda_S = -\frac{1}{e^{-\sum_{j=1}^{m} \lambda_j} \sum_{j=1}^{m} \lambda_j} \]  \hspace{1cm} (11.19)

where

- \( MTTF_S \) is series system mean time to failure.
- \( \lambda_S \) is series system hazard or failure rate.

**Example 11.4**

Assume that an engineering system is composed of three independent subsystems in series. The failure rates of subsystems 1, 2, and 3 are 0.005 failure/hour, 0.004 failure/hour, and 0.003 failure/hour, respectively. Calculate the following:

- engineering system reliability during a 40-hour mission;
- engineering system mean time to failure; and
- engineering system hazard rate.

By substituting the specified data values into Equations (11.17), (11.18), and (11.19), we get

\[ R_S(40) = e^{-0.005 \times 40} \]
\[ = 0.6188, \]

\[ MTTF_S = \frac{1}{0.005 + 0.004 + 0.003} \]
\[ = 83.33 \text{ hours}, \]
Thus, the engineering system reliability, mean time to failure, and hazard rate are 0.6188, 83.33 hours, and 0.012 failures/hour, respectively.

### 11.5.2 Parallel Network

In this case, all units are active and at least one of these units must function normally for the system success. The block diagram of a parallel system containing \( m \) units is shown in Figure 11.3. Each block in the figure denotes a unit.

If we let \( \bar{E}_j \) denote the event that the \( j \)th unit in Figure 11.3 is unsuccessful, then the parallel system failure probability is given by [5]

\[
F_p = P(\bar{E}_1, \bar{E}_2, \ldots, \bar{E}_m)
\]

For independent units, Equation (11.20) becomes

\[
F_p = P(\bar{E}_1) P(\bar{E}_2) \ldots P(\bar{E}_m)
\]

where \( P(\bar{E}_j) \) is probability of occurrence of failure event \( \bar{E}_j; \ j = 1, 2, \ldots, m \).

If we let \( F_j = P(\bar{E}_j) \) for \( j = 1, 2, \ldots, m \) in Equation (11.21) and then subtract the resulting equation from unity, we get the following expression for the parallel system reliability:

\[
R_p = 1 - F_1 F_2 \ldots F_m
\]
where

- $R_p$ is parallel system reliability.
- $F_j$ is failure probability of unit $j$ for $j = 1, 2, \ldots, m$.

For constant failure rate, $\lambda_j$ of unit $j$, by subtracting Equation (11.16) from unity and then substituting it into Equation (11.22), we get

$$R_p(t) = 1 - \prod_{j=1}^{m} (1 - e^{-\lambda_j t})$$  \hspace{1cm} (11.23)

where $R_p(t)$ is parallel system or network reliability at time $t$.

For identical units, by substituting Equation (11.23) into Equation (11.4), we get the following expression for the parallel system or network mean time to failure:

$$MTTF_p = \int_{0}^{\infty} \left[ 1 - (1 - e^{-\lambda t})^m \right] dt$$

$$= \frac{1}{\lambda} \sum_{j=1}^{m} \frac{1}{j}$$  \hspace{1cm} (11.24)

where

- $MTTF_p$ is mean time to failure of the parallel system with identical units.
- $\lambda$ is unit failure rate.

**Example 11.5**

An engineering system is composed of three independent, active, and identical units; at least one of the units must operate normally for system success. The unit failure rate is 0.0002 failure/hour. Calculate

- engineering system reliability for a 100-hour mission; and
- engineering system mean time to failure.

By substituting the given data values into Equations (11.23) and (11.24), we get

$$R_p(100) = 1 - \left[ 1 - e^{-0.0002 \times 100} \right] \left[ 1 - e^{-0.0002 \times 100} \right] \left[ 1 - e^{-0.0002 \times 100} \right]$$

$$= 0.9406$$

and

$$MTTF_p = \frac{1}{0.0002} \left[ \frac{1}{2} + \frac{1}{3} \right]$$

$$= 9,166.7 \text{ hours}$$

Thus, the engineering system reliability and mean time to failure are 0.9406 and 9,166.7 hours, respectively.
11.5.3 K-out-of-m Network

In this case, all \( m \) units are active and at least \( K \) units out of these \( m \) units must work normally for the system success. The parallel and series networks are the special cases of this network for \( K = 1 \) and \( K = m \), respectively.

Using the binomial distribution for independent and identical units, the \( K \)-out-of-\( m \) network or system reliability is expressed by [5]

\[
R_{K/m} = \sum_{j=K}^{m} \binom{m}{j} R^j (1 - R)^{m-j}
\]  

(11.25)

where

\[
\binom{m}{j} = \frac{m!}{(m-j)! j!}
\]  

(11.26)

\( R \) is unit reliability.

\( R_{K/m} \) is \( K \)-out-of-\( m \) network or system reliability.

For constant failure rate, \( \lambda \), of each unit, by substituting Equation (11.3) into Equation (11.25), we get

\[
R_{K/m}(t) = \sum_{j=K}^{m} \binom{m}{j} e^{-j \lambda t} (1 - e^{-\lambda t})^{m-j}
\]  

(11.27)

where \( R_{K/m}(t) \) is \( K \)-out-of-\( m \) network or system reliability at time \( t \).

Using Equation (11.27) in Equation (11.4) yields

\[
MTTF_{K/m} = \int \left[ \sum_{j=K}^{m} \binom{m}{j} e^{-j \lambda t} (1 - e^{-\lambda t})^{m-j} \right] dt
\]  

(11.28)

where \( MTTF_{K/m} \) is \( K \)-out-of-\( m \) network or system mean time to failure.

Example 11.6

Assume that an engineering system is composed of four independent and identical units in parallel. At least two units must operate normally for the system’s success. Calculate the engineering system mean time to failure if the failure rate of each unit is 0.0008 failure/hour.
By substituting the specified data values into Equation (11.28), we get

\[
MTTF_{\frac{1}{4}} = \frac{1}{(0.0008)} \sum_{j=2}^{4} \frac{1}{j} = \frac{1}{(0.0008)} \left[ \frac{1}{2} + \frac{1}{3} + \frac{1}{4} \right] = 1354.16 \text{ hours}
\]

Thus, the engineering system mean time to failure is 1354.16 hours.

### 11.5.4 Standby System

This is another type of redundancy used to improve system reliability. In this case, the system has a total of \((m + 1)\) units, but only one unit operates. The remaining \(m\) 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 \(m\) standby units.

The system fails when all the standby units fail. The system reliability for independent and identical units, time-dependent unit failure rate, and perfect switching mechanism and standby units is given by [5]

\[
R_{SS}(t) = \sum_{j=0}^{m} \left[ \int_{0}^{t} \lambda(t) e^{-\int_{0}^{t} \lambda(t) dt} \right]^{j} / j!
\]

(11.29)

where

- \(R_{SS}(t)\) is standby system reliability at time \(t\).
- \(m\) is total number of standby units.
- \(\lambda(t)\) is unit time-dependent failure rate or hazard rate.

For constant unit failure rate (i.e., \(\lambda(t) = \lambda\)), Equation (11.29) becomes

\[
R_{SS}(t) = \sum_{j=0}^{m} (\lambda t)^{j} e^{-\lambda t} / j!
\]

(11.30)

By inserting Equation (11.30) into Equation (11.4), we get

\[
MTTF_{SS} = \int_{0}^{\infty} \sum_{j=0}^{m} (\lambda t)^{j} e^{-\lambda t} / j! \, dt
\]

(11.31)

\[
= \frac{m+1}{\lambda}
\]
Example 11.7
A standby system has three independent and identical units: one operating and two on standby. The failure rate of each unit is 0.0002 failure/hour. Calculate the standby system mean time to failure if the standby units remain as good as new in their standby mode and the switching mechanism is perfect.

By substituting the given data values into Equation (11.31), we get

\[
MTTF_{SS} = \frac{(2+1)}{(0.0002)} = 15,000 \text{ hours}
\]

Thus, the standby system mean time to failure is 15,000 hours.

11.6 Reliability and Maintainability Relationship

In order to have a clear understanding of the relationship between reliability and maintainability, some of the important aspects of both reliability and maintainability are discussed next.

11.6.1 Reliability

This is a design characteristic that results in durability of the system or item to perform its specified mission subject to stated conditions and time period. It is accomplished through actions such as choosing optimum engineering principles, satisfactory component sizing, controlling processes, and testing. The following are some specific general principles of reliability [5,17]:

- Design to minimize the occurrence of failures.
- Provide fail-safe designs.
- Design for simplicity.
- Provide redundancy when required.
- Use fewer numbers of parts to perform multiple functions.
- Minimize stress on parts.
- Provide for simple periodic adjustment of parts subject to wear.
- Maximize the use of standard parts.
- Use parts with proven reliability.
- Provide satisfactory safety factors between strength and peak stress values.
11.6.2 Maintainability

This is a built-in design and installation characteristic. It provides the end product an inherent ability to be maintained, thus ultimately leading to improved mission availability and reduction in maintenance cost, required tools and equipment, and required man-hours and skill levels. Some of the specific general principles of maintainability include [5,17]:

- Reduce life cycle maintenance costs.
- Reduce the amount, frequency, and complexity of required maintenance tasks.
- Reduce mean time to repair.
- Establish the extent of preventive maintenance to be performed.
- Reduce or eliminate altogether the need for maintenance.
- Reduce the amount of supply supports required.
- Consider benefits of modular replacement versus part repair or throwaway.
- Provide for maximum interchangeability.

11.7 Maintainability Measures

Various maintainability measures are used during the design phase to produce effective products with respect to maintainability. Some of these measures are mean time to repair (MTTR), the probability of completing repair in given time interval (i.e., the maintainability function); mean preventive maintenance time; and maximum corrective maintenance time. All these measures are presented next [5,7,17,18].

11.7.1 Mean Time to Repair (MTTR)

This is probably the most widely used maintainability measure or parameter in maintainability analysis. It is sometimes called mean corrective maintenance time. The system mean time to repair is defined by [5]

\[
MTTR = \left[ \frac{\sum_{i=1}^{m} \lambda_i t_i}{\sum_{i=1}^{m} \lambda_i} \right]
\]  

(11.32)

where

- \(MTTR\) is system mean time to repair.
- \(m\) is number of units.
- \(\lambda_i\) is constant failure rate of unit \(i\) for \(i = 1, 2, 3, \ldots, m\).
- \(t_i\) is time required to repair unit \(i\) for \(i = 1, 2, 3, \ldots, m\).
Example 11.8
Assume that an engineering system is composed of three nonidentical subsystems—1, 2, and 3—with constant failure rates $\lambda_1 = 0.0006$ failure/hour, $\lambda_2 = 0.0005$ failure/hour, and $\lambda_3 = 0.0004$ failure/hour, respectively. Corrective maintenance times of subsystems 1, 2, and 3 are 4, 3, and 2 hours, respectively. Calculate the engineering system mean time to repair.
By substituting the given data values into Equation (11.32), we get

$$MTTR = \frac{(0.0006)(4) + (0.0005)(3) + (0.0004)(2)}{(0.0006 + 0.0005 + 0.0004)} \approx 3.133 \text{ hours}$$

Thus, the engineering system mean time to repair is 3.133 hours.

11.7.2 Maintainability Function
This is concerned with determining the probability of completing repair in a specified time interval. For a known repair time distribution, the maintainability function can be obtained by using the following equation [5, 18]:

$$m(t) = \int_0^t f_r(t) \, dt \quad (11.33)$$

where
- $m(t)$ is maintainability function (i.e., the probability that repair will be accomplished in time $t$ when it starts at time $t = 0$).
- $t$ is time.
- $f_r(t)$ is probability density function of the repair times.

Example 11.9
Assume that the repair times of a system are defined by the following probability density function (i.e., the repair times are exponentially distributed):

$$f_r(t) = \frac{1}{MTTR} e^{-\frac{t}{MTTR}} \quad (11.34)$$

where
- $f_r(t)$ is probability density function of the system repair times.
- $t$ is time.
- $MTTR$ is system mean time to repair.

Obtain an expression for the maintainability function and calculate the probability that a repair will be accomplished in 3 hours if the system mean time to repair is 4 hours.
By substituting Equation (11.34) into Equation (11.33), we get

$$m(t) = \int_0^t \frac{1}{MTTR} e^{\left(\frac{1}{MTTR}\right)t} dt$$

$$= 1 - e^{\left(\frac{1}{MTTR}\right)t}$$

(11.35)

Using the given data values in Equation (11.35) yields

$$m(3) = 1 - e^{-\left(\frac{3\times 1}{MTTR}\right)}$$

$$= 0.5276$$

Thus, the expression for the maintainability function is given by Equation (11.35) and the probability that the system repair will be accomplished in 3 hours is 0.5276.

### 11.7.3 Mean Preventive Maintenance Time

This is a quite useful maintainability measure expressed by [5,18]

$$T_{mp} = \frac{\sum_{i=1}^{K} t_{pi} f_{pi}}{\sum_{i=1}^{K} f_{pi}}$$

(11.36)

where

- $T_{mp}$ is mean preventive maintenance time.
- $K$ is number of preventive maintenance tasks.
- $t_{pi}$ is elapsed time for preventive maintenance task $i$ for $i = 1, 2, 3, \ldots, K$.
- $f_{pi}$ is frequency of preventive maintenance task $i$ for $i = 1, 2, 3, \ldots, K$.

During the computation of $T_{mp}$ note that if the frequencies, $f_{pi}$, are specified in maintenance tasks per hour, then the values of $t_{pi}$ must also be expressed in hours.

### 11.7.4 Maximum Corrective Maintenance Time

This maintainability measure is concerned with estimating the time to complete a specified percentage of all potential repair actions. Usually, the specified percentiles are the 90th and 95th. Because the estimation of maximum corrective maintenance time depends on the probability distribution describing the times to repair, equations for estimating maximum corrective maintenance time for three probability distributions are presented next [5,18].

#### 11.7.4.1 Exponential

In this case, the maximum corrective maintenance time is expressed by

$$MT_{cm} = \alpha (MTTR)$$

(11.37)
where

$MT_{cm}$ is maximum corrective maintenance time.

$MTTR$ is mean time to repair.

$\alpha$ is a constant whose values are 2.312 and 3 for the 90th and 95th percentiles, respectively.

### 11.7.4.2 Normal

In this case, the maximum corrective maintenance time is defined by

$$MT_{cm} = MTTR + \theta \sigma_n$$

where

$\theta$ is a constant and its values are 1.28 and 1.65 for the 90th and 95th percentiles, respectively.

$\sigma_n$ is standard deviation of the repair times.

### 11.7.4.3 Lognormal

In this case, the maximum corrective maintenance time is expressed by

$$MT_{cm} = \text{anti} \log(T_a + \theta \sigma_r)$$

where

$T_a$ is mean of the logarithms of repair times.

$\sigma_r$ is standard deviation of the logarithms of the repair times.

Additional information on the maximum corrective maintenance time is available in Dhillon [5,8].

### 11.8 System Availability and Unavailability

Availability and unavailability of a system are given by [5,18]

$$AV_S(t) = \frac{1}{(\lambda_S + \mu_S)}[\mu_S + \lambda_S e^{-(\lambda_S + \mu_S)t}]$$

and

$$UAV_S(t) = \frac{\lambda_S}{\lambda_S + \mu_S}[1 - e^{-(\lambda_S + \mu_S)t}]$$
where

\[ AV_S(t) \] is system availability at time \( t \).
\( t \) is time.
\( \lambda_s \) is system constant failure rate.
\( \mu_s \) is system constant repair rate.
\( UAV_S(t) \) is system unavailability at time \( t \).

As time \( t \) becomes very large, Equations (11.40) and (11.41) reduce to

\[
\lim_{{t \to \infty}} AV_S(t) = \frac{\mu_s}{\lambda_s + \mu_s} \quad (11.42)
\]

and

\[
\lim_{{t \to \infty}} UAV_S(t) = \frac{\lambda_s}{\lambda_s + \mu_s} \quad (11.43)
\]

where

\( AV_S \) is system steady-state availability.
\( UAV_S \) is system steady-state unavailability.

Because

\[
\lambda_s = \frac{1}{MTTF_S}
\]

and

\[
\mu_s = \frac{1}{MTTR_S}
\]

Equations (11.42) and (11.43) become

\[
AV_S = \frac{MTTF_S}{MTTF_S + MTTR_S} = \frac{\text{System uptime}}{\text{System uptime} + \text{System downtime}} \quad (11.44)
\]

and

\[
UAV_S = \frac{MTTR_S}{MTTF_S + MTTR_S} = \frac{\text{System downtime}}{\text{System uptime} + \text{System downtime}} \quad (11.45)
\]

where

\( MTTF_S \) is system mean time to failure.
\( MTTR_S \) is system mean time to repair.
**Example 11.10**
An engineering system mean time to failure and mean time to repair are 400 hours and 20 hours, respectively. Calculate the system steady-state unavailability.
By substituting the given data values into Equation (11.45), we get

\[ UAV_s = \frac{20}{400 + 20} = 0.0476 \]

Thus, the engineering system unavailability is 0.0476.

---

**11.9 Reliability and Maintainability Tools**

Many methods are used to perform various types of reliability and maintainability analyses. Three of these methods that can be used to perform both reliability and maintainability analyses are as follows:

- failure modes and effect analysis (FMEA);
- fault tree analysis; and
- cause and effect diagram.

Each of these methods is described next.

**11.9.1 Failure Modes and Effect Analysis (FMEA)**

This is an important tool to evaluate engineering design at the initial stage from the reliability and maintainability aspects. FMEA was developed in the early 1950s for evaluating the design of flight control systems [19].

It helps to identify the need for and effects of design change and demands listing of potential failure modes of all system or equipment components on paper and their effects on the listed subsystems. The main steps in performing FMEA are shown in Figure 11.4. FMEA is called failure modes, effects, and criticality analysis (FMECA) when criticalities are assigned to failure mode effects. Additional information on FMEA is available in Dhillon [5].

**11.9.2 Fault Tree Analysis**

This is one of the most widely used methods for performing system reliability analysis; it arranges fault events in a tree-shaped diagram (thus, the name). The method is well suited to determine the combined effects of multiple failures. It was originally developed to evaluate the reliability of the Minuteman launch control system at Bell Telephone Laboratories in the early 1960s [5,20].
The fault tree analysis starts by identifying an undesirable event—called the “top event”—associated with a system under consideration. The fault events that can cause the occurrence of the top event are generated and connected by logic gates known as OR, AND, etc. The construction of a fault tree of a system proceeds by generation of fault events (by asking, “How can this event occur?”) successively until the fault events need not be developed further. These events are called elementary or primary events.

Overall, a fault tree may simply be described as the logic structure relating the primary fault events to the top event. Additional information on fault tree analysis is available in Dhillon [5] and Dhillon and Singh [21].

### 11.9.3 Cause and Effect Diagram

This is a quite useful approach for determining the root cause of a given problem and generating relevant ideas. Other names used for this approach are Ishikawa diagram, after its Japanese originator K. Ishikawa, and “fish bone” diagram because of its resemblance to the skeleton of a fish (as shown in Figure 11.5).

It can be seen from this figure that the right side (i.e., the fish head or the box) represents the effect (the problem or goal) and the dotted box on the left side contains “fish bones” that can be any set of factors considered to be important causes.
The following basic steps are used to develop a cause and effect diagram:

- Develop problem statement.
- Brainstorm to identify all possible causes.
- Develop important cause classifications by stratifying into natural groupings and process steps.
- Develop the diagram.
- Refine all cause classifications by asking questions such as “What causes this?” and “Why does this condition exist?”

Additional information on the cause and effect diagram is available in Dhillon [5,18].

Problems

1. Discuss reliability and maintainability history.
2. Define the following terms:
   - availability;
   - reliability;
   - maintainability; and
   - useful life.
3. Describe the bathtub hazard rate curve.
4. Write three different general formulas for obtaining mean time to failure.
5. Obtain an expression for a parallel system hazard rate by using Equation (11.23).
6. List at least 10 general principles of reliability.
7. Describe two methods that can be used to perform reliability and maintainability analyses.

8. Prove that the sum of Equations (11.40) and (11.41) is equal to unity.

9. Assume that an engineering system is composed of four nonidentical subsystems—1, 2, 3, and 4—with constant failure rates \( \lambda_1 = 0.0001 \) failure/hour, \( \lambda_2 = 0.0002 \) failure/hour, \( \lambda_3 = 0.0003 \) failure/hour, and \( \lambda_4 = 0.0004 \) failure/hour, respectively. Calculate the engineering system mean time to repair if the corrective maintenance times of subsystems 1, 2, 3, and 4 are 2, 4, 6, and 8 hours, respectively.

10. Assume that an engineering system is composed of five independent and identical units in parallel. At least three units must operate normally for the system success. Calculate the engineering system mean time to failure if the constant failure rate of each unit is 0.004 failure/hour.

References


Bibliography: Literature on Life Cycle Costing

Introduction

Over the years, a large number of publications on various aspects of life cycle costing have appeared in the form of journal articles, conference proceedings articles, books, etc. This bibliography presents an extensive list of such publications. The period covered by the listing is from 1988 to 2008. The main objective of this listing is to provide readers with sources for obtaining additional information on life cycle costing.

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Life Cycle Costing for Engineers

B.S. DHILLON

Cradle-to-grave analyses are becoming the norm, as an increasing number of corporations and government agencies are basing their procurement decisions not only on initial costs but also on life cycle costs. And while life cycle costing has been covered in journals and conference proceedings, few, if any, books have gathered this information into an easily accessible resource. Eliminating the need to consult many different sources, *Life Cycle Costing for Engineers* brings together up-to-date life cycle costing concepts and explains their application in various industrial sectors.

The author sets the scene with a chapter on fundamental economics followed by a chapter on reliability and maintainability, providing background information and a platform for further understanding. He then discusses life cycle costing fundamentals; models and estimation methods; reliability, quality, safety, and manufacturing costing; and maintenance, maintainability, usability, and warranty costing. The book includes life cycle costing for computer systems and software, transportation systems, aircraft turbine engines, cargo ships, rail systems, civil engineering structures, and energy systems. An in-depth look at cost estimation models and engineering reliability and maintainability topics, such as bathtub hazard rate curve, common reliability networks, general reliability, mean time to failure, and hazard rate formulas, round out the coverage.

Filled with examples, tables, figures, and equations, this book integrates life cycle costing concepts for use in industrial and other sectors. It provides a modern treatment of the subject that can easily be applied to any industry.