5 Human Error in Maintenance

5.1 INTRODUCTION

Humans play a pivotal role during system/equipment design, production, operation, and maintenance phases. Although the degree of their role may vary from one phase to another, their interactions are subject to deterioration because of human error. Human error may simply be described as the failure to carry out a given task (or the performance of a forbidden action) that could result in disruption of scheduled operations or damage to equipment and property [1–3].

The occurrence of human error in the maintenance activity can impact equipment performance and safety in various ways. For example, poor repairs can play an instrumental role in increasing the number of equipment breakdowns, which in turn can significantly increase the risk associated with equipment failures and the occurrence of personal accidents [4]. Maintenance error is basically due to wrong preventive actions or repairs, and usually the occurrence of maintenance error increases as the equipment/system ages because of the increase in maintenance frequency.

This chapter presents various important aspects of human error in maintenance.

5.2 FACTS, FIGURES, AND EXAMPLES

Some of the facts, figures, and examples, directly or indirectly, concerned with human error in maintenance are as follows:

- Over 50% of all equipment fail prematurely after the performance of maintenance work [5].
- A study of electronic equipment reported that around 30% of failures were the result of operation and maintenance error [6].
- In 1988, 30 people died and 69 were injured seriously at the Clapham Junction Railway accident in the United Kingdom due to a maintenance error in wiring [7].
- In 1989, the explosion at the Phillips 66 Houston Chemical Complex in Pasadena, Texas, was the result of a maintenance error [8].
- In 1993, a study of 122 maintenance-related occurrences classified maintenance error under four distinct categories: wrong installations (30%), omissions (56%), wrong parts (8%), and miscellaneous (6%) [9, 10].
- A study of an incident that involved the blowout preventer (assembly of valves) at the Ekofisk oil field in the North Sea reported that the incident

was caused by the upside-down installation of the device. The total cost of the incident was estimated to be approximately $50 million [11].

- A study of maintenance tasks such as remove, adjust, and align reported a human reliability mean of 0.9871 [12]. It simply means that management should expect human errors by people involved with the maintenance activity on the order of 13 times in 1000 attempts [11].
- A study of maintenance-related errors in missile operations reported a number of causes: wrong installation (28%), dials and controls (misread, misset) (38%), loose nuts/fittings (14%), inaccessibility (3%), and miscellaneous (17%) [11, 13].

5.3 OCCURRENCE OF MAINTENANCE ERROR IN EQUIPMENT LIFE CYCLE AND ELEMENTS OF A MAINTENANCE PERSON'S TIME

The occurrence of maintenance error during the system/equipment life cycle (i.e., from the time of system/equipment acceptance to the beginning of its phase-out period) is an important factor. Approximate breakdowns of the occurrence of human error in a system/equipment life cycle are shown in Figure 5.1 [11, 14].

A good understanding of time spent by maintenance personnel in performing various maintenance tasks can be quite useful to analyze the occurrence of maintenance errors. Various studies performed over the years indicate that most of their time is spent in the area of fault diagnosis. However, according to one study [11], the maintenance person's time in the area of electronic equipment can be classified

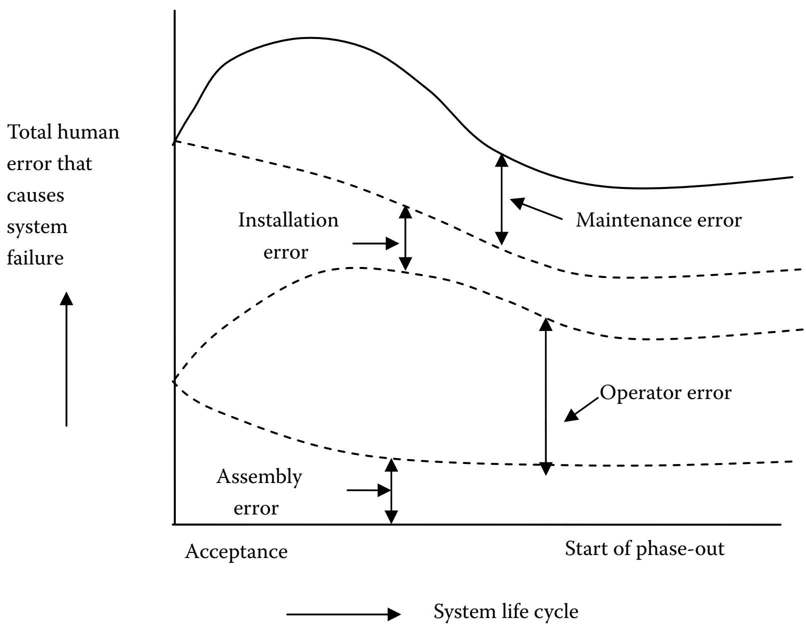

FIGURE 5.1 System life cycle versus four types of human error that cause system failure.

under three categories: diagnosis, remedial actions, and verification. The percentage breakdowns of the time for these three categories are as follows [11]:

- Diagnosis: 65–75%
- Remedial actions: 15–25%
- Verification: 5–15%

5.4 MAINTENANCE ENVIRONMENT AND CAUSES FOR THE OCCURRENCE OF MAINTENANCE ERRORS

As maintenance personnel work directly on equipment, the location of equipment and its design features directly dictate many of the parameters of their work environment. Maintenance environments are susceptible to factors such as noise, poor illumination, and temperature variations. Each of these three factors is described below, separately [15].

5.4.1 Noise

Maintenance environments can be quite noisy as many are not properly sound-controlled. Ambient noise from ongoing activities can interfere with maintenance personnel's tasks. More specifically, sounds can distract maintenance personnel and interfere with their job performance and sufficiently loud sounds can limit the ability of maintenance personnel to converse or to hear verbal instructions.

Finally, although maintenance personnel can wear protective devices to limit adverse noise effects to a certain degree, these devices can interfere with the performance of their assigned tasks if they are uncomfortable, restrict movement, or hinder conversation.

5.4.2 Poor Illumination

Lighting deficiencies occur because the external light that maintenance personnel rely on is frequently designed to illuminate the general work area, not the specific areas on which they actually focus. More specifically, illumination-related deficiencies can exist in enclosed or confined spaces, or in places where the primary source of illumination is the overhead lighting.

Finally, maintenance personnel could use portable lighting fixtures to overcome deficiencies such as these; however, if hand-free operations are not possible, their ability to work effectively will be impeded.

5.4.3 Temperature Variations

Maintenance personnel may be exposed to wide variations in temperature because they often perform their tasks in outdoor environments or in environments that are not fully climate controlled. Past experiences indicate that maintenance workers and people in general perform effectively at a fairly narrow temperature range.

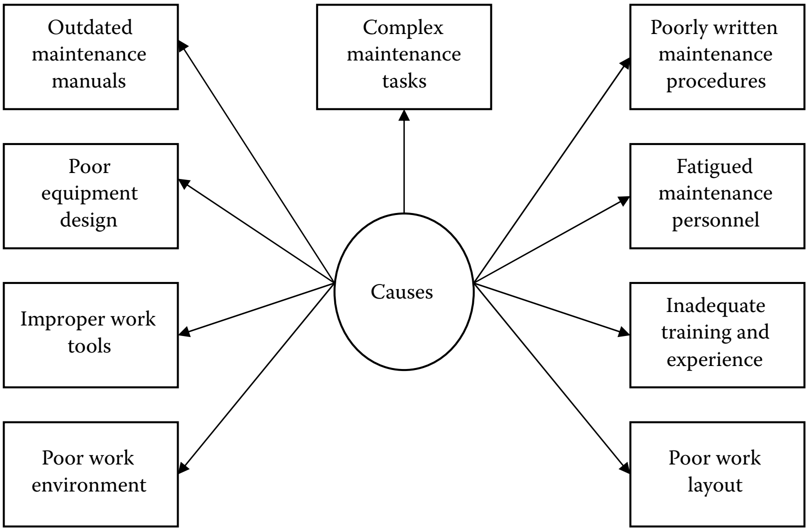

FIGURE 5.2 Causes for the occurrence of maintenance errors.

Furthermore, some studies [15–18] have shown that as the temperature extends beyond a fairly narrow range (i.e., from around 15°C/60°F to about 35°C/90°F), it becomes a stressor that affects the performance of individuals.

Over the years, various studies have identified many different causes for the occurrence of maintenance errors. Some of the important ones are shown in Figure 5.2 [11, 13, 19]. In particular, with regard to training and experience, a study of maintenance personnel reported that those who ranked highest possessed characteristics such as higher aptitude, greater satisfaction with the work group, higher morale, and greater emotional stability [11, 12].

5.5 TYPES OF MAINTENANCE ERRORS AND TYPICAL MAINTENANCE ERRORS

There are basically six types of maintenance errors [5]: recognition failures, memory failures, skill-based slips, knowledge-based errors, rule-based slips, and violation errors.

Recognition failures include items such as nondetection of problem states and misidentification of objects, signals, and messages. Memory failures include items such as input failure (i.e., poor attention is paid to the to-be-remembered item), storage failure (i.e., remembered material decays or suffers interference), premature exit (i.e., terminating a job prior to completing all the necessary actions), and omission following interruptions (i.e., rejoining a sequence of actions and omitting certain necessary steps).

Skill-based slips are usually associated with "automatic" routines and they can include branching errors and overshoot errors. Knowledge-based errors occur when maintenance personnel perform unusual tasks for the first time. Rule-based slips are concerned with misapplying a good rule (i.e., applying a rule in a situation where it is not appropriate) and applying a bad rule (i.e., the rule may get the job/task done under certain conditions, but it can have various consequences).

Finally, violation errors are the deliberate acts which violate procedures. These include thrill-seeking violations (they are frequently committed simply to avoid boredom or win peer praise), routine violations (they are committed to avoid unnecessary effort, get the job/task accomplished quickly, to demonstrate skill acquired, or avoid what is considered as an unnecessarily lengthy procedure/process), and situational violations (they are committed when it is impossible to get the job done if specified procedures are strictly adhered to). Additional information on all the above six types of maintenance errors is available in Ref. [5].

Some of the typical maintenance errors experienced in the industrial sector are as follows [20]:

- Parts installed backward
- Use of incorrect greases, lubricants, or fluids
- Installing incorrect part
- Failure to follow specified procedures and instructions
- Failure to align, check, or calibrate
- Omitting a component or part
- Failure to close or seal properly
- Failure to act on indicators of problems due to factors such as time constraints, priorities, or workload
- Failure to lubricate
- Error resulting from failure to complete task properly because of shift change

5.6 COMMON MAINTAINABILITY DESIGN ERRORS AND USEFUL DESIGN IMPROVEMENT GUIDELINES TO REDUCE EQUIPMENT MAINTENANCE ERRORS

Past experiences indicate that during the equipment design phase often errors are made that adversely affect equipment maintainability and, directly or indirectly, the occurrence of maintenance errors. Some of the common maintainability design errors are as follows [21, 22]:

- Providing poor reliability built-in test equipment
- Placing poor reliability parts beneath other parts
- Placing adjustable screws close to a hot part or an exposed power supply terminal
- Providing inadequate space for maintenance personnel to get their gloved hands into the unit to perform necessary adjustments
- Omitting necessary handles and placing an adjustment out of arm's reach

- Placing adjustable screws in locations difficult for maintenance personnel to find
- Using access doors with numerous small screws and placing screwdriver-related adjustments underneath modules

There are many useful design improvement guidelines for reducing equipment maintenance errors. Some of the important ones are as follows [20]:

- Use operational interlocks in such a way that subsystems cannot be turned on if they are incorrectly assembled or installed.
- Design to facilitate detection of errors and improve warning devices, readouts, and indicators to reduce human decision making.
- Improve fault isolation design by providing appropriate built-in test capability, clearly indicating the direction of fault, and designating test points and procedures.
- Use decision guides to reduce human guesswork by providing appropriate arrows for indicating direction of flow, correct type of fluids/lubricants, and correct hydraulic pressures.
- Improve part-equipment interface by designing interfaces in such a way that the part can only be installed correctly and provide correct mounting pins and other devices for supporting a part/component while it is being bolted or unbolted.

5.7 MAINTENANCE WORK INSTRUCTIONS

Over the years various studies have indicated that omissions account for over 50% of all human factors-related problems in the area of maintenance. Thus, the development and use of effective maintenance work instructions is very essential in managing these types of errors. Some characteristics of good maintenance work instructions are as follows [5]:

- They focus on the risks that may prevent the task/job being carried out safely and to specified quality standards.
- They incorporate sufficient independent inspections at important appropriate points in the instruction.
- They incorporate appropriate and conspicuous reminders for ensuring that important steps are not omitted.
- They group together complex work-related instructions into phases, with each and every phase consisting of many, related tasks/jobs.
- They make use of appropriate pictures and graphics at appropriate places.
- They are written with maintenance personnel who are going to read the instruction in mind.
- They are written clearly and make use of simple and consistent language.

Additional information on the above characteristics is available in Ref. [5].

5.8 MAINTENANCE ERROR ANALYSIS METHODS

Over the years many methods and techniques have been developed to perform various types of analysis in the areas of reliability, quality, and safety. Some of these methods can also be used to perform maintenance error analysis. Four of these methods are presented below.

5.8.1 Probability Tree Method

This is one of the commonly used methods to perform human reliability analysis. It is considered a quite useful approach to perform task analysis in maintenance work. In performing task analysis, the approach diagrammatically represents human actions. Thus, diagrammatic task analysis is denoted by the probability tree branches.

More specifically, the branching limbs denote outcomes (i.e., success or failure) of each event or action associated with a problem under consideration. Also, each branch of the probability tree is assigned an occurrence probability.

The method is described in detail in Chapter 4 and in Refs. [13, 21]. Its application to performing maintenance error analysis is demonstrated through the example presented below.

Example 5.1

Assume that a maintenance person performs two independent tasks, say, m and n. Task m is performed before task n and each of these two tasks can be either performed correctly or incorrectly. Draw the probability tree for the example and obtain probability expressions for the following:

1. Successfully accomplishing the overall mission by the maintenance person.
2. Not successfully accomplishing the overall mission by the maintenance person.

In this case, the maintenance person first performs task m correctly or incorrectly and then proceeds to performing task n. This complete scenario is represented by the probability tree diagram in Figure 5.3.

The four symbols used in Figure 5.3 are defined below.

m denotes the event that task m is performed correctly by the maintenance person.

$\bar{m}$ denotes the event that task m is performed incorrectly by the maintenance person.

n denotes the event that task n is performed correctly by the maintenance person.

$\bar{n}$ denotes the event that task n is performed incorrectly by the maintenance person.

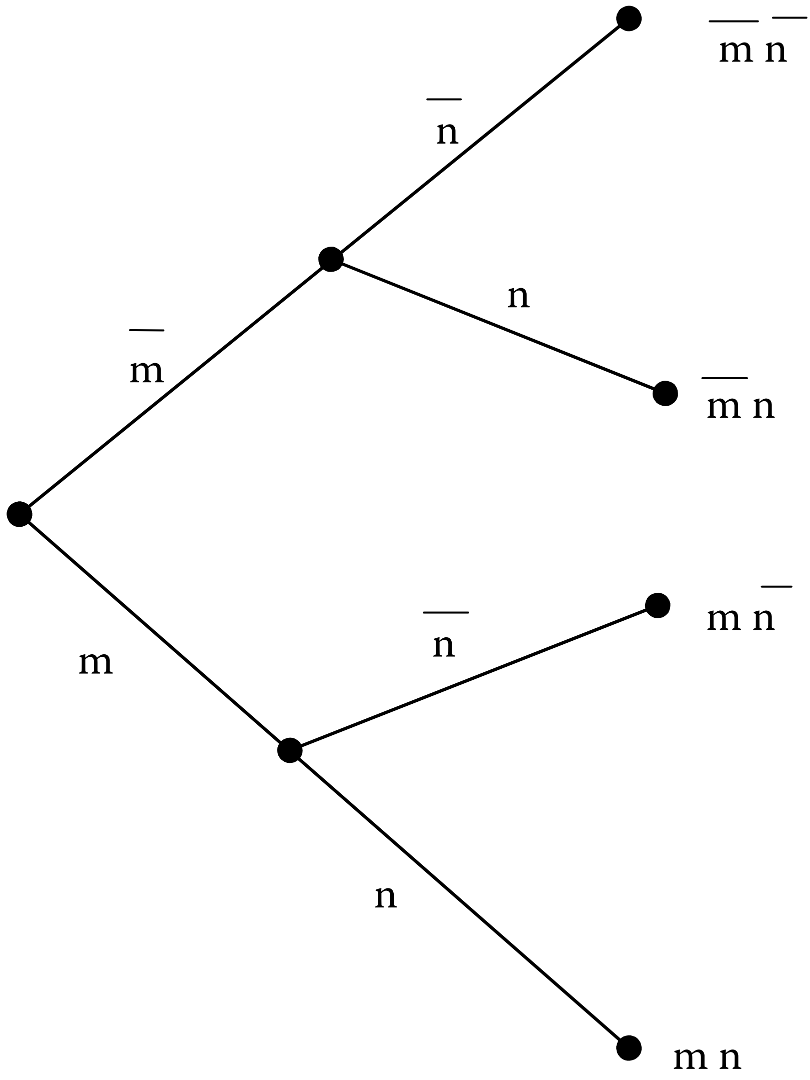

FIGURE 5.3 Probability tree for the maintenance person performing tasks *m* and *n*.

By examining the diagram, it can be noted that there are three distinct possibilities (i.e., $\bar{m}\bar{n}$, $\bar{m}n$, *and* $m\bar{n}$) for not successfully accomplishing the overall mission by the maintenance person. Thus, the probability of not successfully accomplishing the overall mission by the maintenance person is given by

$$\begin{aligned} P_f &= P(\bar{m}\bar{n} + \bar{m}n + m\bar{n}) \\ &= P_{\bar{m}}P_{\bar{n}} + P_{\bar{m}}P_n + P_m\, P_{\bar{n}} \end{aligned} \tag{5.1}$$

where

P_f is the probability of not successfully accomplishing the overall mission by the maintenance person.
P_m is the probability of performing task *m* correctly by the maintenance person.
P_n is the probability of performing task *n* correctly by the maintenance person.
$P_{\bar{m}}$ is the probability of performing task *m* incorrectly by the maintenance person.
$P_{\bar{n}}$ is the probability of performing task *n* incorrectly by the maintenance person.

Because $P_{\bar{m}} = 1 - P_m$ and $P_{\bar{n}} = 1 - P_n$, Equation (5.1) reduces to

$$\begin{aligned} P_f &= (1 - P_m)(1 - P_n) + (1 - P_m)P_n + P_m(1 - P_n) \\ &= 1 - P_n P_m \end{aligned} \tag{5.2}$$

Similarly, by examining Figure 5.3, it can be noted that there is only one possibility (i.e., *mn*) for successfully accomplishing the overall mission by the maintenance person. Thus, the probability of successfully accomplishing the overall mission by the maintenance person is given by

$$\begin{aligned} P_s &= P(mn) \\ &= P_m P_n \end{aligned} \tag{5.3}$$

where P_s is the probability of successfully accomplishing the overall mission by the maintenance person.

Example 5.2

Assume that in Example 5.2, the probabilities of the maintenance person performing tasks *m* and *n* correctly are 0.9 and 0.95, respectively. Calculate the probability of not successfully accomplishing the overall mission by the maintenance person.

By substituting the given data values into Equation (5.2), we get

$$\begin{aligned} P_f &= 1 - (0.95)(0.9) \\ &= 0.855 \end{aligned}$$

Thus, the probability of not successfully accomplishing the overall mission by the maintenance person is 0.855.

5.8.2 Pontecorvo Method

This is a quite useful method that can be used to obtain reliability estimates of task performance by a maintenance person. The method first obtains reliability estimates for separate and discrete subtasks having no correct reliability figures, and then it combines these estimates to obtain the total task reliability. Usually, the Pontecorvo approach is applied during initial design phases and is composed of the six steps shown in Figure 5.4 [13, 22].

Step 1 is concerned with the identification of tasks to be performed. These tasks are to be identified at a gross level (i.e., each task is represented by one complete operation). Step 2 is concerned with the identification of those subtasks that are essential for task completion. Step 3 is concerned with collecting data from sources such as in-house operations and experimental literature.

Step 4 is concerned with rating each subtask according to its potential for error or level of difficulty. Normally, a 10-point scale is used to judge the appropriate subtask rate. The scale varies from least error to most error. Step 5 is concerned with predicting the subtask reliability and is accomplished by expressing the judged ratings of the data and the empirical data in the form of a straight line. The regression line is tested for goodness of fit.

Finally, Step 6 is concerned with determining the task reliability. The task reliability is obtained by multiplying reliabilities of all the subtasks.

It is to be noted that the above approach is used to estimate the performance of a single individual acting alone. However, when a backup person is available, the probability of the task being performed correctly (i.e., the task reliability) improves. Nonetheless, the backup individual may not be available all of the time. In such a scenario, the overall reliability of two individuals working together to accomplish a specified task can be estimated by utilizing the following expression [13, 22]:

$$R_O = \left[\left\{1-(1-R_s)^2\right\}PT_1 + R_s PT_2\right]/(PT_1 + PT_2) \tag{5.4}$$

where R_s denotes the single person reliability, PT_1 denotes the percentage of time the backup person is available, and PT_2 denotes the percentage of time the backup person is unavailable.

Example 5.3

Two maintenance workers are working independently together to carry out a maintenance-related task. The reliability of each worker is 0.90, and the backup worker is only available 40% of the time. Calculate the reliability of performing the maintenance task correctly.

Thus, as per the specified data value, the percentage of time the backup maintenance worker is unavailable is given by

$$\begin{aligned} PT_2 &= 1 - PT_1 \\ &= 1 - 0.40 \\ &= 0.60 \textit{ or } 60\% \end{aligned}$$

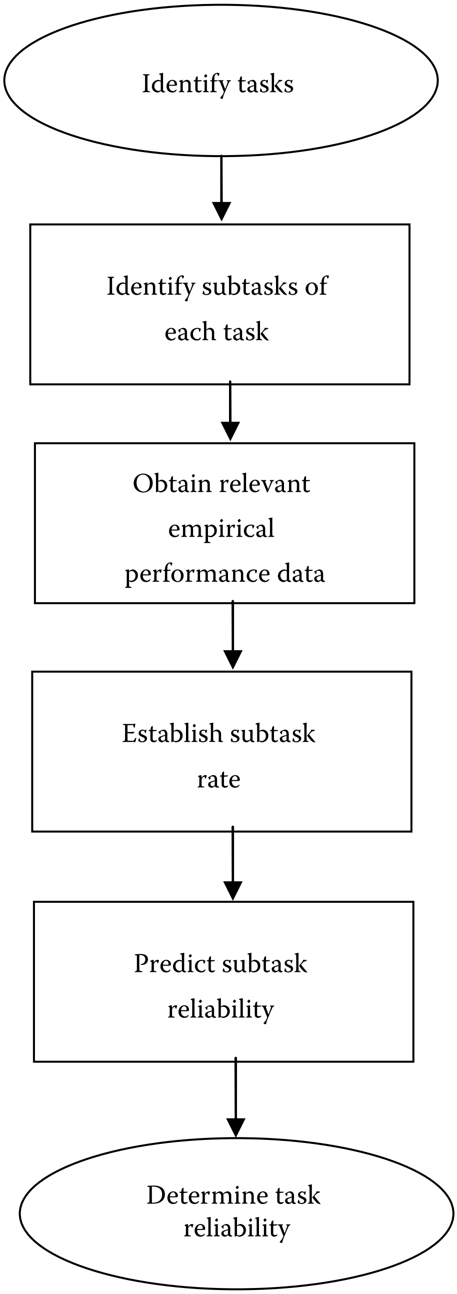

FIGURE 5.4 Pontecorvo method steps.

Using the above calculated value and the given data values in Equation (5.4), we get

$$R_O = [\{1-(1-0.9)^2\}0.4+(0.9)(0.6)]/(0.4+0.6)$$
$$= 0.936$$

Thus, the reliability of carrying out the maintenance task correctly is 0.936.

5.8.3 Pareto Analysis

The method is named after Vilfredo Pareto (1848–1923), an Italian economist, and it is a quite useful method that can be used to separate the important causes of maintenance error-related problems from the trivial ones.

Thus, the method is considered a powerful tool to identify areas for a concerted effort to minimize or eliminate the occurrence of maintenance errors. The method is composed of the six steps listed below [23, 24].

- **Step 1:** List causes in tabular form and count their occurrences.
- **Step 2:** Arrange the causes in descending order.
- **Step 3:** Calculate the total for the entire list.
- **Step 4:** Determine the percentage of the total for each cause.
- **Step 5:** Develop a Pareto diagram that shows percentages vertically and their corresponding causes horizontally.
- **Step 6:** Conclude from the final results.

Additional information on Pareto analysis is available in Refs. [23, 24].

5.8.4 Markov Method

This is a widely used tool to perform various types of reliability analysis, and it can be used to perform human error analysis in maintenance work. The method is described in Chapter 4. Its application in the area of maintenance is demonstrated through the following mathematical model.

This mathematical model represents a maintenance person performing a maintenance task. He or she can make and self-correct an error. The state space diagram of the model is shown in Figure 5.5 [24]. Numerals in boxes denote system states.

The model is subject to the following assumptions:

- The maintenance person's error and self-error-correction rates are constant.
- The maintenance person can self-correct his or her errors.
- After the error correction the maintenance person's performance remains normal.

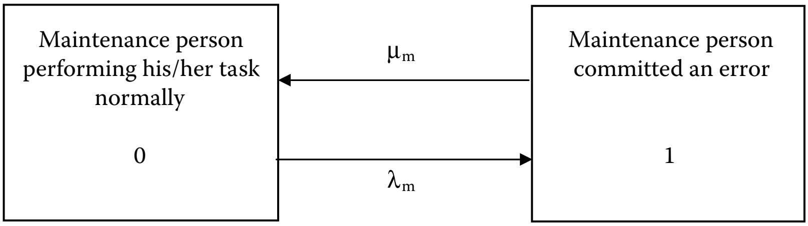

FIGURE 5.5 State space diagram for the maintenance person.

The following symbols are associated with the model:

i is the maintenance person's state; for $i = 1$ (maintenance person performing his or her task normally), $i = 1$ (maintenance person committed an error).
P_i (t) is the probability that the maintenance person is in state i at time t; for $i = 0,1$.
λ_m is constant error rate of the maintenance person.
μ_m is constant self-error-correction rate of the maintenance person.

With the aid of the Markov method, we write down the following equations for the diagram:

$$\frac{dP_0(t)}{dt} + \lambda_m P_0(t) = P_1(t)\mu_m \tag{5.5}$$

$$\frac{dP_1(t)}{dt} + \mu_m P_1(t) = P_0(t)\lambda_m \tag{5.6}$$

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

Solving Equations (5.5) and (5.6), we get

$$P_0(t) = \frac{\mu_m}{(\lambda_m + \mu_m)} + \frac{\lambda_m}{(\lambda_m + \mu_m)} e^{-(\lambda_m + \mu_m)t} \tag{5.7}$$

$$P_1(t) = \frac{\lambda_m}{(\lambda_m + \mu_m)} - \frac{\lambda_m}{(\lambda_m + \mu_m)} e^{-(\lambda_m + \mu_m)t} \tag{5.8}$$

As time t becomes very large, we get the following steady-state probability equations from Equations (5.7) and (5.8), respectively:

$$P_0 = \frac{\mu_m}{\lambda_m + \mu_m} \tag{5.9}$$

$$P_1 = \frac{\lambda_m}{\lambda_m + \mu_m} \tag{5.10}$$

where P_0 and P_1 are the steady-state probabilities of the maintenance person being in states 0 and 1, respectively.

Example 5.4

A maintenance person is performing a maintenance task and his or her error and self-error-correction rates are 0.0003 errors/hour and 0.0001 errors/hour, respectively. Calculate the maintenance person's probability of correctly performing his or her task during an 8-hour period.

By substituting the specified data values into Equation (5.7), we get

$$P_0(8) = \frac{0.0001}{(0.0003+0.0001)} + \frac{(0.0003)}{(0.0003+0.0001)} e^{-(0.0003+0.0001)(8)}$$
$$= 0.9976$$

Thus, the maintenance person's probability of performing his or her task correctly is 0.9976.

5.9 PROBLEMS

1. Give at least four facts and figures concerned with human error in maintenance.
2. Discuss the occurrence of maintenance error in equipment life cycle.
3. Write an essay on the maintenance environment.
4. What are the main causes for the occurrence of maintenance errors?
5. What are the six basic types of maintenance errors?
6. List at least eight typical maintenance errors.
7. What are the common maintainability design errors?
8. Discuss maintenance work instructions.
9. Describe the following two items:
   - Pareto analysis
   - Pontecorvo method
10. Prove Equations (5.7) and (5.8) by using Equations (5.5) and (5.6).

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