Chapter 6
Mining Equipment Maintainability

6.1 Introduction

In the 1950s underground mining equipment (*e.g.*, in coal mines) basically consisted of various types of simple and rugged machines powered by hydraulics and electric motors. These machines played an instrumental role in cutting, digging, loading, and transporting, say coal, from the mine face to the surface level. The equipment was maintained by maintenance personnel with just basic knowledge of machine design, hydraulics, and electricity and were expected to repair such equipment at the mine site using only simple hand tools.

Over the years, due to the boost in productivity and other factors, the old mining equipment has been transformed into complex and powerful systems. In turn, this has increased the need for better equipment maintainability and knowledge and skills of maintenance workers. Some of the factors directly or indirectly considered in regard to mining equipment maintainability are reducing mean time to repair, lowering life cycle maintenance costs, improving safety, reducing or eliminating altogether the need for maintenance, and reducing the amount, frequency, and complexity of required maintenance tasks.

This chapter presents various important aspects of mining equipment maintainability.

6.2 The Meanings of Mining Equipment Maintainability and Design-induced Maintainability Problems of Mining Equipment

Although the meanings of maintainability may be interpreted in various ways, with regard to mining equipment, maintainability basically means the followings [1]:

- Maintenance considered at design stage
- Effective accessibility of all systems and components

- Predictability of all possible potential failures
- Proper initial startup and commissioning
- Continuous improvement of total machine/equipment
- Serviceability and repairability of all involved systems and components

A study of underground mining equipment with respect to maintainability revealed many design limitations that directly impacted maintenance time, cost, and personnel safety [2, 3]. These problems or limitations are shown in Fig. 6.1. "Accessibility limitations" refers to the inability of maintenance workers in accessing failed or suspected parts for inspection or removal and replacing them. Some of the causes for accessibility problems in mining equipment are as follows [3]:

- Poor access opening size
- Poor layout of parts in a compartment
- Inability to use required tools
- Partially or completely disassembly of equipment to locate fasteners and mechanical interfaces

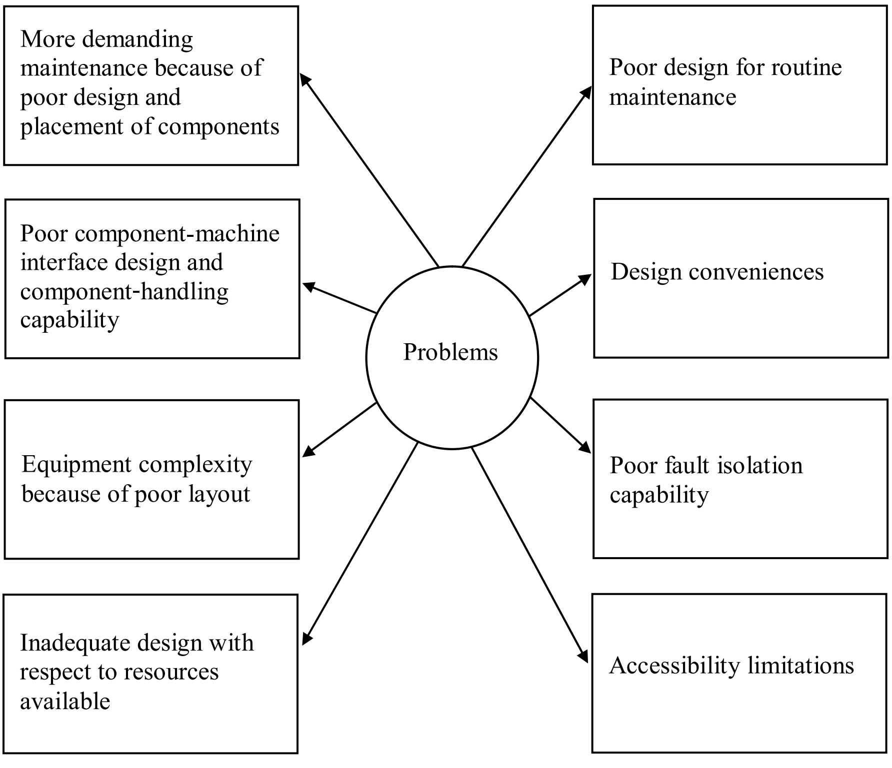

Fig. 6.1 Design-induced maintainability problems of mining equipment

“Poor component-machine interface design and component-handling capability” are basically concerned with the ineffectiveness of the component-handling capability and component-machine interface design. “More demanding maintenance because of poor design and placement of components” is concerned with increased maintenance burden due to poor design and placement of parts or components, subjecting them to impact damage.

“Poor fault isolation capability” is concerned with items such as those listed below:

- Accessing parts or components to carry out visual inspection and to perform appropriate checks
- Difficulty in determining the exact cause and location of a fault or failure
- Lack of appropriate fault indexes
- Limited or existence of absolutely no designed-in fault diagnostic capabilities

“Equipment complexity because of poor layout” is concerned with crowding of parts/components into compartments without paying any attention to factors such as the need to maintain or replace individual items and overlaying hoses and power cables. “Design conveniences” are basically concerned with multiplying the number of connectors, valves, and other high-frequency replacement parts as a design convenience.

“Poor design for routine maintenance” is concerned with tasks such as quickly removing and replacing leaking water lines and hydraulic hoses, performing routine lubrication, removing and replacing failed hydraulic valves, and performing physical and visual inspections. “Inadequate design with respect to resources available” is basically concerned with maintenance workers to “jerry-rig” tools, to handle 45-kg to 450-kg parts, and to use brute human strength for overcoming ineffective component interface design or lack of requisite tools.

6.3 Advantages of Improved Mining Equipment Maintainability Design

The main objectives of the maintainability engineering application to mining equipment are to increase efficiency and safety and to reduce maintenance cost. This starts with improving the mining equipment design. Nonetheless, although the application of maintainability engineering will not eliminate the need for service and maintenance of mining equipment, it will certainly provide advantages such as the following [2]:

- Reduction in maintenance-related injuries
- Reduction in time required to accomplish scheduled and unscheduled maintenance
- Reduction in maintenance-related human errors
- Reduction in incorrect installations

- Improvements in troubleshooting performance
- Minimization of the unscheduled maintenance frequency due to improvements in accessibility for inspection and servicing
- Reduction in the need for the training of maintenance personnel
- Improvement in postmaintenance inspection

6.4 Mining Equipment Maintainability Design Characteristics

Many maintainability design characteristics must be considered with care during the mining equipment design phase. These characteristics include those factors or features that play an important role in reducing the mining equipment downtime and unavailability. These features or factors include standardization, interchangeability, accessibility, and safety. Each of these features is described below, separately [4–8].

6.4.1 Standardization

This is an important design feature and is basically concerned with restricting to a minimum the variety of parts and components that can be used to meet the equipment/product requirements. Some of the primary goals of standardization are to maximize the use of interchangeable and standard parts, minimize the use of different types of parts, maximize the use of common parts in different products, and minimize the number of different models and makes of equipment in use.

Some of the main advantages of standardization are improvement in equipment reliability and maintainability, reduction in incorrect use of parts, reduction in manufacturing costs, design time, and maintenance time and cost, and reduction in the probability of occurrence of accidents stemming from wrong or unclear procedures [7, 8].

6.4.2 Interchangeability

Interchangeability is an important maintainability design factor, and it simply means that a given item can be replaced by any similar item, and the replacing item can perform the specified functions of the replaced item in an effective manner. There are two types of interchangeability: physical interchangeability and functional interchangeability. In the case of physical interchangeability, two items can be connected, mounted, and used in the same location and in the same way. Similarly, in the case of functional interchangeability, two given items serve the same function.

Needless to say, maximum interchangeability can only be achieved if the design professionals carefully consider items such as providing effective information in the task instructions and physical similarities (*e.g.*, shape and size).

6.4.3 Accessibility

Accessibility may simply be described as the relative ease with which an item can be reached for repair, replacement, or service. As per past experiences, lack of accessibility is an important maintainability problem and often a cause of poor maintenance [4]. Some of the important factors that affect maintainability are as follows [4, 5, 8]:

- Environment and location of the item to be accessed
- Frequency with which the access opening is entered
- The type of maintenance tasks to be performed through the access opening
- Work clearances necessary for carrying out the required tasks
- Types of accessories and tools required to carry out the tasks
- Distance to be reached to access the item in question
- Visual requirements of personnel performing the tasks
- The degree of danger involved in using the access opening
- Specified time requirements for carrying out the tasks

6.4.4 Safety

This is an important maintainability design factor because maintenance personnel performing various types of tasks may be exposed to hazardous conditions. These conditions could be the result of poor consideration given to the safety aspect during the design phase. Nonetheless, some of the human safety guidelines are to install fail-safe devices as considered appropriate, fit all access openings with appropriate fillets, study the potential sources of injury by electric shock, install items requiring maintenance in such a way that hazard in accessing them is minimized, and provide appropriate emergency doors.

6.5 Maintainability Measures for Mining Equipment

Normally quantitative maintainability specifications are based on desired limiting conditions imposed on equipment maintenance labor-hours, downtime, and so on. Thus, in order to have an effective and mining equipment maintainability, it is important to have knowledge of various maintainability parameters or measures during the design phase. These measures include mean time to repair, mean preventive maintenance time, and the probability of completing repair in a given time interval (*i.e.*, the maintainability function). All of these measures are presented below, separately [4, 7–10].

6.5.1 Mean Time to Repair

This is probably the most widely used measure or parameter in maintainability analysis and is also referred to as mean corrective maintenance time. Normally, probability distributions such as normal, log-normal, and exponential are used to represent corrective maintenance times.

The system/equipment mean time to repair (MTTR) is defined by

$$MTTR = \left[\sum_{i=1}^{m} \lambda_i T_i \right] / \sum_{i=1}^{m} \lambda_i \,, \tag{6.1}$$

where

- m is the number of units;
- λ_i is the constant failure rate of unit i; for $i = 1, 2, 3, 4, \ldots, m$;
- T_i is the corrective maintenance or repair time required to repair unit i; for $i = 1, 2, 3, 4, \ldots, m$.

Example 6.1

Assume that a piece of mining equipment is composed of four replaceable subsystems 1, 2, 3, and 4 with constant failure rates $\lambda_1 = 0.0004$ failures/h, $\lambda_2 = 0.0005$ failures/h, $\lambda_3 = 0.0007$ failures/h, and $\lambda_4 = 0.0008$ failures/h, respectively. Corrective maintenance times associated with subsystems 1, 2, 3, and 4 are $T_1 = 2$ h, $T_2 = 3$ h, $T_3 = 1.5$ h, and $T_4 = 0.5$ h, respectively.

Calculate the mining equipment mean time to repair.

Inserting the specified data values into Eq. (6.1) we get

$$\begin{aligned} MTTR &= \frac{(0.0004)(2) + (0.0005)(3) + (0.0007)(1.5) + (0.0008)(0.5)}{(0.0004) + (0.0005) + (0.0007) + (0.0008)} \\ &= 1.565\,\text{h} \,. \end{aligned}$$

Thus, the mining equipment mean time to repair is 1.565 h.

6.5.2 Mean Preventive Maintenance Time

In order to keep mining equipment at a specified performance level, various preventive maintenance-associated activities such as calibrations, tuning, and inspections are performed. A well-planned and well-executed preventive maintenance program can be helpful in reducing, directly or indirectly, mining equipment downtime and improving its performance. Nonetheless, the equipment mean preventive maintenance time (*MPMT*) is defined by

$$MPMT = \left[\sum_{i=1}^{m} ET_i F_i \right] / \sum_{i=1}^{m} F_i \,, \tag{6.2}$$

where

- m is the number of preventive maintenance tasks;
- ET_i is the elapsed time for preventive maintenance task i; for $i = 1, 23, \ldots, m$;
- F_i is the frequency of preventive maintenance task i; for $i = 1, 2, 3, \ldots, m$.

In calculating the value of $MPMT$, it is to be noted that if the frequencies, F_i, are specified in maintenance tasks per hour, then the ET_i must be expressed in hours.

6.5.3 Maintainability Function

The maintainability function is used to compute the probability of accomplishing a repair in a given time interval; it is defined by

$$m(t) = \int_0^t f_r(t)\, \mathrm{d}t \,, \tag{6.3}$$

where

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

Maintainability functions for normal and exponential repair time distributions are obtained as follows:

Normal Distribution

The distribution repair time probability density function is expressed by

$$f_r(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2} \left\{ \frac{t-\mu}{\sigma} \right\}^2 \right] \,, \tag{6.4}$$

where

μ is the mean of repair times,
σ is the standard deviation of the variable repair time t around the mean μ.

Inserting Eq. (6.4) into Eq. (6.3) we obtain

$$m(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{1}{2}\left\{\frac{t-\mu}{\sigma}\right\}^2\right] \mathrm{d}t \,. \tag{6.5}$$

The mean of repair times is given by

$$\mu = \sum_{i=1}^{n} \frac{t_i}{n} \,, \tag{6.6}$$

where

n is the number of repair times,
t_i is the repair time i, for $i = 1, 2, 3, \ldots, n$.

The standard deviation is expressed by

$$\sigma = \left[\sum_{i=1}^{n} (t_i - \mu)^2 / (n-1)\right]^{1/2} \,. \tag{6.7}$$

Exponential Distribution

The distribution repair time probability density function is defined by

$$f_r(t) = \theta \exp(-\theta t) \,, \tag{6.8}$$

where

θ is the constant repair rate (*i.e.*, the reciprocal of the mean time to repair, *MTTR*),
t is the variable repair time.

Substituting Eq. (6.8) into Eq. (6.3) yields

$$m(t) = \int_{0}^{t} \theta \exp(-\theta t)\, \mathrm{d}t = 1 - \exp(-\theta t) \,. \tag{6.9}$$

Since $\theta = \frac{1}{MTTR}$, Eq. (6.9) becomes

$$m(t) = 1 - \exp\left(-\frac{t}{MTTR}\right) \,. \tag{6.10}$$

Example 6.2

Assume that the repair times of a piece of mining equipment are exponentially distributed with a mean value of 2 h (*i.e.*, $MTTR = 2$ h). Calculate the probability of completing a repair action in 4 h.

Substituting the specified data values into Eq. (6.10) we get

$$m(4) = 1 - \exp\left(-\frac{4}{2}\right) = 0.8647 \, .$$

This means that the probability of completing a repair action within 4 h is 0.8647.

6.6 Common Maintainability Design Errors and Useful Maintainability Design Guidelines for Mining Equipment

During equipment design, often various types of errors are made that adversely affect equipment maintainability. Therefore, it is important that careful attention be given during the design of mining equipment to such errors that may impact its maintainability. Nonetheless, some of the common maintainability-related design errors are as follows [7, 8, 11]:

- Locating adjustable screws close to an exposed power supply terminal or a hot component
- Placing an adjustment out of arm's reach
- Providing unreliable built-in test equipment
- Using access doors with numerous small screws
- Placing low-reliability items beneath other items
- Omitting appropriate handles
- Placing screwdriver-related adjustments underneath modules
- Placing removable parts in such a way that they cannot be dismantled without taking the entire unit from its case
- Providing inadequate space for maintenance workers to get their gloved hands into the unit to carry out necessary adjustments
- Placing adjustable screws in locations difficult for maintenance workers to find

Over the years professionals working in the area of maintainability engineering have developed various guidelines for use during the equipment design phase to improve the effectiveness of equipment maintainability. These guidelines can equally be applied to mining equipment. Some of these guidelines are as follows [11]:

- Design so as to minimize the need for tools and adjustments.
- Design so as to minimize the need for maintenance skills.
- Provide effective troubleshooting methods.
- Design for safety.

- Provide test points at appropriate places.
- Use color coding.
- Provide for effective visual inspection.
- Avoid the use of large cable connectors.
- Make use of captive-type chassis fasteners.
- Label units.
- Use standard interchangeable parts.
- Make use of plug-in instead of solder-in modules.
- Provide appropriate handles on heavy parts for ease of handling.
- Group subsystems.

6.7 Conclusions: State of Maintainability in the Underground Mining Industry

A study conducted by the US Bureau of Mines analyzed various aspects of equipment maintainability in the mining industry [3]. Some of its conclusions are as follows [3]:

- There is little evidence of the systematic application of maintainability principles in the design of operational underground coal mining equipment.
- Similarly, there is little evidence of the systematic application of human-factor principles in the design of this equipment in regard to maintenance.
- Although in the case of some machines heavy maintenance tasks could be carried out on the surface or in high-roof underground shops equipped with the requisite lifting devices, at the mine face it is extremely difficult, time consuming, and risky to perform the same tasks.
- In the case of newer and larger mining machines, there is a significant increase in task complexity and completion times with respect to maintenance.
- With the exception of some machines, task completion times for the ten most frequently performed maintenance tasks could be reduced by approx. 10 to 30% with simple improvements in equipment design.
- Maintenance risk could be reduced quite substantially with the application of accepted human-factor engineering design standards and criteria.

6.8 Problems

1. Discuss the meanings of mining equipment maintainability.
2. List the five most important design-induced maintainability problems of mining equipment.
3. What are the advantages of improved mining equipment maintainability design?
4. Discuss the following items:

- Interchangeability
- Accessibility

5. Define mean preventive maintenance time.
6. Assume that a mining system is made up of three replaceable subsystems 1, 2, and 3 with constant failure rates $\lambda_1 = 0.005$ failures/h, $\lambda_2 = 0.007$ failures/h, and $\lambda_3 = 0.009$ failures/h, respectively. Corrective maintenance times associated with subsystems 1, 2, and 3 are $T_1 = 0.5$ h, $T_2 = 2$ h, and $T_3 = 3$ h, respectively. Calculate the mining system mean time to repair.
7. Define maintainability function.
8. Prove Eq. (6.9).
9. What are the commonly occurring maintainability design errors?
10. List at least ten design guidelines useful for improving mining equipment maintainability.

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