4 Methods for Performing Human Reliability and Error Analysis in Engineering Maintenance

4.1 INTRODUCTION

Today, quality, human factors, safety, and reliability are recognized as well-established disciplines. Over the years, many new concepts and methods have been developed in these areas. Many of the methods are being applied quite successfully across many diverse areas including engineering design, production, maintenance, management, and health care. Two important examples of these methods are failure modes and effect analysis (FMEA) and fault tree analysis (FTA).

FMEA was developed by the United States Department of Defense in the early 1950s for analyzing engineering systems from the reliability aspect. Nowadays, FMEA is being used across many diverse areas including maintenance, management, and health care [1–3]. FTA was developed in the early 1960s at the Bell Telephone Laboratories to perform safety and reliability analysis of the Minuteman Launch Control System [3–5]. This method has rapidly gained favor over other reliability and safety analysis methods because of its versatility in degree of detail of complex systems. Today, FTA is being used widely in the industrial sector to analyze problems ranging from management-related to engineering-related.

This chapter presents a number of methods considered useful for performing human reliability and error analysis in engineering maintenance, extracted from the published literature in the areas of quality, human factors, safety, and reliability.

4.2 FAILURE MODES AND EFFECT ANALYSIS (FMEA)

FMEA may simply be described as a powerful method widely used to analyze each potential failure mode in the system under consideration for determining the effects of such modes on the total system [6]. In the event when FMEA is extended to classify each and every potential effect according to its severity, it is called failure mode effects and criticality analysis (FMECA) [7].

The history of FMEA may be traced back to the early 1950s when the United States Navy's Bureau of Aeronautics used it in the design and development of flight control systems [1, 8]. The following main steps are used in performing FMEA [7]:

- **Step 1: Establish system definition.** This is basically concerned with decomposing the system into main blocks and defining their functions, in addition to defining the interface between blocks.
- **Step 2: Establish appropriate ground rules.** This is concerned with formulating the ground rules for performing FMEA. Some examples of these rules are limits of operational stress, statement of primary and secondary mission objectives, delineation of mission phases, limits of environmental stress, and analysis level statement.
- **Step 3: Describe the system and its associated functional blocks.** This is concerned with preparing the description of the system under consideration. This description is normally grouped under two parts:
  - **System block diagram.** This graphically shows the system elements to be analyzed, the system inputs and outputs, series and redundant relationships among the system components/parts, and inputs and outputs of system components.
  - **Functional statement.** This is developed for the total system and for each subsystem and part. The statement is prepared for each operational mode/phase of each item. The degree of detail depends on factors such as the application of the item under consideration and the uniqueness of the function performed.
- **Step 4: Identify possible failure modes and their effects.** This is concerned with systematically identifying the failure modes and their effects. Usually, this is accomplished by using a well-designed worksheet or a form. The worksheet collects data on various areas including item identification and function, failure modes and causes, failure detection approach, failure effects on system/personnel/mission/subsystems, and criticality classification.
- **Step 5: Compile a list of critical items.** This is concerned with developing a list of critical items for providing useful input to sound management decisions. The list contains information on various areas including item identification, concise statement of item's failure mode, classification of criticality, the FMEA worksheet page number, degree of loss effect, and retention rationale.
- **Step 6: Document the analysis.** This is the final step and is concerned with the documentation of analysis. The final document includes items such as system definition and description, ground rules of FMEA, failure modes and their effects, and critical items list.

Some of the important characteristics of the FMEA are as follows:

- By evaluating failure effects of each part, the entire system is screened completely.
- It improves communication quite significantly among individuals involved in the design interface activity.
- It is a routine upward approach that starts from the detail level.

- It highlights weak spots in system design and identifies areas where detailed analysis is necessary.

Additional information on this method is available in Refs. [3, 9].

4.3 MAN–MACHINE SYSTEMS ANALYSIS

This is probably the first method ever developed for reducing human error-caused unwanted effects to some acceptable level, in a system. It was developed in the early 1950s at the Wright-Patterson Air Force Base, United States Air Force, Ohio [10]. The method is composed of the following steps [10].

- **Step 1:** Define the system goals and the associated functions.
- **Step 2:** Define all the situational characteristics; more specifically, the performance shaping factors under which humans will be performing their tasks. Some examples of these factors are quality of air, illumination, and union actions.
- **Step 3:** Define the characteristics (e.g., experience, skills, training, and motivation) of all involved individuals.
- **Step 4:** Define the tasks performed by all involved individuals.
- **Step 5:** Analyze tasks to identify potential error-likely conditions and other associated difficulties.
- **Step 6:** Estimate the chances/other information in regard to the occurrence of each and every potential human error.
- **Step 7:** Estimate the chances that each potential error will remain undetected and uncorrected.
- **Step 8:** Determine the type of consequences if potential human errors remain undetected.
- **Step 9:** Make necessary recommendations for required changes.
- **Step 10:** Reevaluate with care each change by repeating most of the above steps as considered appropriate.

Additional information on this method is available in Ref. [10].

4.4 ROOT CAUSE ANALYSIS (RCA)

RCA may be described as a systematic investigation method that uses data collected during an assessment of an accident, for determining the underlying causes for the deficiencies that led to the occurrence of the accident [11]. As per Ref. [12], RCA was originally developed by the United States Department of Energy.

RCA begins with outlining the event sequence that led to the accident. Starting with the adverse event itself, the analyst involved conducts his or her tasks backward in time, by recording and ascertaining all important events. In collecting such data, it is important for the analyst concerned to avoid making any premature judgment, blame, and attribution, but to specifically focus on the incident-related facts with

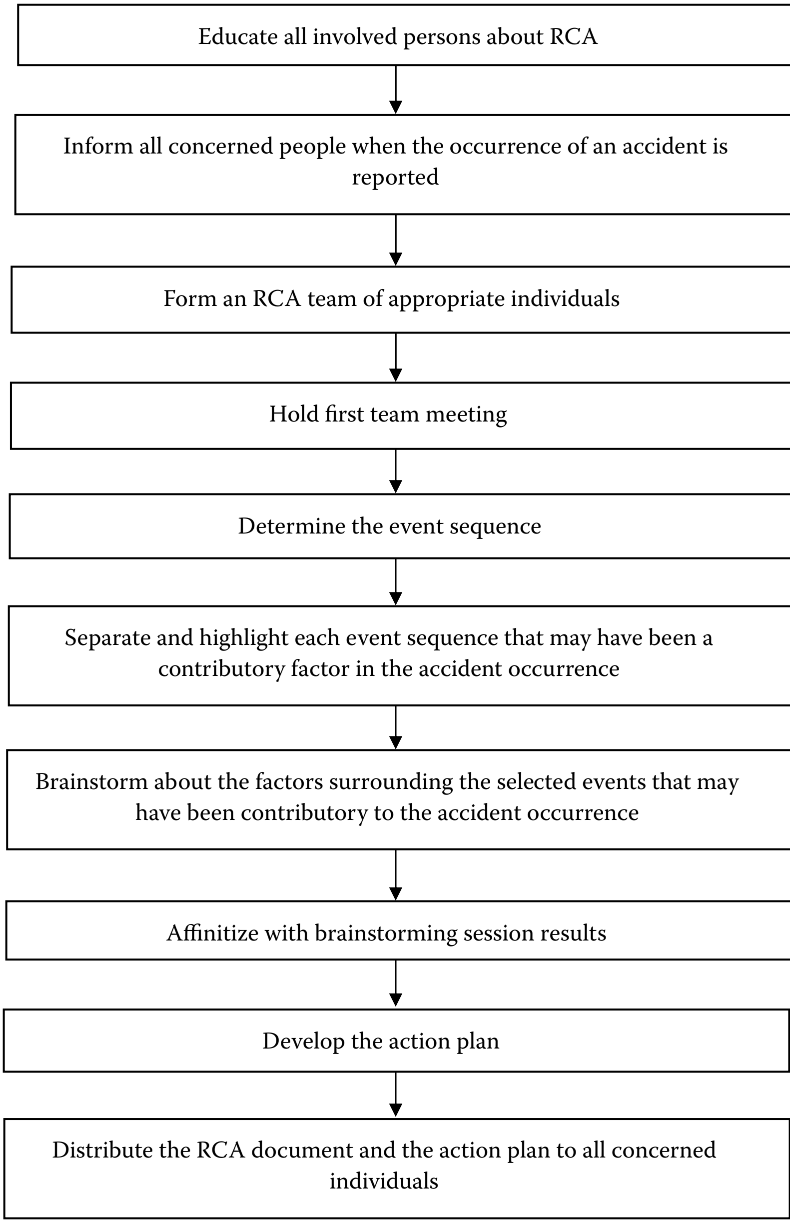

FIGURE 4.1 General steps for performing RCA.

utmost care. Thus, the clearly defined actions leading to an event will be very helpful to the investigation team members to ask a question with confidence: Why did it (event) occur? [13].

General steps for performing RCA are shown in Figure 4.1 [14]. Additional information on RCA is available in Refs. [14, 15].

4.5 ERROR-CAUSE REMOVAL PROGRAM (ECRP)

This method was developed specifically for reducing the occurrence of human errors in production operations. The emphasis of the method is on preventive measures rather than merely on remedial ones. Nonetheless, ECRP may simply be described as the production worker participation program to reduce the occurrence of human errors.

The workers who participate in the program include assembly personnel, machinists, inspection personnel, maintenance workers, and so on [16]. All these workers are grouped under various teams and each team has its own coordinator. The maximum size of the team is twelve workers. Team meetings are held periodically, during which the workers present their error and error-likely reports. The team recommendations are presented to the management for remedial or preventive measures. Usually, teams and management are assisted by various specialists including human factors specialists.

The basic elements of the ECRP are as follows [16, 17]:

- Production workers report and determine errors and error occurrence-likely situations and propose design-related solutions to eradicate error causes.
- Human factors and other specialists evaluate proposed design solutions with respect to cost.
- All people involved with ECRP are educated about its usefulness.
- Management implements the most promising proposed design solutions and recognizes production workers' efforts in an appropriate manner.
- Each worker and team coordinator is properly trained in data collection and analysis approaches.
- The effects of the changes made to the production process are evaluated by human factors and other specialists, with the aid of the ECRP inputs.

Additional information on ECRP is available in Refs. [16, 17].

4.6 CAUSE-AND-EFFECT DIAGRAM (CAED)

This method was developed by a Japanese man named K. Ishikawa in the early 1950s. Occasionally CAED is also called an Ishikawa diagram or a "fishbone diagram" because of its resemblance to the skeleton of a fish as shown in Figure 4.2. As shown in the figure, the extreme right-hand side of the diagram (i.e., box or the fish head) represents the effect and the left-hand side represents all the possible causes that are linked to the central line known as the "fish spine."

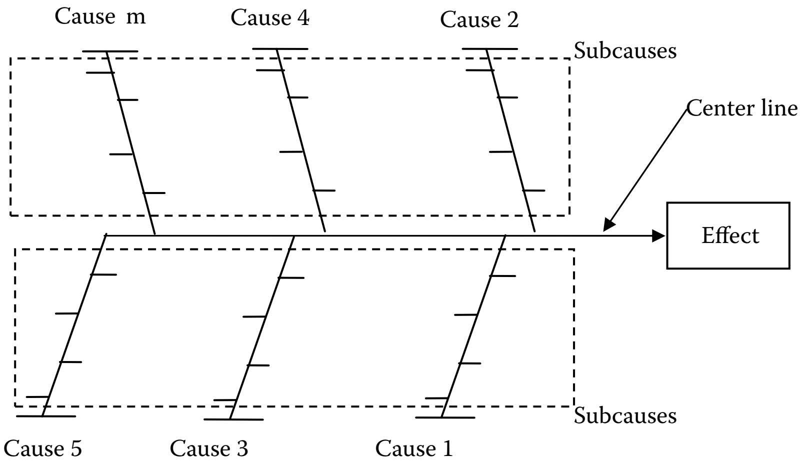

FIGURE 4.2 A cause-and-effect diagram with *m* causes.

In maintenance work, CAED could be a valuable tool to determine the root causes of a given human error-related problem.

The following main steps are used to develop a CAED [18, 19]:

- **Step 1:** Develop problem statement.
- **Step 2:** Brainstorm to identify all possible causes.
- **Step 3:** Develop main cause classifications by stratifying them into natural groups and process steps.
- **Step 4:** Develop the diagram by connecting all the identified causes by following appropriate process steps and fill in the problem or the effect in the diagram box (i.e., the fish head) on the extreme right.
- **Step 5:** Refine the cause classifications by asking questions such as follows:
  - What causes this?
  - What is the real reason for the existence of this condition?

Some of the main benefits of the CAED are that it is a valuable tool to produce ideas, useful to identify root causes, useful to guide further inquiry, and a useful tool for presenting an orderly arrangement of theories [18, 19]. Additional information on CAED is available in Refs [18, 19].

4.7 PROBABILITY TREE METHOD

This method is used to perform task analysis by diagrammatically representing important human actions and other related events. Often, the method is used to perform tasks analysis in the technique for the human error rate prediction (THERP) [20]. In this method, the branches of the probability tree represent diagrammatic task analysis. More specifically, the tree's branching limbs represent the outcome (i.e., success or failure) of each event, and each branch is assigned an appropriate occurrence probability.

Some of the important benefits of the method are as follows [20]:

- A useful visibility tool
- Simplified mathematical computations
- Possesses a good flexibility for incorporating (i.e., with some modifications) factors such as interaction effects, emotional stress, and interaction stress

Additional information on the method is available in Refs. [17, 20]. The following example demonstrates the application of the method.

Example 4.1

A maintenance worker performs three independent tasks: x, y, and z. Task x is performed before task y and task y before task z. Each of these three tasks can be performed either correctly or incorrectly. Develop a probability tree and obtain an expression for the probability of not successfully accomplishing the overall mission by the maintenance worker. In addition, calculate the probability of not successfully accomplishing the overall mission by the maintenance worker if the probabilities of performing tasks x, y, and z successfully are 0.8, 0.9, and 0.95, respectively.

In this case, the maintenance worker first performs task x correctly or incorrectly and then proceeds to perform task y. Task y can also be performed correctly or incorrectly. After task y, the worker proceeds to perform task z. This task can also be performed correctly or incorrectly by the maintenance worker. This complete scenario is depicted by Figure 4.3.

The symbols used in Figure 4.3 are defined below.

x denotes the event that task x is performed successfully.
y denotes the event that task y is performed successfully.
z denotes the event that task z is performed successfully.
$\bar{x}$ denotes the event that task x is performed incorrectly.
$\bar{y}$ denotes the event that task y is performed incorrectly.
$\bar{z}$ denotes the event that task z is performed incorrectly.

By examining the diagram, it can be concluded that there are seven distinct possibilities (i.e., $xy\bar{z}, x\bar{y}z, x\bar{y}\bar{z}, \bar{x}yz, \bar{x}y\bar{z}, \bar{x}\bar{y}z, \textit{and } \bar{x}\bar{y}\bar{z}$) for not successfully accomplishing the overall mission by the maintenance worker. Thus, the probability of not successfully accomplishing the overall mission by the maintenance worker is expressed by

$$\begin{aligned} P_{ns} &= P(xy\bar{z} + \bar{x}yz + \bar{x}y\bar{z} + \bar{x}\bar{y}z + x\bar{y}z + x\bar{y}\bar{z} + \bar{x}\bar{y}\bar{z}) \\ &= P_x P_y P_{\bar{z}} + P_{\bar{x}} P_y P_z + P_{\bar{x}} P_y P_{\bar{z}} + P_{\bar{x}} P_{\bar{y}} P_z + P_x P_{\bar{y}} P_z + P_x P_{\bar{y}} P_{\bar{z}} + P_{\bar{x}} P_{\bar{y}} P_{\bar{z}} \end{aligned} \tag{4.1}$$

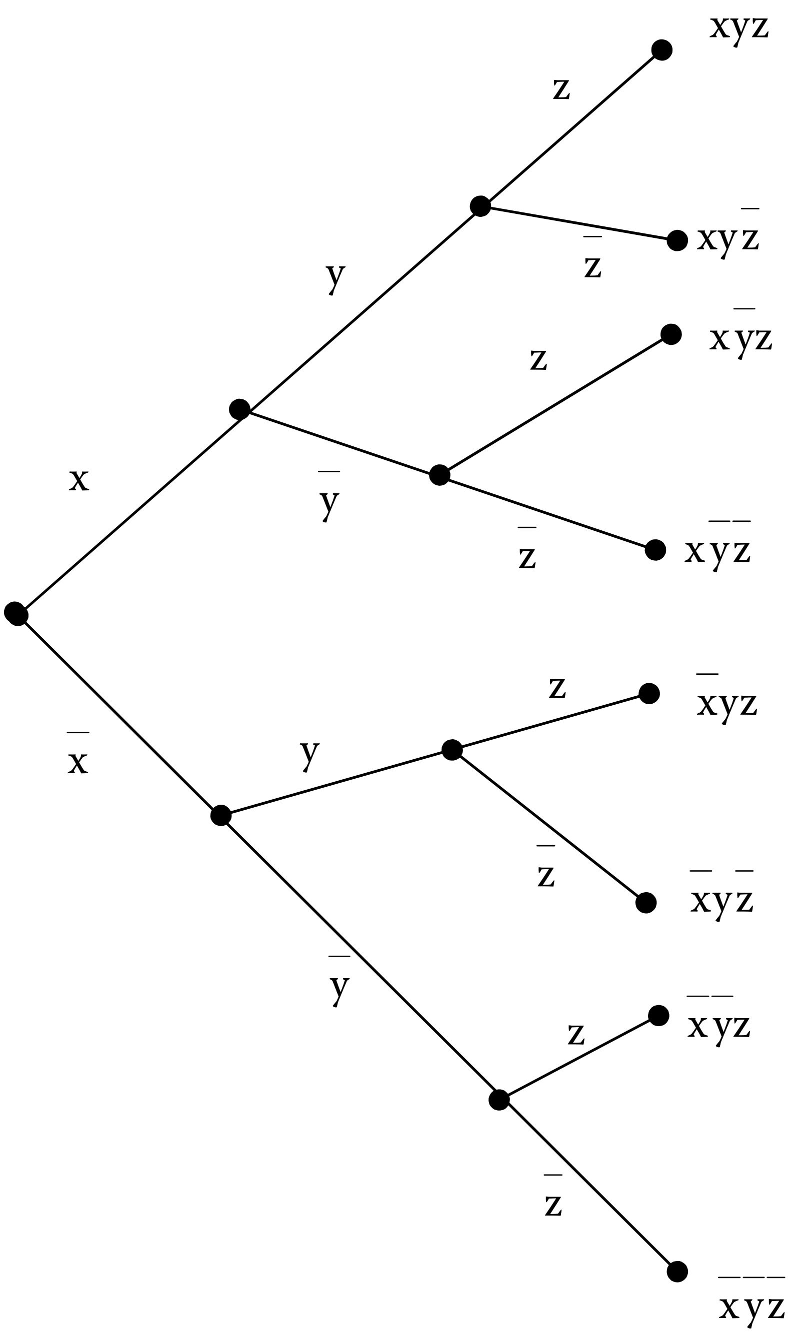

FIGURE 4.3 Probability tree for the maintenance worker performing tasks *x*, *y*, and *z*.

where

P_{ns} is the probability of not successfully accomplishing the overall mission by the maintenance worker.
P_x is the probability of performing task x correctly by the maintenance worker.
P_y is the probability of performing task y correctly by the maintenance worker.
P_z is the probability of performing task z correctly by the maintenance worker.
$P_{\bar{x}}$ is the probability of performing task x incorrectly by the maintenance worker.
$P_{\bar{y}}$ is the probability of performing task y incorrectly by the maintenance worker.
$P_{\bar{z}}$ is the probability of performing task z incorrectly by the maintenance worker.

Because $P_{\bar{x}} = 1 - P_x$, $P_{\bar{y}} = 1 - P_y$, and $P_{\bar{z}} = 1 - P_z$, by substituting the given data values into Equation (4.1), we get

$$\begin{aligned} P_{ns} &= (0.8)(0.9)(1-0.95) + (1-0.8)(0.9)(0.95) + (1-0.8)(0.9)(1-0.95) \\ &\quad + (1-0.8)(1-0.9)(0.95) + (0.8)(1-0.9)(0.95) + (0.8)(1-0.9)(1-0.95) \\ &\quad + (1-0.8)(1-0.9)(1-0.95) \\ &= 0.036 + 0.17 + 0.009 + 0.019 + 0.076 + 0.004 + 0.01 \\ &= 0.316 \end{aligned}$$

Thus, the probability of not successfully accomplishing the overall mission by the maintenance worker is 0.316.

4.8 FAULT TREE ANALYSIS (FTA)

This is a widely used method in the industrial sector for evaluating engineering systems during their design and development phase from reliability and safety aspects. The method was developed in the early 1960s at the Bell Telephone Laboratories by H. A. Watson to perform reliability/safety analysis of the Minuteman Launch Control System [4, 5].

A fault tree may simply be described as a logical representation of the relationship of basic events that lead to a defined undesirable event known as the "top event" and is depicted using a tree structure with logic gates such as AND and OR.

4.8.1 Fault Tree Symbols

There are many symbols used to construct fault trees of engineering systems. Four of these symbols are shown in Figure 4.4.

The AND gate means that an output fault event occurs only if all the input fault events occur. The OR gate means that an output fault event occurs if one or more input fault events occur. A rectangle represents a fault event that results from the logical combination of fault events through the input of a logic gate such as OR and AND.

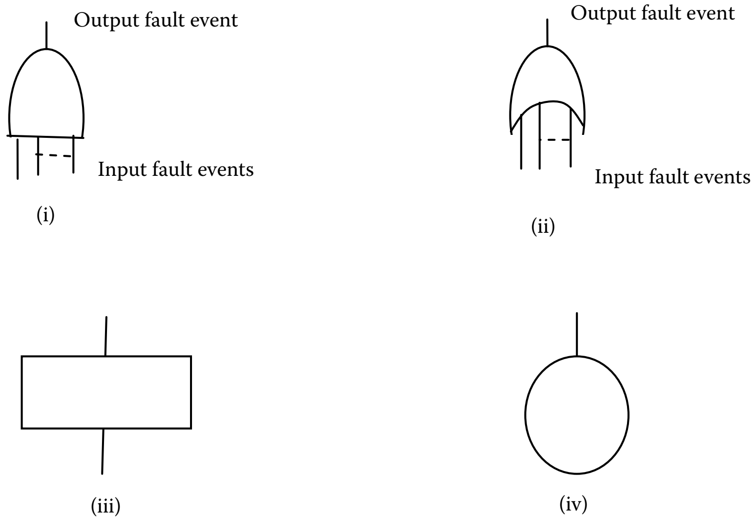

FIGURE 4.4 Four commonly used fault tree symbols: (i) AND gate, (ii) OR gate, (iii) rectangle, (iv) circle.

Finally, a circle denotes a basic fault event or the failure of an elementary part. The fault event's probability of occurrence, failure rate, and repair rate are normally obtained from empirical data. A comprehensive list of fault tree symbols is available in Ref. [21].

4.8.2 Steps for Performing FTA

Usually, the seven steps shown in Figure 4.5 are used to perform FTA [22].

Example 4.2

After a careful study of a task being performed by a maintenance worker, it was concluded that he or she can commit an error due to five factors: poor training, inadequate tools, poor instructions, poor environment, or carelessness. Two principal reasons for the poor environment are poor illumination or high noise level. Similarly, two main causes for the poor instructions are poor verbal instructions or poorly written maintenance procedures. Develop a fault tree for the top event "Maintenance worker committed an error" by using the fault tree symbols shown in Figure 4.4.

A fault tree for the example is shown in Figure 4.6. The single capital letters in the diagram denote corresponding fault events (e.g., M: poor environment, N: poor instructions, and A: poor illumination).

4.8.3 Probability Evaluation of Fault Trees

When the probability of occurrence of basic fault events (e.g., events in circles in Figure 4.6) is given, the probability of occurrence of the top event (e.g., event T in

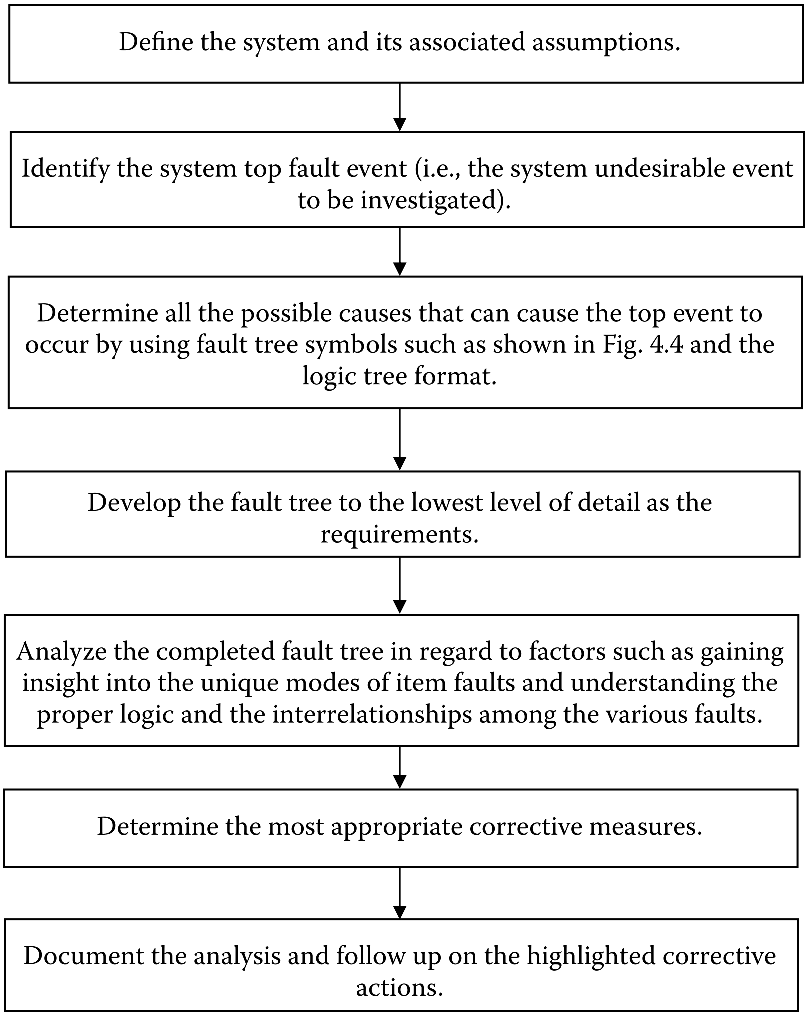

FIGURE 4.5 Steps for performing fault tree analysis (FTA).

Figure 4.6) can be calculated. This can only be calculated by first calculating the probability of occurrence of the output fault events of all the lower and intermediate logic gates (e.g., AND and OR gates).

Thus, the probability of occurrence of the AND gate output fault event, A, is given by [3]

$$P(A) = \prod_{i=1}^{n} P(A_i) \tag{4.2}$$

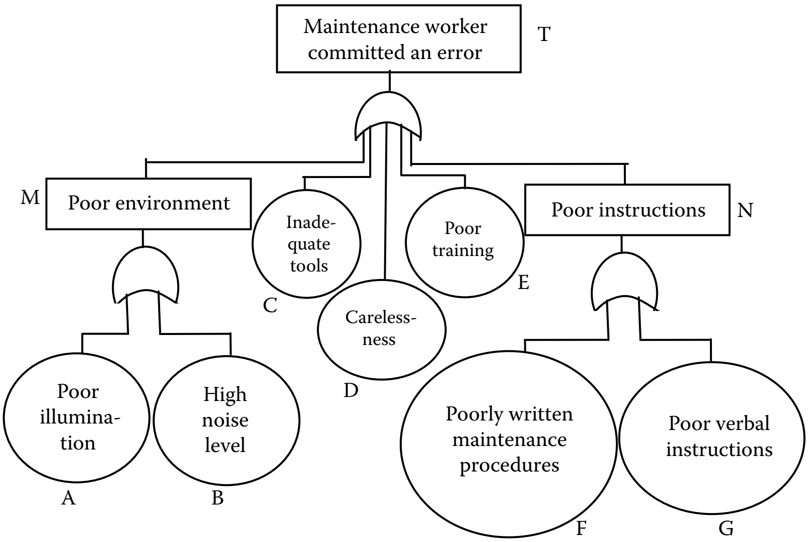

FIGURE 4.6 A fault tree for Example 4.1.

where $P(A)$ is the probability of occurrence of the AND gate output fault event, A; n is the number of AND gate input fault events; and $P(A_i)$ is the occurrence probability of the AND gate input fault event A_i, for $i = 1, 2, 3, n$.

Similarly, the probability of occurrence of the OR gate output fault event, B, is given by [3]

$$P(B) = 1 - \prod_{i=1}^{k} \{1 - P(B_i)\} \tag{4.3}$$

where $P(B)$ is the probability of occurrence of the OR gate output fault event, B; k is the number of OR gate input fault events; and $P(B_i)$ is the occurrence probability of the OR gate input fault event B_i, for $i = 1, 2, 3, k$.

Example 4.3

Assume that the occurrence probabilities of events A, B, C, D, E, F, and G in Figure 4.6 are 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, and 0.09, respectively. Calculate the probability of occurrence of the top event T: maintenance worker committed an error.

By substituting the specified occurrence probability values of the events A and B into Equation (4.3), the probability of the occurrence of event M (i.e., poor environment) is

$$\begin{aligned} P(M) &= 1 - (1 - 0.03)(1 - 0.04) \\ &= 0.0688 \end{aligned}$$

Similarly, by substituting the given occurrence probability values of the events F and G into Equation (4.3), the probability of the occurrence of event N (i.e., poor instructions) is

$$P(N) = 1 - (1 - 0.08)(1 - 0.09)$$
$$= 0.1628$$

By substituting the above two calculated values and the given data values into Equation (4.3), we get

$$P(T) = 1 - (1 - 0.0688)(1 - 0.05)(1 - 0.06)(1 - 0.07)(1 - 0.1628)$$
$$= 0.6474$$

where $P(T)$ is the probability of occurrence of the top event T.

Thus, the probability of occurrence of the top event T: maintenance worker committed an error is 0.6474.

4.9 MARKOV METHOD

This is a widely used method in the industrial sector to perform various types of reliability-related studies and is named after the Russian mathematician Andrei Andreyevich Markov (1856–1922). The method is considered quite useful to perform human reliability and error analysis [17]. The following assumptions are associated with the method [22]:

- All occurrences are independent of each other.
- The probability of occurrence of a transition from one state to another in the finite time interval Δt is given by $\alpha\Delta t$, where α is the constant transition rate (e.g., human error rate) from one state to another.
- The transitional probability of two or more occurrences in the finite time interval Δt from one state to another is negligible (e.g., $(\alpha\Delta t)\,(\alpha\Delta t) \to 0$).

The following example demonstrates the application of the Markov method, in performing human reliability and error analysis in engineering maintenance.

Example 4.4

A maintenance worker is performing a maintenance task on a system used in nuclear power generation. He or she makes errors at a constant rate, α. This scenario is described in more detail by the state space diagram shown in Figure 4.7. The numerals in the circle and box denote system states.

Develop expressions for the maintenance worker's reliability and unreliability at time t and mean time to human error by using the Markov method.

Using the Markov method, we write down the following equations for the diagram [17, 22]:

$$P_0(t + \Delta t) = P_0(t)(1 - \alpha\Delta t) \tag{4.4}$$

$$P_1(t + \Delta t) = P_1(t) + P_0(t)(\alpha\,\Delta t) \tag{4.5}$$

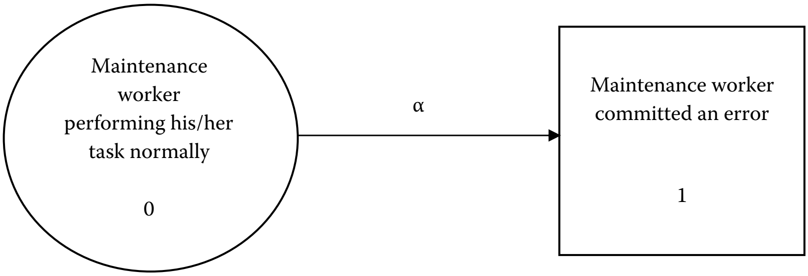

FIGURE 4.7 State space diagram representing the maintenance worker.

where

t is time.

α is the constant error rate of the maintenance worker.

$\alpha \Delta t$ is the probability of human error by the maintenance worker in finite time interval Δt.

$(1 - \alpha \Delta t)$ is the probability of no human error by the maintenance worker in finite time interval Δt.

i is the ith state of the maintenance worker; $i = 0$ means that the maintenance worker is performing his or her task normally, $i = 1$ means that the maintenance worker has committed an error.

$P_i(t)$ is the probability that the maintenance worker is in state i at time t, for $i = 0, 1$.

$P_i(t + \Delta t)$ is the probability that the maintenance worker is in state i at time $(t + \Delta t)$, for $i = 0, 1$.

By rearranging Equations (4.4) and (4.5) and taking the limit as $\Delta t \to 0$, we obtain

$$\lim_{\Delta t \to 0} \frac{P_0(t + \Delta t) - P_0(t)}{\Delta t} = -\alpha P_0(t) \tag{4.6}$$

$$\lim_{\Delta t \to 0} \frac{P_1(t + \Delta t) - P_1(t)}{\Delta t} = \alpha P_0(t) \tag{4.7}$$

Thus, from Equations (4.6) and (4.7), we get

$$\frac{dP_0(t)}{dt} + \alpha P_0(t) = 0 \tag{4.8}$$

$$\frac{dP_1(t)}{dt} - \alpha P_0(t) = 0 \tag{4.9}$$

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

By solving Equations (4.8) and (4.9), we obtain

$$P_0(t) = e^{-\alpha t} \tag{4.10}$$

$$P_1(t) = 1 - e^{-\alpha t} \tag{4.11}$$

Thus, expressions for the maintenance worker's reliability and unreliability are given by

$$R_{mw}(t) = P_0(t) = e^{-\alpha t} \tag{4.12}$$

and

$$UR_{mw}(t) = P_1(t) = 1 - e^{-\alpha t} \tag{4.13}$$

where $R_{mw}(t)$ is the maintenance worker's reliability at time t and $UR_{mw}(t)$ is the maintenance worker's unreliability at time t.

The maintenance worker's mean time to human error is given by [17]

$$\begin{aligned} MTTHE_{mw} &= \int_0^\infty R_{mw}(t)dt \\ &= \int_0^\infty e^{-\alpha t} dt \\ &= \frac{1}{\alpha} \end{aligned} \tag{4.14}$$

where $MTTHE_{mw}$ is the maintenance worker's mean time to human error.

Thus, expressions for the maintenance worker's reliability and unreliability at time t and mean time to human error are given by Equations (4.12), (4.13), and (4.14), respectively.

Example 4.5

A maintenance worker's constant error rate is 0.0009 errors/hour. Calculate his or her unreliability for an 8-hour mission and mean time to human error.

By substituting the specified data values into Equations (4.13) and (4.14), we get

$$\begin{aligned} UR_{mw}(8) &= 1 - e^{-(0.0009)(8)} \\ &= 0.0072 \end{aligned}$$

and

$$\begin{aligned} MTTHE_{mw} &= \frac{1}{(0.0009)} \\ &= 1111.1 \text{ hours} \end{aligned}$$

Thus, the maintenance worker's unreliability and mean time to human error are 0.0072 and 1111.1 hours, respectively.

4.10 PROBLEMS

1. Discuss at least three important characteristics of failure modes and effect analysis.
2. Describe man-machine systems analysis.
3. Compare failure modes and effect analysis with root cause analysis.
4. What are the basic elements of the error-cause removal program?
5. Describe the cause-and-effect diagram. What are its main benefits?
6. A maintenance worker performs two independent tasks: C and D. Task C is performed before task D, and each of these two tasks can be performed either correctly or incorrectly. Develop a probability tree and obtain an expression for the probability of not successfully accomplishing the overall mission by the maintenance worker.
7. What are the main steps for performing fault tree analysis?
8. Describe the following two terms:
   - AND gate
   - OR gate
9. What are the assumptions associated with the Markov method?
10. Prove Equations (4.10) and (4.11) by using Equations (4.8) and (4.9).

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