Chapter 5
Human Factors and Error in Mining

5.1 Introduction

The field of human factors exists because people make various types of errors in using engineering systems. Human factors may simply be described as a body of scientific facts concerning the characteristics of human beings [1–3]. Similarly, human error is defined as the failure to perform a specified task (or the performance of a forbidden action) that could result in the disruption of scheduled operations or damage to equipment and property [2, 3].

The history of the study of human factors may be traced back to 1898, when Frederick W. Taylor performed various studies to determine the most effective design of shovels [4]. By 1945 human-factor engineering was recognized as a specialized discipline, and in 1958 H.L. Williams recognized that human-element reliability must be taken into consideration in the overall system-reliability prediction; otherwise, such a prediction would not be realistic [5]. In 1960, a study conducted by the US military reported that human error is the cause of 20 to 50% of equipment failures [6]. Today, a wide range of published literature is available on various aspects of human factors including human error [3, 7, 8].

In the area of human factors in mining, the first formal human-factor study was conducted in 1971 and was concerned with identifying human-factor-related problems in underground coal mines [9, 10]. In 1982, two human-factor-problem-identification studies directed at surface mining were reported: one concerning the mining process itself and the other the processing plants [11, 12].

Over the years many publications on various aspects of human factors in mining including human error have appeared [10, 13]. This chapter presents various important aspects of human factors and error that are, directly or indirectly, concerned with mining.

5.2 The Need to Apply Human Factors in Mining and Common Roadblocks to the Introduction of Human Factors in an Organization

Technology plays a pivotal role in increasing productivity and safety in the mining industry. New advances in technology have placed new demands on mine workers. This, in turn, has created the need for paying greater attention to determine how people and technology can work together effectively. More specifically, how should mining equipment and tasks be designed to match the capabilities and limitations of mine workers who will be operating and maintaining such equipment in the field [10]?

The application of human-factor principles can be very useful in addressing questions such as this.

Over the years various types of roadblocks to the application of human factors in organizations have been experienced. Some of the common ones are shown in Fig. 5.1 [10]. Counterarguments to each of these roadblocks are presented below.

To the notion that all humans are created equal can be added that no two humans are identical. Thus, systems must be designed in such a way that they effectively accommodate the diversity in the human population. As for the idea that humans can be trained to overcome design-related shortcomings, although this is true to a certain degree, training can be somewhat unreliable. More specifically, as experience has shown, under stressful conditions humans usually respond the way they think systems/equipment should operate, which may not be how the systems/equipment actually operate.

Regarding the idea that engineers and designers know best how humans think and act, one may add that engineers and designers may know how engineers and design-

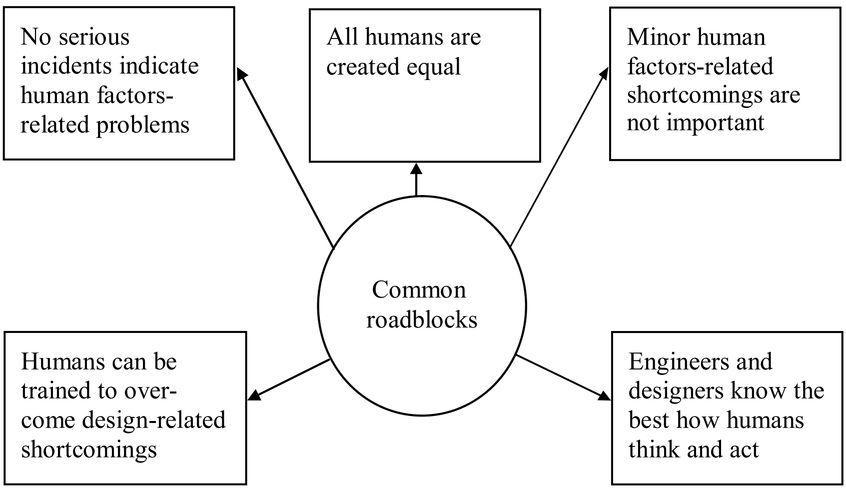

Fig. 5.1 Common roadblocks to the application of human factors in organizations

ers usually think and act, but they (*i.e.*, engineers and designers) do not necessarily think or act like other members of the society at large.

In regard to the idea that no serious incidents indicate human-factor-related problems, one may add that, although the Three Mile Island Nuclear Generating Station had various human-factor-related shortcomings in the control room, until the very day it came within 60 min of meltdown, the station reported no serious incidents [10].

Finally, the idea that minor human-factor-related shortcomings are not important is undermined by past experiences, which shows that minor shortcomings often compound into major shortcomings and usually have a way of insidiously eating into efficiency and productivity.

5.3 Human Sensory Capacities and Human-Factor Considerations in Equipment Design

Human sensory capacities include touch, sight, noise, vibration, and smell. Humans can recognize a minute change in these sensors over a wide range and then react to them automatically. As in the area of mining equipment, human sensory capabilities play an important role, and four of the five above-mentioned capacities are discussed below, separately [14–16].

Sight

Sight is stimulated by electromagnetic radiation of certain wavelengths known as the visible segment of the electromagnetic spectrum. Various parts of this spectrum, as seen by the human eye, appear to vary quite significantly in brightness. For example, in the daylight, the eye is quite sensitive to greenish-yellow light, and from different angles it sees differently.

Although looking straight ahead human eyes can perceive all colors, with an increase in the viewing angle color perception begins to decrease.

Some of the useful sight-related guidelines for designers are as follows [15, 16]:

- Choose colors such that color-weak individuals do not get confused.
- Do not rely too much on color when critical operations or tasks are to be performed by fatigued personnel.
- Try to use red filters with a wavelength greater than 6500 Angstrom units.

Vibration

Vibration is basically concerned with the effects on the performance of humans of periodically occurring mechanical forces impinging on body tissues. Past experience shows that the unsatisfactory performance of mental and physical tasks by people such as equipment operators and maintainers could be partially or wholly due to vibrations. For example, low-frequency and large-amplitude vibrations can lead to headaches, motion sickness, fatigue, deterioration in the ability to read and interpret instruments, and eye strain.

Some of the useful guidelines to reduce the effects of vibration and motion are as follows [15–18]:

- Use cushioned seats or dumping material seats to reduce vibration transmissions.
- Eliminate vibrations with an amplitude greater than 0.08 mm for critical maintenance or other tasks requiring letter or digit discrimination.
- Use devices such as springs, shock absorbers, and cushion mountings wherever possible.

Touch

Touch is closely associated with humans' ability to interpret auditory and visual stimuli. It adds, or sometime may even replace, the information transmitted to the brain by the ears and eyes. Thus, in mining equipment design the touch sensor can be utilized to relieve ears and eyes of a part of the load.

An example of the touch sensor's application could be the recognition of control knob shapes with or without the use of other sensors.

Noise

Noise may be described as sounds that lack coherence; it can affect the performance quality of a task requiring intense concentration. Past experience shows that noise contributes to human feelings such as well-being, irritability, and boredom.

Although the ear can detect sounds of frequencies from 20 to 20,000 Hz, it is most sensitive to frequencies between 600 and 900 Hz [15–17]. Furthermore, a noise level below 90 decibels (dB) is considered quite safe, and above 100 dB unsafe. All in all, with respect to mining equipment it is to be noted that above-normal noise may make verbal communication, say, between operators and maintenance personnel, impossible. In turn, this can lead to various serious problems including accidents.

5.3.1 Human-Factor Considerations in Equipment Design

In order to have a piece of effective human-compatible equipment, it is essential to consider the relevant human factors during the design stage. At this stage the main objective should be to design a piece of equipment so that it does not subject humans to extreme mental or physical stress or hazards and allows them to perform in the most effective manner.

During the four stages of equipment design shown in Fig. 5.2, design engineers and others should consider human factors from various different perspectives [16, 19]. At the pre-conceptual stage, design-related professionals should systematically define items such as the mission and operational requirements, the functions required to carry out each mission event, and the performance requirements for each mission.

During the concept stage, in addition to the pre-conceptual-stage tasks, the design professionals should also include items such as a preliminary definition of manning and training needs; preliminary task descriptions of users, operators, and maintainers; and analysis for defining the most suitable design method to accomplish each hardware functional assignment. At the pre-design stage, design engineers and associated professionals, in addition to reviewing the analyses of the concept stage, should also conduct time line and link analyses, perform man-machine mock-up studies, etc.

Finally, during the detailed design stage, design-related professionals should consider developing an equipment/system statement, identifying critical skill requirement specifications, creating and evaluating critical man-machine mock-ups, performing link analysis for all important man-machine interfaces, and so on.

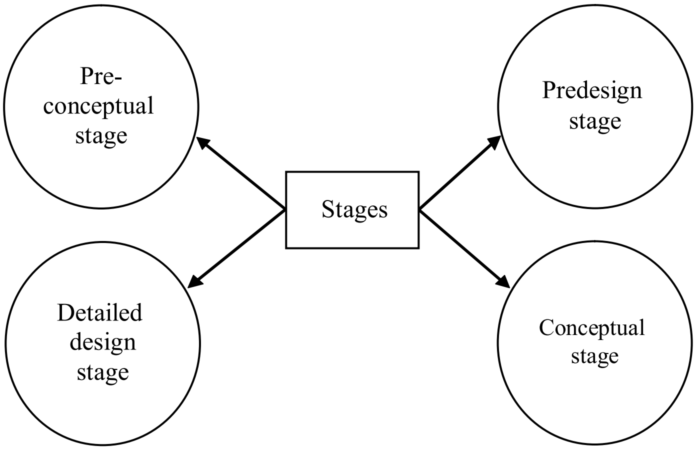

Fig. 5.2 Equipment design stages

5.4 Human-Factor Formulas

There are many mathematical formulas for estimating human-factor-related information. This section presents some of these formulas considered useful for application in the mining industry [16, 17].

5.4.1 Formula I

This formula is concerned with calculating the length of rest periods for humans performing various types of tasks. In mining equipment design, the rest period requirement for humans must be taken into consideration for its ultimate effectiveness.

The duration of a rest period, depending on the task average energy cost, can be estimated by using the following formula [18]:

$$T_r = T_w\,(AE - SEE)\,/\,(AE - R)\ , \tag{5.1}$$

where

- T_r is the required rest period, expressed in minutes;
- T_w is the working time, expressed in minutes;
- SEE is the standard energy expenditure expressed in kilocalories per minute. In the event of having no data, the value of SEE may be taken as 5 Kcal/minute;
- AE is the average energy expenditure expressed in kilocalories per minute of work;
- R is the resting level. Its approximate value is taken as 1.5 Kcal/min.

Example 5.1

A person is performing a maintenance task involving mining equipment for 100 min and his average energy expenditure is 4 Kcal per minute. Calculate the length of the required rest period if the value of $SEE = 3$ Kcal/min.

Substituting the given data values into Eq. (5.1) we get

$$T_r = 100\,(4-3)\,/\,(4-1.5) = 40\,\text{min}\ .$$

Thus, the length of the required rest period is 40 min.

5.4.2 Formula II

As the ability of humans to make visual discrimination depends on factors such as size, exposure time, and illumination, this formula is concerned with estimating character height by considering factors such as illumination, viewing distance, viewing conditions, and the importance of reading accuracy. Thus, the character height is expressed by [21]

$$C_{\mathrm{h}} = \theta D_{v} + CF_{i} + CF_{v} \; , \tag{5.2}$$

where

C_{h} is the character height expressed in inches;
D_{v} is the viewing distance expressed in inches;
θ is a constant whose value is taken as 0.0022;
CF_{i} is the correction factor for importance or criticality. For critical and noncritical markings, its recommended values are 0.075 and 0, respectively;
CF_{v} is the correction factor for viewing and illumination conditions. For its recommended values, see Ref. [22].

5.4.3 Formula III

This formula is concerned with estimating the level of noise/sound intensity in terms of decibels. Thus, the sound-pressure level (*SPL*), in decibels (dB), is defined by [23, 24]

$$SPL\,(\mathrm{dB}) = 10\log_{10}\left[\frac{P^{2}}{P_{0}^{2}}\right] \; , \tag{5.3}$$

where

P_{0}^{2} is the standard reference sound pressure squared denoting zero decibels. In particular, P_{0} is ordinarily the faintest 1,000-Hz tone that an average young individual can hear;
P is the sound pressure squared of the sound to be measured.

5.4.4 Formula IV

This formula is concerned with estimating the maximum lifting load for a person. The maximum lifting load for a person is expressed by [25]

$$L_{\mathrm{m}} = \alpha\,(IBMS) \; , \tag{5.4}$$

where

L_m is the maximum lifting load for a person,
α is a constant whose values for males and females are 1.1 and 0.95, respectively,
IBMS is the isometric back muscle strength.

5.5 Useful General Human Factors Guidelines for Application in Mining Equipment Design

There are many different aspects of human factors that must be considered during equipment design. Some of the useful human-factor guidelines for application in mining equipment design are as follows [19]:

- Review equipment/system objective with respect to human factors.
- Acquire all appropriate human-factor-design guide and reference documents.
- Develop a human-factor-design checklist for application during design and production phases.
- Use the services of human-factor specialists as the need arises.
- Ensure that the above checklist is used effectively throughout the design and production phases.
- Use appropriate mock-ups for "testing" the effectiveness of user-hardware interface designs.
- Review final equipment production drawings with care with regard to human factors.
- Fabricate a hardware prototype (if possible) for evaluating it under real-life use environments.
- Perform appropriate experiments when cited reference guides fail to provide satisfactory information for making design-related decisions.
- Conduct appropriate field tests of the equipment/system design prior to its approval for final delivery to customers.

5.6 Classifications and Causes of Human Errors Leading to Fatal Accidents in Mines

A study of 794 human errors that resulted in fatal accidents in mines classified these errors under six distinct classifications, as shown in Fig. 5.3 [26].

Causes for the failure to perceive a warning were inadequate inspection technique, neglecting to inspect, obstruction to line of sight, inattention or distraction, masking noise, etc. Three identifiable main causes for the failure to recognize a perceived warning were inadequate information, lack of training, and lack of experience. The main cause for the failure to respond to a recognized warning was

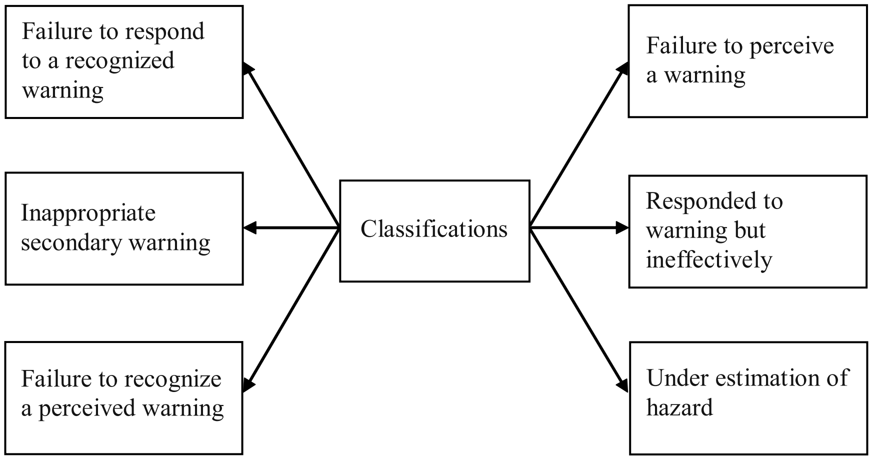

Fig. 5.3 Classifications of human errors leading to fatal accidents in mines

the underestimation of hazard. Three identifiable causes for ineffective response to a warning were negligence or carelessness, inappropriate standard practice, and well-intended but ineffective direct action. Finally, the causes for underestimating a hazard and an inappropriate secondary warning were unidentifiable [26].

5.7 Typical Mining Equipment Maintenance Errors, Factors Contributing to Maintenance Error, and Useful Engineering Design Improvements to Reduce Mining Equipment Maintenance Errors

Some of the typical mining equipment maintenance errors are as follows [27]:

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

There are many factors that contribute to maintenance-related human error. Some of these factors are as follows [27]:

- Poor manuals
- Poor layout of parts in a compartment
- Confined workspaces
- Inadequate provision for hose and cable management
- Poor task inspection and check-out time
- Inability to make visual inspections
- Lack of proper tools and troubleshooting guides
- Inaccessible components on parts
- Excessive weight of parts or components being manually handled
- Inappropriate placement of parts or components on equipment

Some of the useful engineering design improvement guidelines to reduce mining equipment maintenance errors are as follows [27]:

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

5.8 Types of Chemicals Released in Human-Error-Related Events in the Mining and Manufacturing Industries and Factors Responsible for Failing to Reduce the Occurrence of Human Error in Mines

Past experience shows that human error has played an important role in several large-scale hazardous material events. A study of 3,282 human-error-related events that occurred in the mining and manufacturing industries during the period 1996–2003 revealed that various types of chemicals were released. Most of these chemicals are listed below [28].

- Ammonia
- Chlorine

- Pesticides
- Hydrocarbons
- Acids
- Polymers
- Oxy-organics
- Hetero-organics
- Paints and dyes
- Bases
- Volatile organic compounds
- Polychlorinated biphenyls

Although the number of chemicals released per human-error-released event ranged from 1 to 14, in most of the 3,282 events only one chemical was released.

Some of the important direct or indirect factors in the failure to reduce the occurrence of human errors in mines are as follows [29]:

- Miners are performing their tasks under more difficult environmental, physical, and geo-mining conditions than ever before.
- The greater degree of automation and mechanization in today's mines requires greater understanding, capability, and efficiency from mine workers.
- There is greater worry and mental tension among mine workers due to a greater desire to have more than others.
- Stress in the home is on the rise worldwide.

5.9 Human-Error-Analysis Methods for Application in the Area of Mining

Over the years many methods and techniques have been developed to perform human-error analysis of engineering systems [3]. This section presents three of these methods considered useful for application in the area of mining.

5.9.1 Probability Tree Method

This method is concerned with performing task analysis by diagrammatically representing critical human actions and other events associated with the system under consideration. The branches of the probability tree denote diagrammatic task analysis. More specifically, the outcomes of each event are denoted by the branching limbs of the tree and each of these branching limbs is assigned the probability of occurrence.

The probability tree method has many advantages. It is [30]

- A useful visibility tool;

- A useful tool to decrease the probability of error due to computation resulting from computational simplification;
- A useful tool to readily estimate conditional probability, which may otherwise be obtained through complex probability equations;
- A useful tool to incorporate, with some modifications, factors such as emotional stress, interaction stress, and interaction effects.

The method is demonstrated through the following example.

Example 5.2

A mine worker performs two consecutive tasks, say *m* and *n*, and each of which can either be performed correctly or incorrectly. Furthermore, both tasks are independent of each other (*i.e.*, the performance of task *m* does not affect the performance of task *n* or vice versa), and task *m* is carried out before task *n*.

Obtain an expression for the probability, by developing a probability tree, that the mine worker will not successfully complete the overall mission.

A probability tree for this example is shown in Fig. 5.4. The tree shows that the mine worker first performs task *m* correctly or incorrectly and then proceeds to task *n*, which can also be performed correctly or incorrectly.

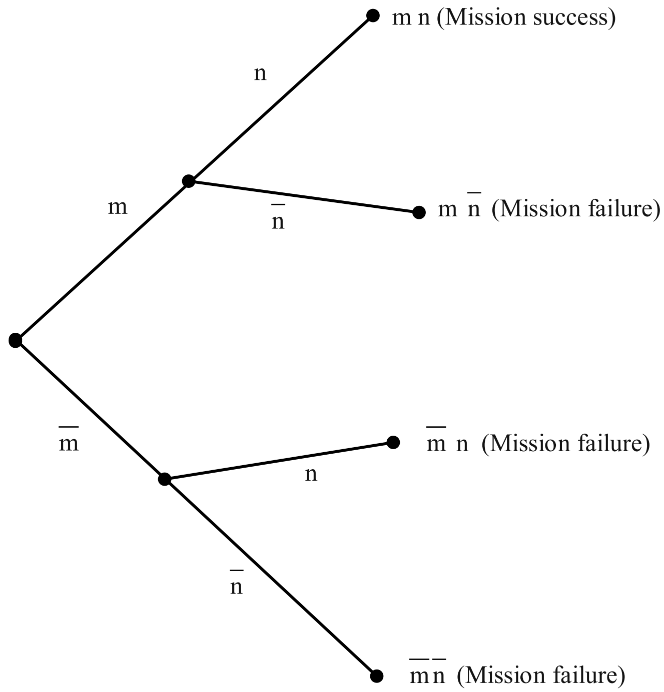

Fig. 5.4 Probability tree for Example 5.2

In Fig. 5.4, m and n with bars denote unsuccessful events and without bars successful events. Other symbols used to obtain the solution expression for the example are defined below.

P_m is the probability of performing task m correctly,
P_n is the probability of performing task n correctly,
$P_{\bar{m}}$ is the probability of performing task m incorrectly,
$P_{\bar{n}}$ is the probability of performing task n incorrectly,
P_{nsu} is the probability of not completing the overall mission.

Using Fig. 5.4, the probability of the mine worker not completing the overall mission is given by

$$P_{nsu} = P_m P_{\bar{n}} + P_{\bar{m}} P_n + P_{\bar{m}} P_{\bar{n}} . \qquad (5.5)$$

Thus, the expression for the probability that the mine worker will not complete the overall mission is given by Eq. (5.5).

5.9.2 Throughput Ratio Method

This method was developed by the US Navy Electronic Laboratory Center [31]. The ratio generated by the method determines the operability of man-machine interfaces. The term "throughput" implies transmission, because the ratio is expressed in terms of responses per unit time emitted by the equipment/system operator. The throughput ratio in percentage is expressed by

$$R_{\text{mo}} = \left(\frac{\lambda}{\theta} - CF \right) (100) , \qquad (5.6)$$

where

R_{mo} is the man-machine operability,
CF is the correction factor (*i.e.*, correction for error or out-of-tolerance output),
λ is the number of throughput items generated per unit time,
θ is the number of throughput items to be generated per unit time to meet design expectations.

The correction factor, CF, is expressed by

$$CF = \left[\left(\frac{n_1}{n_2} \right) \left(\frac{\lambda}{\theta} \right) \right] \left[\left(\frac{n_1}{n_2} \right) \left(\frac{\lambda}{\theta} \right) P_{\text{en}}^2 P_{\text{ff}} \right] , \qquad (5.7)$$

where

n_1 is the number of trials in which the control-display operation is performed incorrectly,
n_2 is the number of trials in which the control-display operation is performed,
P_{en} is the probability that the error will not be detected by the equipment/system operator,
P_{ff} is the probability of function failure due to human error.

All in all, the throughput ratio may be used for various purposes including to demonstrate system acceptability, to establish system feasibility, and to make comparisons of alternative design operabilities [3, 31].

Example 5.3

For the following given values of λ, θ, n_1, n_2, P_{en}, and P_{ff}, calculate the value of the throughput ratio:

$$\lambda = 7\,,\ \theta = 13\,,\ n_1 = 4\,,\ n_2 = 16\,,\ P_{en} = 0.4\,,\ \text{and}\ P_{ff} = 0.8\,.$$

$$CF = \left[\left(\frac{4}{16}\right)\left(\frac{7}{13}\right)\right]\left[\left(\frac{4}{16}\right)\left(\frac{7}{13}\right)(0.4)^2\,(0.8)\right] = 0.00232\,.$$

Substituting the above-calculated value and the given data values into Eq. (5.6) we get

$$R_{mo} = \left(\frac{7}{13} - 0.00232\right)(100) = 53.61\%\,.$$

Thus, the value of the throughput ratio (*i.e.*, the man-machine operability) is 53.61%.

5.9.3 Fault Tree Analysis

This method is widely used to perform various types of reliability analysis and can also be used to perform human error analysis in the mining industry. The method is described in Chap. 3. The following examples demonstrate the application of the method to perform human error analysis in the area of mining.

Example 5.4

Assume that a mine worker is required to perform a certain job, say X, composed of three independent tasks I, J, and K. All three of these tasks must be performed correctly for the successful completion of the job.

Task I is composed of two subtasks I_1 and I_2. If any one of these two subtasks is performed correctly, task I can be accomplished successfully. Similarly, task J is also composed of two subtasks J_1 and J_2. However, both these subtasks must be carried out correctly for the successful completion of task J.

Both subtasks, I_2 and J_2, are made up of three steps each, *i.e.*, i_1, i_2, i_3 and j_1, j_2, j_3, respectively. All steps for each of these two subtasks must be accomplished correctly for subtask success. Develop a fault tree for the event that job X will be performed incorrectly by the mine worker.

Figure 5.5 shows the fault tree for Example 5.4.

Example 5.5

Assume that the probability of occurrence of the basic events (*i.e.*, events denoted by circles) in Fig. 5.5 is 0.02. Calculate the probability of occurrence of the top fault tree event (*i.e.*, job X will be performed incorrectly by the mine worker) by assuming that all the fault tree events occur independently.

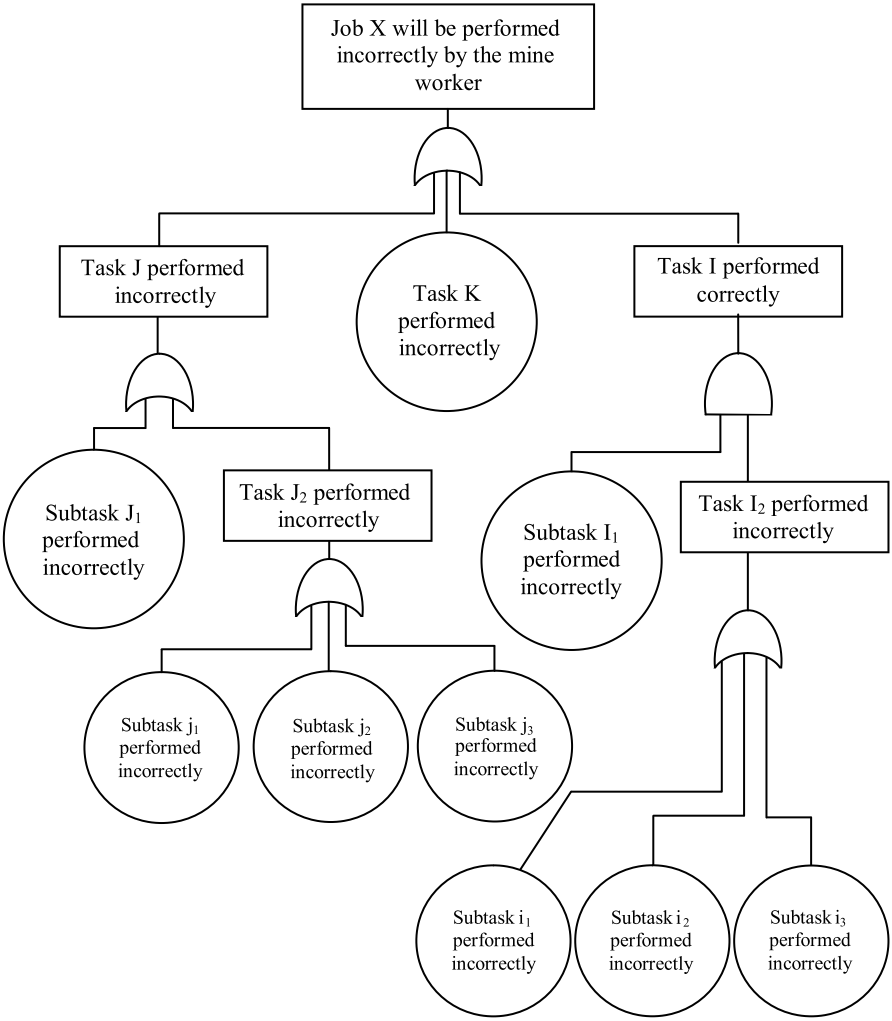

Fig. 5.5 Fault tree for Example 5.4

Using Chap. 3, we perform calculations as follows:
The probability of performing subtask I_2 incorrectly is given by

$$\begin{aligned} P(\mathrm{I}_2) &= 1-(1-P(\mathrm{i}_1))(1-P(\mathrm{i}_2))(1-P(\mathrm{i}_3)) \\ &= 1-(1-0.02)(1-0.02)(1-0.02) \\ &= 0.0588\,, \end{aligned}$$

where

$P(\mathrm{i}_n)$ is the probability of performing step i_n incorrectly, for $n = 1,2,3$.

Similarly, the probability of performing subtask J_2 incorrectly is expressed by

$$\begin{aligned} P(\mathrm{J}_2) &= 1-(1-P(\mathrm{j}_1))(1-P(\mathrm{j}_2))(1-P(\mathrm{j}_3)) \\ &= 1-(1-0.02)(1-0.02)(1-0.02) \\ &= 0.0588\,, \end{aligned}$$

where

$P(\mathrm{j}_n)$ is the probability of performing step j_n incorrectly, for $n = 1,2,3$.

The probability of performing task J incorrectly is given by

$$\begin{aligned} P(\mathrm{J}) &= 1-(1-P(\mathrm{J}_1))(1-P(\mathrm{J}_2)) \\ P(\mathrm{J}) &= 1-(1-0.02)(1-0.0588) \\ &= 0.0776\,, \end{aligned}$$

where

$P(\mathrm{J}_n)$ is the probability of performing step J_n incorrectly, for $n = 1,2$.

Using one of the above-calculated values, the probability of performing task I incorrectly is expressed by

$$P(\mathrm{I}) = P(\mathrm{I}_1)P(\mathrm{I}_2) = (0.02)(0.0588) = 0.0012$$

where

$P(\mathrm{I}_1)$ is the probability of performing subtask I_1 incorrectly.

Finally, the probability of the mine worker performing job X incorrectly is

$$\begin{aligned} P(\mathrm{X}) &= 1-(1-P(\mathrm{J}))(1-P(\mathrm{K}))(1-P(\mathrm{I})) \\ &= 1-(1-0.0776)(1-0.02)(1-0.0012) \\ &= 0.0971\,. \end{aligned}$$

Thus, the probability that job X will be performed incorrectly by the mine worker is 0.0971.

5.10 Problems

1. Discuss the need for human-factor applications in the mining industry.
2. What are the common roadblocks to the introduction of human factors in an organization?
3. Discuss the following human sensory capacities:

   - Sight
   - Touch
   - Noise

4. Discuss human-factor considerations in equipment design.
5. Assume that a mine worker is performing a maintenance task for 100 min and his average energy expenditure is 5 Kcal per minute. Calculate the length of the required rest period if the value of standard energy expenditure (SEE) is 2 Kcal/min.
6. List at least eight general human-factor guidelines considered useful for application in mining equipment design.
7. What are the main causes of human errors leading to fatal accidents in mines?
8. What are the types of chemicals released in human-error-related events in the mining and manufacturing industries.
9. Discuss two human-error-analysis methods considered useful for application in the area of mining.
10. Discuss important factors responsible for failing to reduce the occurrence of human error in mines.

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