Chapter 3
Introduction to Reliability, Maintainability, and Safety

3.1 Introduction

The history of the reliability field may be traced back to the early 1930s when probability concepts were applied to problems associated with electric power generation [1–3]. However, generally the real beginning of the reliability field is regarded as World War II, when Germans applied basic reliability concepts to improve the reliability of their V1 and V2 rockets. Today, reliability engineering is a well-developed discipline and has branched out into specialized areas such as software reliability, mechanical reliability, and human reliability. A detailed history of the reliability field is available in Ref. [4].

The beginning of the maintainability field may be traced back to 1901 to the United States Army Signal Corps contract for the development of the Wright brothers' airplane. In this document, it was clearly stated that the aircraft should be "simple to operate and maintain" [5]. The first commercially available book entitled *Electronic Maintainability* appeared in 1960, and in the latter part of the 1960s many military documents on maintainability were published by the United States Department of Defense [6–8]. A detailed history of the maintainability field is given in Refs. [9, 10].

The history of the safety field goes back to 1868, when a patent was awarded for a barrier safeguard in the United States [11]. In 1893, the Railway Safety Act was passed by the U.S. Congress, and in 1931 the first commercially available book, *Industrial Accident Prevention*, was published [12]. A detailed history of safety is available in Ref. [13].

This chapter presents various important introductory aspects of reliability, maintainability, and safety considered useful for the mining industry.

3.2 Need for Reliability and Bathtub Hazard Rate Curve

Today reliability has become an important factor during the design phase of engineering systems because our daily lives and schedules are increasingly becoming more dependent than ever before on the satisfactory functioning of such systems. Some examples of these systems are aircraft, trains, automobiles, space satellites, and computers. Some of the specific factors responsible for the consideration of reliability in system/product design are the insertion of reliability-related clauses in design specifications, product/system complexity and sophistication, high acquisition cost, competition, public demand, past system/product failures, loss of prestige, and the increasing number of reliability-/safety-/quality-related lawsuits.

The bathtub hazard rate curve, shown in Fig. 3.1, is widely used to represent the failure rate of various types of engineering items. As shown in Fig. 3.1, the curve is divided into three regions: burn-in period, useful-life period, and wear-out period. During the burn-in period the item hazard rate or time-dependent failure rate decreases with time t. Some of the reasons for the occurrence of failures during this period are poor quality control, substandard materials and workmanship, poor manufacturing methods, inadequate debugging, poor processes, and human error [14].

During the useful-life period the item hazard rate remains constant. Some of the reasons for the occurrence of failures during this period are low safety factors, undetectable defects, natural failures, abuse, higher-than-expected random stress, and human error. Finally, during the wear-out period the item hazard rate increases with time t. Some of the causes for the occurrence of failures during this period are

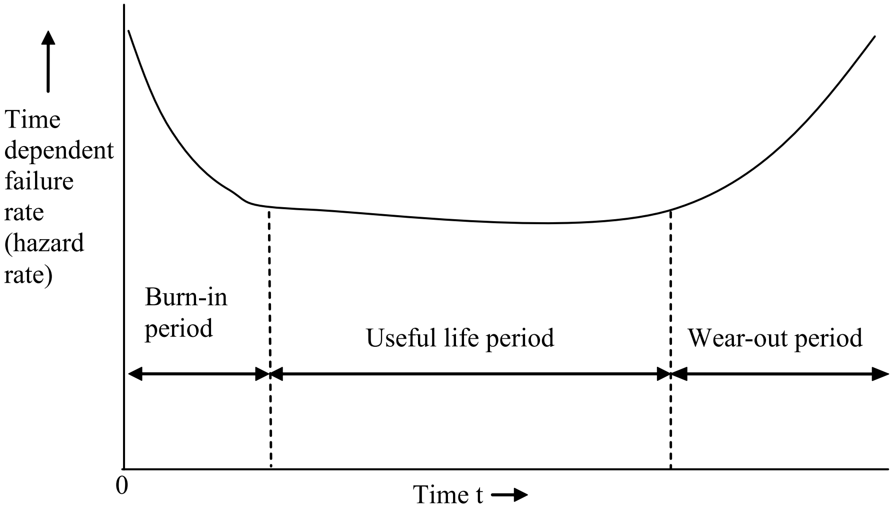

Fig. 3.1 Bathtub hazard rate curve

wear caused by friction, poor maintenance, wear caused by aging, corrosion and creep, incorrect overhaul practices, and short designed-in life of the item.

3.3 General Reliability, Hazard Rate, and Mean Time to Failure Functions

Many general functions are frequently used in performing reliability analysis. Three of these functions are presented below.

3.3.1 General Reliability Function

This is expressed by

$$R(t) = \mathrm{e}^{-\int_0^t \lambda(t)\,\mathrm{d}t} , \tag{3.1}$$

where

$R(t)$ is the reliability at time t,
$\lambda(t)$ is the hazard rate or time-dependent failure rate.

Equation (3.1) is the general expression for the reliability function. It is used to obtain the reliability of an item whose times to failure are described by statistical distributions such as exponential, Rayleigh, Weibull, and normal.

Example 3.1

Assume that the times to failure of a piece of mining equipment are exponentially distributed. Thus, the equipment's hazard rate is given by

$$\lambda(t) = \lambda , \tag{3.2}$$

where

λ is the mining equipment constant failure rate.

Obtain an expression for the equipment reliability function.

Substituting Eq. (3.2) into Eq. (3.1) we get

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

Equation (3.3) is the reliability function for the piece of mining equipment.

3.3.2 Hazard Rate Function

The hazard rate function is expressed by

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{3.4}$$

or

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{\mathrm{d}R(t)}{\mathrm{d}t} , \tag{3.5}$$

where

$f(t)$ is the failure (or probability) density function.

Example 3.2

Prove Eq. (3.2) using Eqs. (3.3) and (3.5).

Thus, substituting Eq. (3.3) into Eq. (3.5) we get

$$\lambda(t) = -\frac{1}{\mathrm{e}^{-\lambda t}} \cdot \frac{\mathrm{d}\,\mathrm{e}^{-\lambda t}}{\mathrm{d}t} = \lambda . \tag{3.6}$$

Equations (3.2) and (3.6) are identical.

3.3.3 Mean Time to Failure

Mean time to failure can be obtained using any of the following formulas [15]:

$$MTTF = \int_0^\infty R(t)\,\mathrm{d}t \tag{3.7}$$

or

$$MTTF = \lim_{s \to 0} R(s) \tag{3.8}$$

or

$$MTTF = \int_0^\infty t f(t)\,\mathrm{d}t , \tag{3.9}$$

where

$MTTF$ is the mean time to failure,
s is the Laplace transform variable,
$R(s)$ is the Laplace transform of the reliability function, $R(t)$.

Example 3.3

Using Eq. (3.3), obtain an expression for the mining equipment mean time to failure.

Substituting Eq. (3.3) into Eq. (3.7) we get

$$MTTF = \int_0^{\infty} \mathrm{e}^{-\lambda t}\,\mathrm{d}t = \frac{1}{\lambda}\,. \tag{3.10}$$

Equation (3.10) is the expression for the mining equipment mean time to failure.

3.4 Reliability Networks

A system can form various types of networks or configurations in performing reliability analysis. Some commonly occurring configurations are presented below.

3.4.1 Series Configuration

This is probably the most widely occurring configuration in engineering systems; it is depicted by the block diagram shown in Fig. 3.2. Each block in the diagram denotes a component or unit. In this arrangement or configuration, all the units must operate normally for the successful operation of the system (*i.e.*, the series system).

If we let X_j denote the event that the jth unit in Fig. 3.2 is successful, then the reliability of the series configuration/system is given by

$$R_\mathrm{s} = P\left(X_1 X_2 X_3 \ldots X_m\right)\,, \tag{3.11}$$

where

R_s is the series system or configuration reliability,
$P\left(X_1 X_2 X_3 \ldots X_m\right)$ is the occurrence probability of success events $X_1 X_2 X_3 \ldots$ and X_m.

For independent units, Eq. (3.11) becomes

$$R_\mathrm{s} = P\left(X_1\right) P\left(X_2\right) P\left(X_3\right) \ldots P\left(X_m\right)\,, \tag{3.12}$$

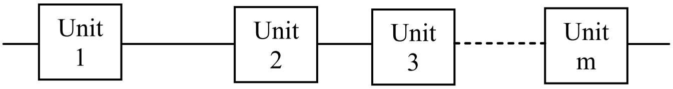

Fig. 3.2 A series configuration with *m* units

where

$P(X_j)$ is the probability of occurrence of success event X_j, for $j = 1,2,3,\ldots,m$.

If we let $R_j = P(X_j)$ for $j = 1,2,3,\ldots,m$ in Eq. (3.12), the equation becomes

$$R_s = \prod_{j=1}^{m} R_j \,, \tag{3.13}$$

where

R_j is the unit j reliability; for $j = 1,2,3,\ldots,m$.

For constant failure rate, λ_j, of unit j, using Eq. (3.1) the reliability of unit j is given by

$$R_j(t) = \mathrm{e}^{-\int_0^t \lambda_j \, \mathrm{d}t} = \mathrm{e}^{-\lambda_j t} \,, \tag{3.14}$$

where

$R_j(t)$ is the reliability of unit j at time t.

Substituting Eq. (3.14) into Eq. (3.13) we get

$$R_s(t) = \mathrm{e}^{-\sum_{j=1}^{m} \lambda_j t} \,, \tag{3.15}$$

where

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

Inserting Eq. (3.15) into Eq. (3.7) we get

$$MTTF_s = \int_0^\infty \mathrm{e}^{-\sum_{j=1}^{m} \lambda_j t \, \mathrm{d}t} = \frac{1}{\sum_{j=1}^{m} \lambda_j} \,, \tag{3.16}$$

where

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

Example 3.4

Assume that a mining system is composed of five independent and identical subsystems in series. The constant failure rate of each subsystem is 0.0006 failures per hour. Calculate the mining system mean time to failure and reliability for a 100-h mission.

Using the data values given in Eq. (3.16) yields

$$MTTF_s = \frac{1}{5(0.0006)} = 333.3\,\mathrm{h} \,.$$

Substituting the specified data into Eq. (3.15) we get

$$R_s(100) = e^{-5(0.0006)(100)} = 0.7408 .$$

Thus, the mining system mean time to failure and reliability are 333.3 h and 0.7408, respectively.

3.4.2 Parallel Configuration

In this case, all m units are active and at least one of these units must operate normally for the successful operation of the system. The block diagram of an "m" unit parallel configuration/system is shown in Fig. 3.3; each block in the diagram represents a unit.

If we let $\bar{X}_j$ represent the event that the jth unit is unsuccessful, then the failure probability of the parallel system/configuration is given by

$$F_p = P(\bar{X}_1 \bar{X}_2 \ldots \bar{X}_m) , \qquad (3.17)$$

where

F_p is the parallel system/configuration reliability,
$P(\bar{X}_1 \bar{X}_2 \ldots \bar{X}_m)$ is the occurrence probability of failure events $\bar{X}_1, \bar{X}_2, \ldots, \bar{X}_m$.

For independent units, Eq. (3.17) becomes

$$F_p = P(\bar{X}_1) P(\bar{X}_2) \ldots P(\bar{X}_m) , \qquad (3.18)$$

where

$P(\bar{X}_j)$ is the occurrence probability of failure event $\bar{X}_j$; for $j = 1, 2, 3, \ldots, m$.

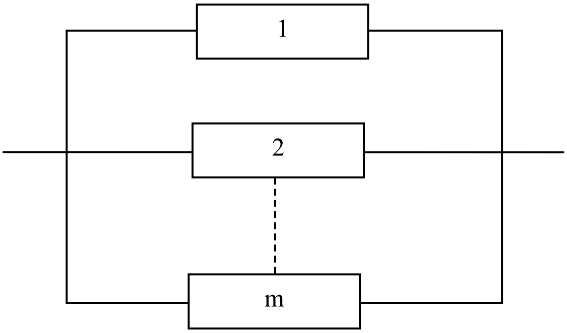

Fig. 3.3 Block diagram of a parallel configuration containing m units

If we let $F_j = P(\bar{X}_j)$ for $j = 1,2,\ldots,m$ in Eq. (3.18), the equation becomes

$$F_\mathrm{p} = \prod_{j=1}^{m} F_j \,, \tag{3.19}$$

where

F_j is the failure probability of unit j; for $j = 1,2,\ldots,m$.

Subtracting Eq. (3.19) from unity we obtain

$$R_\mathrm{p} = 1 - \prod_{j=1}^{m} F_j \,, \tag{3.20}$$

where

R_p is the parallel system/configuration reliability.

For the constant failure rate, λ_j, of unit j, subtracting Eq. (3.14) from unity; then, substituting it into Eq. (3.20) yields

$$R_\mathrm{p}(t) = 1 - \prod_{j=1}^{m} \left(1 - \mathrm{e}^{-\lambda_j t}\right) \,, \tag{3.21}$$

where

$R_\mathrm{p}(t)$ is the parallel system/configuration reliability at time t.

For identical units, using Eq. (3.7) and (3.21) we get

$$MTTF_\mathrm{p} = \int_0^\infty \left[1 - \left(1 - \mathrm{e}^{-\lambda t}\right)^m\right] \mathrm{d}t = \frac{1}{\lambda} \sum_{j=1}^{m} \frac{1}{j} \,, \tag{3.22}$$

where

λ is the unit constant failure rate,
$MTTF_\mathrm{p}$ is the parallel system/configuration mean time to failure.

Example 3.5

A mining system is composed of three independent and identical units in parallel, and their constant failure rates are 0.0005 failures per hour. Calculate the system mean time to failure and reliability for a 200-h mission.

Substituting the specified data values into Eq. (3.22) we get

$$MTTF_\mathrm{p} = \frac{1}{(0.0005)} \left(1 + \frac{1}{2} + \frac{1}{3}\right) = 3666.7\,\mathrm{h} \,.$$

Using the given data values in Eq. (3.21) yields

$$R_{\mathrm{p}}(200) = 1 - \left(1 - \mathrm{e}^{-(0.0005)(200)}\right)^2 = 0.9909\,.$$

Thus, the mining system mean time to failure and reliability are 3666.7 h and 0.9909, respectively.

3.4.3 *k*-out-of-*m* Configuration

In this case *m* number of units are active and at least k units must operate normally for the system success. The parallel and series configurations are special cases of this configuration for $k = 1$ and $k = m$, respectively.

Using the binomial distribution, for independent and identical units, we write down the following expression for the *k*-out-of-*m* configuration reliability:

$$R_{k/m} = \sum_{j=k}^{m} \binom{m}{j} R^j (1-R)^{m-j}\ , \tag{3.23}$$

where

$$\binom{m}{j} = \frac{m!}{(m-j)!j!}\ , \tag{3.24}$$

$R_{k/m}$ is the *k*-out-of-*m* configuration/system reliability,
R is the unit reliability.

For constant failure rates of units, using Eqs. (3.3) and (3.23) we get

$$R_{k/m}(t) = \sum_{j=k}^{m} \binom{m}{j} \mathrm{e}^{-j\lambda t} \left(1 - \mathrm{e}^{-\lambda t}\right)^{m-j}\ , \tag{3.25}$$

where

$R_{k/m}(t)$ is the *k*-out-of-*m* configuration/system reliability at time *t*,
λ is the unit constant failure rate.

Substituting Eq. (3.25) into Eq. (3.7) we get

$$MTTF_{k/m} = \int_0^{\infty} \left[\sum_{j=k}^{m} \binom{m}{j} \mathrm{e}^{-j\lambda t} \left(1 - \mathrm{e}^{-\lambda t}\right)^{m-j}\right] \mathrm{d}t = \frac{1}{\lambda} \sum_{j=k}^{m} \frac{1}{j}\ , \tag{3.26}$$

where

$MTTF_{k/m}$ is the mean time to failure of the *k*-out-of-*m* configuration/system.

Example 3.6

A mining system is composed of three independent and identical units operating in parallel. At least two of these units must operate normally for the system to succeed. Calculate the mining system mean time to failure if the unit failure rate is 0.001 failures per hour.

Substituting the specified data values into Eq. (3.26) we get

$$MTTF_{2/3} = \frac{1}{(0.001)} \sum_{j=2}^{3} \frac{1}{j} = 833.3\,\text{h}\,.$$

Thus, the mining equipment mean time to failure is 833.3 h.

3.4.4 Standby System

In this case, the system is composed of $(n+1)$ units and only one unit operates and the remaining n units are kept in their standby mode. As soon as the operating unit fails, the switching mechanism detects the failure and then turns on one of the n standby units. The system fails when all the n standby units fail.

For independent and identical units (*i.e.*, the operating plus standby units), perfect switching mechanism and standby units, the standby system reliability is expressed by

$$R_{\text{sb}}(t) = \sum_{j=0}^{n} \left[\left[\int_0^t \lambda(t)\,\mathrm{d}t \right]^j \mathrm{e}^{-\int_0^t \lambda(t)\,\mathrm{d}t} \right] / j!\,, \tag{3.27}$$

where

$R_{\text{sb}}(t)$ is the standby system reliability at time t,
$\lambda(t)$ is the unit time dependent failure rate,
n is the number of standby units.

For constant unit failure rate (*i.e.*, $\lambda(t) = \lambda$), using Eq. (3.27), we get

$$R_{\text{sb}}(t) = \sum_{j=0}^{n} \left[(\lambda t)^j\, \mathrm{e}^{-\lambda t} \right] / j!\,. \tag{3.28}$$

Substituting Eq. (3.28) into Eq. (3.7) we obtain

$$MTTF_{\text{sb}} = \int_0^{\infty} \left[\sum_{j=0}^{n} (\lambda t)^j\, \mathrm{e}^{-\lambda t} / j! \right] \mathrm{d}t = \frac{n+1}{\lambda}\,, \tag{3.29}$$

where

$MTTF_{\text{sb}}$ is the standby system mean time to failure.

Example 3.7

A standby mining system is composed of three independent and identical units: one operating, two on standby. The unit constant failure rate is 0.0005 failures per hour. The standby unit turn-on mechanism is perfect and both the standby units remain as good as new in their standby mode. Calculate the mining system mean time to failure.

Substituting the given data values into Eq. (3.29) we get

$$MTTF_{\mathrm{sb}} = \frac{(2+1)}{(0.0005)} = 6000\,\mathrm{h}\,.$$

Thus, the standby mining system mean time to failure is 6000 h.

3.4.5 Bridge Configuration

This type of configuration also occurs in engineering systems. The block diagram of a bridge configuration is shown in Fig. 3.4. Each block in the diagram denotes a unit.

For independent units, the reliability of the Fig. 3.4 bridge configuration is expressed by [16]

$$\begin{aligned} R_{\mathrm{b}} = {} & 2R_1R_2R_3R_4R_5 + R_2R_3R_4 + R_1R_3R_5 + R_1R_4 + R_2R_5 - R_2R_3R_4R_5 \\ & - R_1R_2R_3R_4 - R_5R_1R_2R_3 - R_1R_3R_4R_5 - R_1R_2R_4R_5\,, \end{aligned} \tag{3.30}$$

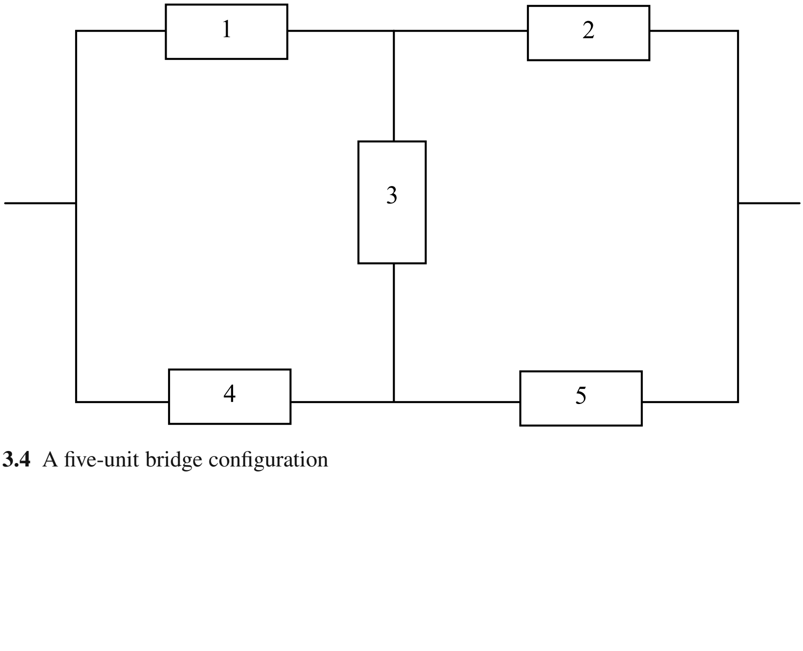

Fig. 3.4 A five-unit bridge configuration

where

R_{b} is the bridge configuration/system reliability.
R_j is the reliability of unit j; for $j = 1,2,3,\ldots,5$.

For identical units and constant failure rates of units, using Eq. (3.1) and (3.30) we get

$$R_{\mathrm{b}}(t) = 2\,\mathrm{e}^{-5\lambda t} - 5\,\mathrm{e}^{-4\lambda t} + 2\,\mathrm{e}^{-3\lambda t} + 2\,\mathrm{e}^{-2\lambda t}\,, \tag{3.31}$$

where

$R_{\mathrm{b}}(t)$ is the bridge configuration/system reliability at time t,
λ is the unit constant failure rate.

Substituting Eq. (3.31) into Eq. (3.7) we get

$$MTTF_{\mathrm{b}} = \int_0^\infty \left[2\,\mathrm{e}^{-5\lambda t} - 5\,\mathrm{e}^{-4\lambda t} + 2\,\mathrm{e}^{-3\lambda t} + 2\,\mathrm{e}^{-2\lambda t}\right] \mathrm{d}t = \frac{49}{60\lambda}\,, \tag{3.32}$$

where

$MTTF_{\mathrm{b}}$ is the bridge configuration/system mean time to failure.

Example 3.8

Assume that five independent and identical units of a mining system form a bridge configuration. Calculate the bridge configuration reliability for a 100-h mission and mean time to failure, if the constant failure rate of each unit is 0.0004 failures per hour.

Using the specified data values in Eq. (3.31) yields

$$\begin{aligned} R_{\mathrm{b}}(100) &= 2\,\mathrm{e}^{-5(0.0004)(100)} - 5\,\mathrm{e}^{-4(0.0004)(100)} \\ &\quad + 2\,\mathrm{e}^{-3(0.0004)(100)} + 2\,\mathrm{e}^{-2(0.0004)(100)} \\ &= 0.9968\,. \end{aligned}$$

Substituting the given data value into Eq. (3.32) we get

$$MTTF_{\mathrm{b}} = \frac{49}{60(0.0004)} = 2041.67\,\mathrm{h}\,.$$

Thus, the bridge configuration reliability and mean time to failure are 0.9968 and 2041.67 h, respectively.

3.5 Commonly Used Methods in Reliability Analysis

Over the years many methods have been developed to perform reliability analysis of engineering systems. These methods are particularly useful for analyzing engineering systems more complex than the ones forming the standard reliability configurations.

This section presents three of these methods considered useful for application in the mining industry [4, 17–19].

3.5.1 Failure Modes and Effect Analysis (FMEA)

This is one of the most widely used methods for performing reliability analysis of engineering systems and is basically a qualitative approach. It was developed in the early 1950s to assess the designs of flight control systems [20].

FMEA usually starts during the early phases of system design and is performed by following the seven steps shown in Fig. 3.5. Some of the questions asked during the performance of FMEA with respect to components/subsystems are as follows:

- What are the possible failure modes of the component/subsystem?
- What are the possible consequences of the failure mode?
- How is failure detected?
- How critical are the consequences?
- What are the effective safeguards against the failure in question?

Some of the important applications of FMEA are as follows [19]:

- To identify weak spots in design,
- To choose design alternatives during the early stages of design,
- To serve as a basis for design improvement action,
- To identify weak areas in design,
- To ensure the understanding of all possible failure modes and their anticipated effects,
- To choose design alternatives during the early stages of design, and
- To recommend appropriate test programs.

Additional information on FMEA is available in Ref. [4].

3.5.2 Markov Method

This is a widely used method to handle reliability and availability analyses of repairable systems. The approach proceeds by the enumeration of system states, and then the resulting system of differential equations are solved to obtain reliability-

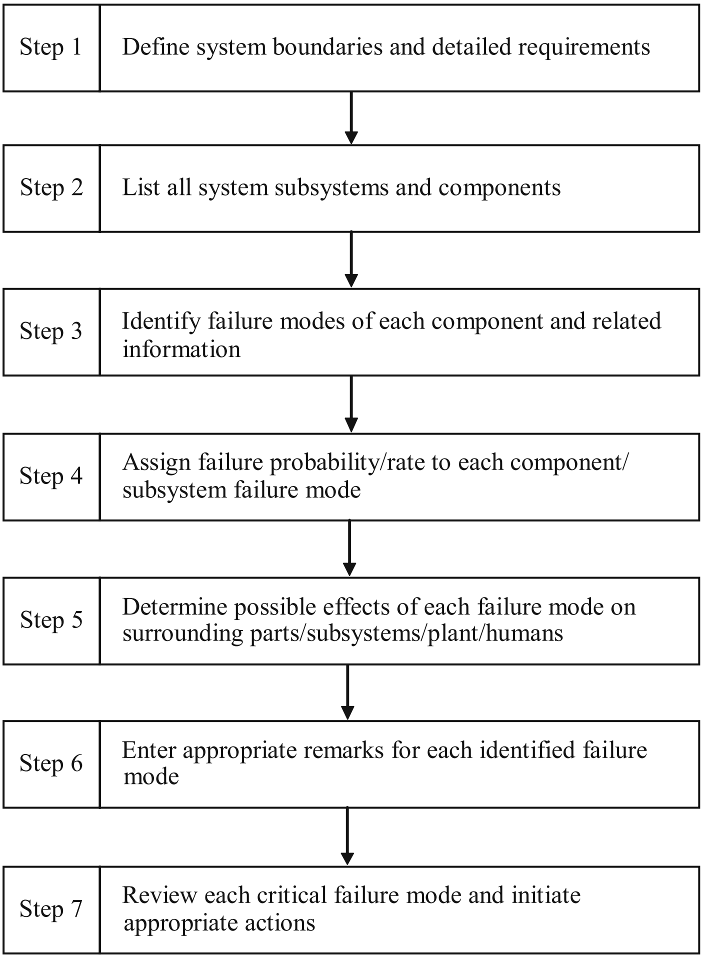
Step 1
Define system boundaries and detailed requirements
Step 2
List all system subsystems and components
Step 3
Identify failure modes of each component and related information
Step 4
Assign failure probability/rate to each component/ subsystem failure mode
Step 5
Determine possible effects of each failure mode on surrounding parts/subsystems/plant/humans
Step 6
Enter appropriate remarks for each identified failure mode
Step 7
Review each critical failure mode and initiate appropriate actions

Fig. 3.5 Steps for performing FMEA

related measures. The following assumptions are associated with the Markov method [21]:

- All system transition rates (*i.e.*, failure and repair rates) are constant.
- All occurrences are independent of each other.
- The probability of transition from one system state to another in the finite time interval Δt is given by $\lambda \Delta t$, where λ is the transition rate (*e.g.*, system failure or repair rate) from one system state to another.
- The probability of more than one transition occurrence in finite time interval Δt from one system state to another is very small or negligible [*e.g.*, $(\lambda \Delta t)(\lambda \Delta t) \rightarrow 0$].

The application of the method is demonstrated by solving the following example.

Example 3.9

A mining system can either be in an operating state or a failed state, and its constant failure and repair rates are λ_m and μ_m, respectively. The system state-space diagram is shown in Fig. 3.6. The numerals in boxes denote system states. Obtain expressions for the mining system state probabilities using the Markov method.

Using Fig. 3.6 and the Markov method, we write down the following two equations [4,21]:

$$P_0(t+\Delta t) = P_0(t)(1-\lambda_m \Delta t) + P_1(t)\mu_m \Delta t \,, \tag{3.33}$$

$$P_1(t+\Delta t) = P_1(t)(1-\mu_m \Delta t) + P_0(t)\lambda_m \Delta t \,, \tag{3.34}$$

where

λ_m is the mining system constant failure rate,
μ_m is the mining system constant repair rate,
t is time,
$\lambda_m \Delta t$ is the probability of the mining system failure in finite time interval Δt.
$\mu_m \Delta t$ is the probability of the mining system repair in finite time interval Δt.
$(1-\lambda_m \Delta t)$ is the probability of no mining system failure in finite time interval Δt.
$(1-\mu_m \Delta t)$ is the probability of no mining system repair in finite time interval Δt.
$P_i(t+\Delta t)$ is the probability of the mining system being in state i at time $(t+\Delta t)$; for $i=0$ (operating normally), $i=1$ (failed).
$P_i(t)$ is the probability that the mining system is in state i at time t; for $i=0,1$.

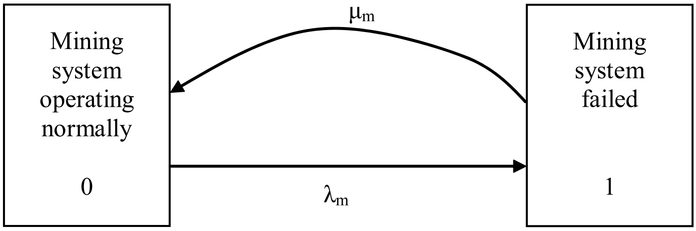

Fig. 3.6 Mining system state-space diagram

In the limiting case, Eqs. (3.32) and (3.33) become

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} + \lambda_m P_0(t) = P_1(t)\mu_m \, , \tag{3.35}$$

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} + \mu_m P_1(t) = P_0(t)\lambda_m \, . \tag{3.36}$$

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

By solving Eqs. (3.35) and (3.36), we obtain

$$P_0(t) = \frac{\mu_m}{(\lambda_m + \mu_m)} + \frac{\lambda_m}{(\lambda_m + \mu_m)} \mathrm{e}^{-(\lambda_m+\mu_m)t} \tag{3.37}$$

$$P_1(t) = \frac{\lambda_m}{(\lambda_m + \mu_m)} - \frac{\lambda_m}{(\lambda_m + \mu_m)} \mathrm{e}^{-(\lambda_m+\mu_m)t} \tag{3.38}$$

Thus, Eqs. (3.37) and (3.38) are the expressions for the mining system state probabilities.

Example 3.10

Assume that in Example 3.9 the values of λ_m and μ_m are 0.002 failures per hour and 0.004 repairs per hour, respectively. Calculate the probabilities of the mining system operating normally and failed for a 100-h mission.

Substituting the given data values into Eqs. (3.37) and (3.38) we get

$$P_0(100) = \frac{0.004}{(0.002+0.004)} + \frac{0.002}{(0.002+0.004)} \mathrm{e}^{-(0.002+0.004)(100)} = 0.8496$$

and

$$P_1(100) = \frac{0.002}{(0.002+0.004)} - \frac{0.002}{(0.002+0.004)} \mathrm{e}^{-(0.002+0.004)(100)} = 0.1504 \, .$$

Thus, the probabilities of the mining system operating normally and failed are 0.8496 and 0.1504, respectively.

3.5.3 Fault Tree Analysis

This is another widely used method to perform reliability analysis of engineering systems. It was developed at the Bell Telephone Laboratories in the early 1960s to analyze the Minuteman Launch Control System with respect to reliability and safety [22].

Although this method makes use of a large number of symbols, the four commonly used symbols are shown in Fig. 3.7 [4,22].

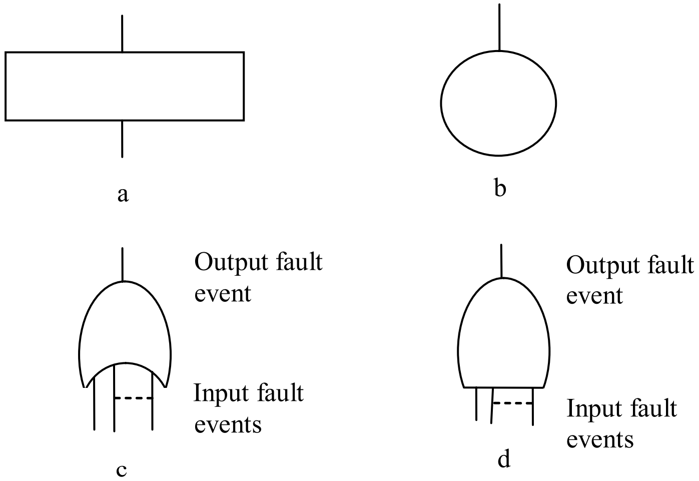

Fig. 3.7a–d Commonly used fault tree symbols. **a** Rectangle. **b** Circle. **c** OR gate. **d** AND gate

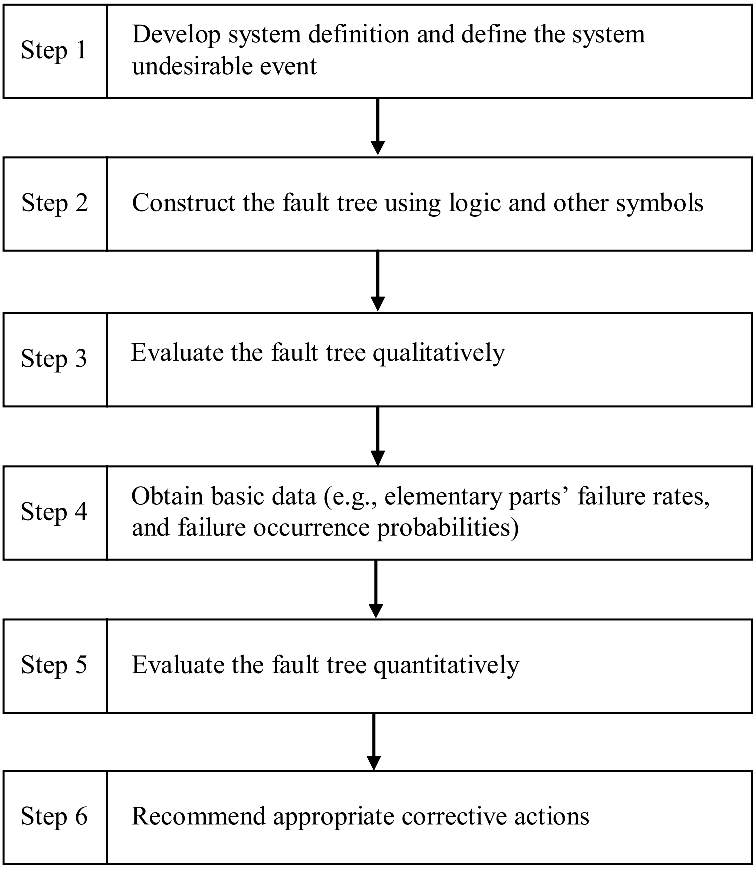
Step 1 Develop system definition and define the system undesirable event
Step 2 Construct the fault tree using logic and other symbols
Step 3 Evaluate the fault tree qualitatively
Step 4 Obtain basic data (e.g., elementary parts' failure rates, and failure occurrence probabilities)
Step 5 Evaluate the fault tree quantitatively
Step 6 Recommend appropriate corrective actions

Fig. 3.8 Steps for developing a fault tree

The Fig. 3.7 symbols are defined below.

- **Rectangle.** This represents a resultant event that results from the combination of fault events through the input of a logic gate.
- **Circle.** This denotes a basic fault event or the failure of an elementary part.
- **OR gate.** This denotes that an output fault event occurs if one or more of the input fault events occur.
- **AND gate.** This denotes that an output fault event occurs only if all the input fault events occur.

Six basic steps used to develop a fault tree are shown in Fig. 3.8. The fault tree construction starts from the undesirable event known as the top event and then successively asking the question "How could this event occur?" until reaching the desirable basic fault events.

In order to estimate the probability of occurrence of the top event, it is essential to estimate the probability of occurrence of the logic gates' output fault events. Thus, equations to estimate the probability of occurrence of OR and AND logic gates' output fault events are presented below.

OR Gate

The probability of occurrence of an OR gate's output fault event is given by [4]

$$P(X_\mathrm{o}) = 1 - \prod_{j=1}^{m} (1 - P(X_j)) \ , \tag{3.39}$$

where

m is the number of input fault events;
$P(X_\mathrm{o})$ is the probability of occurrence of OR gate's output fault event X_o;
$P(X_j)$ is the probability of occurrence of input fault event X_j; for $j = 1, 2, 3, \ldots, m$.

AND Gate

The probability of occurrence of an AND gate's output fault event is given by

$$P(X_\mathrm{a}) = \prod_{j=1}^{m} P(X_j) \ , \tag{3.40}$$

where

$P(X_\mathrm{a})$ is the probability of occurrence of AND gate's output fault event X_a.

The application of the fault tree analysis method is demonstrated through the following example.

Example 3.11

A windowless room has four lightbulbs controlled by a single switch that can only fail to close. Using Fig. 3.7 symbols, construct a fault tree for an undesirable event (top event): dark room. Furthermore, calculate the probability of occurrence of the undesirable event, if all basic fault events occur independently and their occurrence probability (*i.e.*, each event's) is 0.15.

The fault tree shown in Fig. 3.9 was developed using Fig. 3.7 symbols. Single capital letters in parentheses in circles and rectangles denote corresponding fault events. Probabilities of occurrence of events T, A, and B in Fig. 3.9 are calculated below.

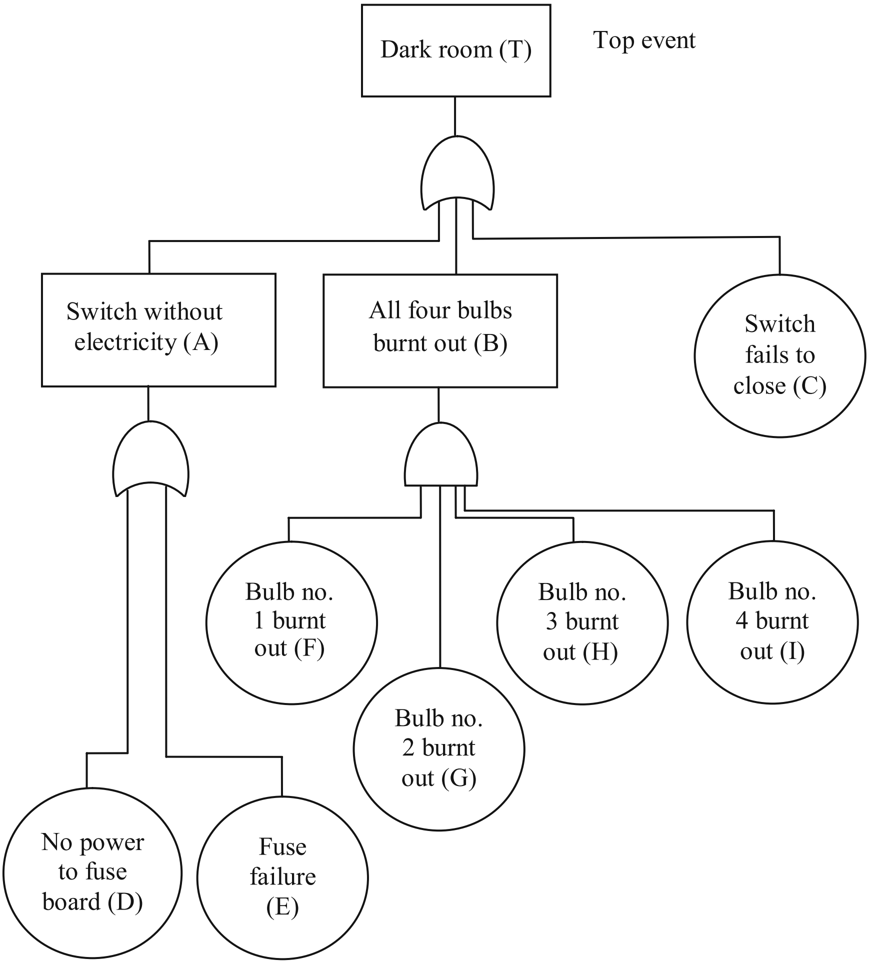

Fig. 3.9 Fault tree for the dark room undesirable event

Substituting the given data values into Eq. (3.39), we get the following probability of occurrence of fault event A:

$$\begin{aligned} P(A) &= 1-(1-P(D))\,(1-P(E)) \\ &= 1-(1-0.15)\,(1-0.15) \\ &= 0.2775\,, \end{aligned}$$

where

$P(A)$ is the probability of having the switch without electricity,
$P(D)$ is the probability of having no power to fuse board,
$P(E)$ is the probability of the fuse failure.

Using the specified data values in Eq. (3.40) we get

$$\begin{aligned} P(B) &= P(F)P(G)P(H)P(I) \\ &= (0.15)(0.15)(0.15)(0.15) \\ &= 0.0005\,, \end{aligned}$$

where

$P(B)$ is the probability of having all four bulbs burn out,
$P(F)$ is the probability of bulb number 1 burning out,
$P(G)$ is the probability of bulb number 2 burning out,
$P(H)$ is the probability of bulb number 3 burning out,
$P(I)$ is the probability of bulb number 4 burning out.

Substituting the calculated and given values into Eq. (3.39) we obtain

$$\begin{aligned} P(T) &= 1-(1-P(A))(1-P(B))(1-P(C)) \\ &= 1-(1-0.2775)(1-0.0005)(1-0.15) \\ &= 0.3862\,, \end{aligned}$$

where

$P(T)$ is the probability of occurrence of the top event: dark room,
$P(C)$ is the probability of having switch fails to close.

Thus, the probability of occurrence of the dark room undesirable event is 0.3862.

3.6 Need for Maintainability and Maintainability Versus Reliability

The need for maintainability is becoming increasingly important because of the alarmingly high operating and support costs of engineering systems. For example, each year over \$300 billion is being spent by American manufacturers on plant maintenance and operations [23]. Thus, some of the main objectives of applying maintainability principles to engineering systems are to reduce projected maintenance costs and time, to use maintainability data to estimate system/equipment availability/unavailability, and to determine labor-hours and other related resources needed to perform the projected maintenance.

Maintainability is a built-in design and installation characteristic that provides the resulting system/equipment with an inherent ability to be maintained, leading to lower maintenance costs, required skill levels, required tools and equipment, required man-hours, and better mission availability. In contrast, reliability is a design characteristic that leads to the durability of the system as it performs its specified mission according to a stated condition and time period. It is accomplished through various measures including selecting optimum engineering principles, controlling processes, satisfactory component sizing, and testing.

Some of the specific principles of maintainability (and of the corresponding reliability) are reducing life cycle maintenance costs (maximize the use of standard parts), reducing or eliminating the need for maintenance (minimizing stress on components and parts), reducing the amount, frequency, and complexity of required maintenance tasks (use fewer components for performing multiple functions), providing for maximum interchangeability (provide fail-safe designs), and reducing mean time to repair (design for simplicity) [24].

3.7 Maintainability Functions

There are many maintainability functions depending on the time to repair distribution. The maintainability function is used to predict the probability that a repair, starting at time $t = 0$, will be accomplished within time t. Mathematically, the maintainability function is defined by [5]

$$m(t) = \int_0^t f_r(t)\,\mathrm{d}t \,, \tag{3.41}$$

where

$m(t)$ is the maintainability function,
t is time,
$f_r(t)$ is the repair time probability density function.

Maintainability functions for two commonly occurring repair time distributions are presented below [26, 27]. Similarly, one can obtain maintainability functions for other repair time distributions.

3.7.1 Maintainability Function I: Exponential Distribution

In this case times to repair are exponentially distributed and are defined by

$$f_r(t) = \mu \, \mathrm{e}^{-\mu t} \,, \tag{3.42}$$

where

t is the variable repair time,
μ is the constant repair rate or reciprocal of the mean time to repair (MTTR).

Using Eq. (3.42) in Eq. (3.41) yields the following maintainability function for the exponential distribution:

$$m_{\mathrm{e}}(t) = \int_0^t \mu \, \mathrm{e}^{-\mu t} \, \mathrm{d}t = 1 - \mathrm{e}^{-\left(\frac{1}{MTTR}\right)t} \,, \tag{3.43}$$

where

$$\mu = \frac{1}{MTTR} \,,$$

$m_{\mathrm{e}}(t)$ is the maintainability function for exponential distribution.

Example 3.12

Assume that the repair times of pieces of mining equipment are exponentially distributed with a mean value (*i.e.*, MTTR) of 10 h. Calculate the probability of accomplishing a repair within 15 h.

Inserting the given data values into Eq. (3.43) we get

$$m_{\mathrm{e}}(15) = 1 - \mathrm{e}^{-\left(\frac{1}{10}\right)(15)} = 0.7769 \,.$$

Thus, there is a 77.69% chance that the mining equipment repair will be accomplished within 15 h.

3.7.2 Maintainability Function II: Weibull Distribution

In this case, times to repair are Weibull distributed and are defined by

$$f_r(t) = \frac{b}{\alpha^b} t^{b-1} \, \mathrm{e}^{-\left(\frac{t}{\alpha}\right)^b} \,, \tag{3.44}$$

where

b is the distribution shape parameter,
α is the distribution scale parameter.

Inserting Eq. (3.44) into Eq. (3.41) we get

$$m_{\mathrm{w}}(t) = \int_0^t \frac{b}{\alpha^b} t^{b-1} \mathrm{e}^{-\left(\frac{t}{\alpha}\right)^b} \mathrm{d}t = 1 - \mathrm{e}^{-\left(\frac{t}{\alpha}\right)^b} , \tag{3.45}$$

where

$m_{\mathrm{w}}(t)$ is the maintainability function for Weibull distribution.

3.8 Maintainability Design Factors and Maintainability Analysis Tools

There are numerous goals of maintainability design including increasing ease of maintenance, minimizing preventive and corrective maintenance tasks, minimizing the logistical burden through resources required for maintenance and support, and reducing support costs [5]. Thus, some of the commonly addressed maintainability design factors are accessibility, test points, controls, labeling and coding, handles, standardization, lubrication, interchangeability, modular design, ease of removal and replacement, displays, skill requirements, indication and location of failures, and safety factors [5].

Over the years, many methods have been developed for performing various types of reliability and quality analyses. These methods include failure modes and effect analysis, fault tree analysis, Markov method, total quality management, and cause and effect diagram [4, 10, 13]. The first three of these methods are described in Sect. 3.5. The remaining two (*i.e.*, total quality management and cause-and-effect diagram) are presented below.

3.8.1 Total Quality Management

This method may simply be described as a philosophy of pursuing continuous improvement in all processes through the integrated or team efforts of all personnel in an organization. Over the years, the method has proven to be an effective tool to organizations in pursuit of improving the maintainability aspect of their products. Continuous improvement and customer satisfaction are the two fundamental principles of total quality management (TQM). In addition, seven important elements of TQM are team effort, supplier participation, management commitment and leadership, statistical tools, cost of quality, customer service, and training [27].

TQM can be implemented by following the five steps listed below [10]:

- **Step 1:** Create a vision.
- **Step 2:** Plan an appropriate action.
- **Step 3:** Create an effective structure (*e.g.*, eliminate roadblocks, involve employees, create cross-functional teams, and institute training).
- **Step 4:** Measure progress through appropriate means.
- **Step 5:** Update plans and vision.

In the past, many organizations have experienced various difficulties in the implementation of TQM. These difficulties include failure of senior management to delegate decision-making authority to lower organizational levels, failure of top management to devote sufficient time to the effort, and insufficient allocation of resources for training and developing manpower [28]. Additional information on TQM is available in Ref. [28].

3.8.2 Cause and Effect Diagram

This is a deductive analysis method developed by K. Ishikawa of Japan [29], and it can be quite useful in performing maintainability analysis. The method is also known as a fishbone diagram because of its resemblance to the skeleton of a fish. The right side (*i.e.*, the fish head) of the diagram denotes the effect (*e.g.*, the problem), and to the left of this are all possible problem-related causes connected to the central fish spine.

The cause and effect diagram can be developed by following the five steps listed below.

- **Step 1:** Identify the effect to be investigated or develop a problem statement.
- **Step 2:** Brainstorm to identify problem-related causes.
- **Step 3:** Group main causes into appropriate categories and stratify them.
- **Step 4:** Construct the diagram by linking the problem-related causes under appropriate process steps and write down the effect/problem in the diagram box (*i.e.*, the fish head) on the right side.
- **Step 5:** Refine cause categories by asking questions such as “What is the real reason of the existence of this condition?” and “What causes this?”

Some of the main benefits of the cause and effect diagram are its usefulness in generating ideas, in identifying root causes of the problem, in presenting an orderly arrangement of theories, and in guiding further inquiry.

Additional information on cause and effect diagrams is available in Ref. [29].

3.9 Maintainability-Management-Related Tasks During the Equipment Life Cycle

The life cycle of a piece of equipment may be divided into four phases: concept-development phase, validation phase, production phase, and operation phase. During its life cycle, to handle maintainability issues, various types of maintainability-management-related tasks are performed. In the concept-development phase, the maintainability management tasks are basically concerned with determining the equipment effectiveness needs, in addition to determining, from the equipment's purpose and intended operation, the required field support policies and other provisions.

In the validation phase, the maintainability management tasks include developing a maintainability program plan that satisfies contractual requirements, performing maintainability allocations and predictions, coordinating and monitoring maintainability efforts throughout the organization, participating in design reviews, developing a plan for maintainability testing and demonstration, and developing a planning document for data collection, analysis, and evaluation [30].

In the production phase, the maintainability management tasks include evaluating all proposals for changes with respect to their impact on maintainability, evaluating production test trends from the standpoint of adverse effects on maintainability requirements, monitoring production processes, etc. Finally, during the operation phase, although there are no specific maintainability management tasks, the phase is probably the most significant because during this period the equipment's true logistical support and cost effectiveness are demonstrated.

3.10 Need for Safety and Safety-Related Facts and Figures

Safety has become an important issue because each year a vast number of people die and get seriously injured due to various types of accidents. For example, in 1996 in the USA alone, according to the National Safety Council (NSC), there were 93,400 deaths and a large number of disabling injuries due to accidents [31]. Other factors that also play an important role in demanding the need for better safety include public pressures, government regulations, and the increasing number of lawsuits.

Some of the important safety-related facts and figures are as follows:

- In 2000, there were approximately 97,300 unintentional injury deaths in the USA and their cost to the US economy was estimated to be approx. $512.4 million [32].
- In a typical year in the USA, approximately 35 million work-hours are lost due to accidents [33].
- In the 1990s, the average annual cost of accidents per worker in the USA was approximately $420 [11].

- Over the 40-year period 1960–2000 work-related accidental deaths in the USA dropped by 60% [34, 35].
- In 1980, employers in the USA spent approximately $22 billion to insure or self-insure against work-related injuries [36].

Additional safety-related factors and figures are available in Ref. [13].

3.11 Equipment Hazard Classifications and Common Mechanical Injuries

There are many equipment-related hazards. They may be grouped under six distinct classifications: energy hazards, kinematic hazards, electrical hazards, misuse-and-abuse-related hazards, environmental hazards, and human-factor hazards [37]. All these classifications are described in detail in Ref. [37].

Humans interact with various types of equipment in the industrial sector to perform tasks such as drilling, chipping, shaping, cutting, punching, stitching, stamping, and abrading. Past experiences indicate that various types of injuries can occur in performing such tasks. The common ones include injuries related to shearing, crushing, puncturing, breaking, straining and spraining, and cutting and tearing. Additional information on all these injuries is available in Ref. [11].

3.12 Safety Analysis Methods

Over the years, a large number of methods have been developed to perform analysis in safety and related areas [4, 13]. These methods include failure modes and effect analysis, fault tree analysis, Markov method, cause and effect diagram, hazard and operability analysis, job safety analysis, and technic of operations review. The first four of these methods are described earlier in the chapter. The remaining three methods (*i.e.*, hazard and operability analysis, job safety analysis, and technic of operations review) are presented below.

3.12.1 Hazard and Operability Analysis (HAZOP)

This method was developed for application in the chemical industry, and its fundamental objectives are as follows [11, 13, 38–41]:

- To produce a complete description of a process or facility,
- To review each process/facility element for determining how deviations from the design intentions can occur, and
- To decide whether the deviations can result in operating problems or hazards.

A HAZOP study can be conducted by following the seven steps listed below [13,40].

- **Step 1:** Select the process system to be analyzed.
- **Step 2:** Form the team of experts.
- **Step 3:** Explain the HAZOP process to all team members.
- **Step 4:** Establish goals and appropriate time schedules.
- **Step 5:** Conduct brainstorming sessions as appropriate.
- **Step 6:** Perform analysis.
- **Step 7:** Document the study.

Additional information on HAZOP is available in Refs. [11,42].

3.12.2 Job Safety Analysis

This method is used to find and rectify potential hazards that are intrinsic to or inherent in a given workplace. Generally, people who participate in performing job safety analysis are worker, supervisor, and safety professionals. Job safety analysis can be performed by following the five steps listed below [43].

- **Step 1:** Choose the job to be analyzed.
- **Step 2:** Break down the job under consideration into a number of steps/tasks.
- **Step 3:** Identify potential hazards and propose necessary actions to control them to appropriate levels.
- **Step 4:** Apply the proposed actions.
- **Step 5:** Evaluate the results.

All in all, past experience indicates that the success of this method very much depends on the degree of rigor exercised by the job safety analysis team members throughout the analysis process.

3.12.3 Technic of Operations Review (TOR)

This is basically a hands-on analytical methodology used for determining the root system causes of an operation failure. The method or methodology was developed by D.A. Weaver of the American Society of Safety Engineers (ASSE) in the early 1970s [11]. It makes use of a worksheet containing simple terms requiring yes/no decisions. The basis for the activation of TOR is an incident occurring at a specific time and place involving certain individuals. The method is composed of the following steps [11,44]:

- **Step 1:** Form the TOR team with individuals having appropriate expertise and experience.
- **Step 2:** Hold a roundtable session with all members of the team.

- **Step 3:** Identify one important factor that has been pivotal in the occurrence of an incident or accident.
- **Step 4:** Use the team consensus in responding to a sequence of yes/no options.
- **Step 5:** Evaluate identified factors as well as ensure the existence of consensus among the team members.
- **Step 6:** Prioritize contributing factors.
- **Step 7:** Develop preventive/corrective strategies with respect to each contributing factor.
- **Step 8:** Implement strategies.

Additional information on TOR is available in Refs. [11,44].

3.13 Safety Indexes

Over the years, many safety indexes have been developed to measure the safety performance of organizations. This section presents two of these safety indexes proposed by the American National Standards Institute [45].

3.13.1 Index I: Disabling Injury Frequency Rate

This index is defined by

$$DI_{\mathrm{fr}} = \frac{N(1{,}000{,}000)}{T_{\mathrm{e}}}\,, \tag{3.46}$$

where

DI_{fr} is the disabling injury frequency rate,
N is the number of disabling injuries,
T_{e} is the employee exposure time expressed in hours.

The index is based on four events (*i.e.*, deaths, permanent disabilities, permanent partial disabilities, and temporary disabilities) that occur during the period covered by the rate. Additional information on the index is available in Refs. [45,46].

3.13.2 Index II: Disabling Injury Severity Rate

This index is defined by

$$DI_{\mathrm{sr}} = \frac{d_{\mathrm{c}}(1{,}000{,}000)}{T_{\mathrm{e}}}\,, \tag{3.47}$$

where

DI_{sr} is the disabling injury severity rate,
d_{c} is the number of days charged.

The index is based on four factors [*i.e.*, total scheduled charges (days) for all deaths, permanent total disabilities, permanent partial disabilities, and the number of days of disability from all temporary injuries] occurring during the time period covered by the rate. Additional information on the index is available in Refs. [45, 46].

3.14 Problems

1. Discuss the bathtub hazard rate curve.
2. Prove Eqs. (3.7)–(3.9) using Eq. (3.3).
3. Prove Eq. (3.22).
4. Describe failure modes and effect analysis.
5. Prove that the sum of Eqs. (3.37) and (3.38) is equal to unity.
6. Prove Eq. (3.38) using Eqs. (3.35) and (3.36).
7. Define the following terms:
   - OR gate
   - AND gate
8. Define maintainability function.
9. Describe total quality management.
10. What are the common equipment-related injuries?

References

1. Layman, W.J.: Fundamental consideration in preparing a master system plan. Electric. World 101, 778–792 (1933)
2. Smith, S.A.: Service reliability measured by probabilities of outage. Electric. World 103, 371–374 (1934)
3. Dhillon, B.S.: Power System Reliability, Safety, and Management. Ann Arbor Science Publishers, Ann Arbor, MI (1983)
4. Dhillon, B.S.: Design Reliability: Fundamentals and Applications. CRC, Boca Raton, FL (1999)
5. AMCP706-133, Engineering Design Handbook: Maintainability Engineering Theory and Practice, US Department of Defense, Washington, DC (1976)
6. Akenbrandt, F.L. (ed.): Electronic Maintainability. Engineering Publishers, Elizabeth, NJ (1960)
7. MIL-STD-470, Maintainability Program Requirements, US Department of Defense, Washington, DC (1966)
8. MIL-HDBK-472, Maintainability Prediction, US Department of Defense, Washington, DC (1966)
9. Retterer, B.L., Kowalski, R.A.: Maintainability: a historical perspective. IEEE Trans. Reliabil. 33, 56–61 (1984)
10. Dhillon, B.S.: Engineering Maintainability. Gulf, Houston, TX (1999)
11. Goetsch, D.L.: Occupational Safety and Health. Prentice-Hall, Englewood Cliffs, NJ (1996)
12. Heinrich, H.W.: Industrial Accident Prevention, 3rd edn. McGraw-Hill, New York (1950)

13. Dhillon, B.S.: Engineering Safety: Fundamentals, Techniques, and Applications. World Scientific, River Edge, NJ (2003)
14. Kapur, K.C.: Reliability and maintainability. In: Salvendy, G. (ed.) Handbook of Industrial Engineering. Wiley, New York, pp. 8.5.1–8.5.34 (1982)
15. Dhillon, B.S.: Mechanical Reliability: Theory, Models, and Applications, American Institute of Aeronautics and Astronautics, Washington, DC (1988)
16. Lipp, J.P.: Topology of Switching Elements vs. Reliability. IRE Reliabil. Qual. Control 7, 21–34 (1957)
17. Elsayed, E.A.: Reliability Engineering. Addison Wesley Longman, Reading, MA (1996)
18. Ramakumar, R.: Engineering Reliability: Fundamentals and Applications. Prentice-Hall, Englewood Cliffs, NJ (1993)
19. Dhillon, B.S.: Advanced Design Concepts for Engineers. Technomic, Lancaster, PA (1998)
20. Countinho, J.S.: Failure effect analysis. Trans. N.Y. Acad. Sci. 26, 564–584 (1964)
21. Shooman, M.L.: Probabilistic Reliability: An Engineering Approach. McGraw-Hill, New York (1968)
22. Vesley, W.E., Goldberg, F.F., Roberts, N.H., Haasal, D.F.: Fault Tree Handbook, Report No. NUREG-0492, US Nuclear Regulatory Commission, Washington, DC (1981)
23. Latino, C.J.: Hidden Treasure: Eliminating Chronic Failures Can Cut Maintenance Costs Up to 60%, Report, Reliability Center, Hopewell, VA (1999)
24. AMCP-706-134, Engineering Design Handbook: Maintainability Guide for Design, US Department of Defense, Washington, DC (1972)
25. Blanchard, B.S., Verma, D., Peterson, E.L.: Maintainability. Wiley, New York (1995)
26. Von Alven, W.H. (ed.): Reliability Engineering. Prentice-Hall, Englewood Cliffs, NJ (1964)
27. Burati, J.L., Matthews, M.F., Kalidindi, S.N.: Quality management organizations and techniques. J. Construct. Eng. Manage. 118, 112–128 (1992)
28. Gevirtz, C.D.: Developing New Products with TQM. McGraw-Hill, New York (1994)
29. Ishikawa, K.: Guide to Quality Control. Asian Productivity Organization, Tokyo, 1976.
30. Dhillon, B.S., Reiche, H.: Reliability and Maintainability Management. Van Nostrand Reinhold, New York (1985)
31. Accident Facts, Report, National Safety Council, Chicago (1996)
32. Report on Injuries in America 2000, National Safety Council, Chicago (2000)
33. Accident Facts, National Safety Council, Chicago (1990–1993)
34. Report on Injuries in America, National Safety Council, Chicago (2001)
35. Blake, R.P. (ed.): Industrial Safety. Prentice-Hall, Englewood Cliffs, NJ (1964)
36. Lancianese, F.: The soaring costs of industrial accidents. Occupat. Hazards pp. 30–35 (August 1983)
37. Hunter, T.A.: Engineering Design for Safety. McGraw-Hill, New York (1992)
38. Guidelines for Hazard Evaluation Procedures, American Institute of Chemical Engineers, New York (1985)
39. Dhillon, B.S., Rayapati, S.N.: Chemical systems reliability: a survey. IEEE Trans. Reliabil. 37, 199–208 (1988)
40. Roland, H.E., Moriarty, B.: System Safety Engineering and Management. Wiley, New York (1983)
41. Gloss, D.S., Wardle, M.G.: Introduction to Safety Engineering. Wiley, New York (1984)
42. Risk Analysis Requirements and Guidelines, Report No. CAN/CSA-Q634-91, prepared by the Canadian Standards Association, 1991. Available from the Canadian Standards Association, 178 Rexdale Boulevard, Rexdale, Ontario, Canada
43. Hammer, W., Price, D.: Occupational Safety Management and Engineering. Prentice-Hall, Upper Saddle River, NJ (2001)
44. Hallock, R.G.: Technic of operations review analysis: determine cause of accident/incident. Safety Health 60, 38–39, 46 (August 1991)
45. Z-16.1, Method of Recording and Measuring Work Injury Experience, American National Standards Institute, New York (1985)
46. Tarrants, W.E.: The Measurement of Safety Performance. Garland STPM, New York (1980)