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SYLLABUS

M-245 **MAINTENANCE MANAGEMENT**

UNIT-1: Maintenance Overview and Management System

1. Maintenance Management and Terotechnology: An Overview
2. Maintenance Objectives and Strategies
3. Preparation of Maintenance Planning and Scheduling
4. Planned Maintenance Management System and Control

UNIT-2: Maintenance Resource Management and Costing

5. Maintenance Organization
6. Maintenance Costing and Budgeting
7. Spare Parts Inventory Management
8. IT enabled Maintenance Management

UNIT-3: Key Issues in Maintenance Management

9. Reliability, Availability and Maintainability Concepts
10. Safety and Environmental Aspects in Maintenance Management
11. Human Resource Development in Maintenance Management
12. TQM and Maintenance Management

UNIT-4: Analytical Methods in Maintenance Management

13. Failure Statistics, Data Analysis and Methods of Qualitative Analysis
14. Economic of Repair and Replacement of Equipment
15. Planning and Scheduling of Plant and Overhauling Shutdown

UNIT-5: Trends in Maintenance Management

16. Condition Based Maintenance (CBM)
17. Reliability Centered Maintenance (RCM)
18. Total Productive Maintenance (TPM)
19. Maintenance Audit

NOTES

UNIT I MAINTENANCE OVERVIEW AND MANAGEMENT SYSTEM

★ STRUCTURE ★

1.1 Maintenance Management and Terotechnology: An Overview
1.2 Plant Maintenance and Life Cycle Profits
1.3 Terotechnology
1.4 Present Status of Maintenance in Indian Industry
1.5 Systematic Approach to Maintenance Management
1.6 Maintenance Objectives and Strategies
1.7 Functions and Objectives of Maintenance
1.8 Maintenance Strategy
1.9 Break-Down Maintenance/Corrective Maintenance
1.10 Fixed Time Maintenance/Preventive Periodic Maintenance
1.11 Condition Based Maintenance
1.12 Opportunistic Maintenance
1.13 Design-out Maintenance
1.14 Guidelines for Selecting Best Maintenance Strategy
1.15 Recent Developments in Maintenance Approach
1.16 Preparation of Maintenance Planning and Scheduling
1.17 Maintenance Planning
1.18 Maintenance Scheduling
1.19 Planned Maintenance Management System and Control
1.20 Planned Maintenance System
1.21 Maintenance Control
1.22 Benefits of Planned Maintenance
- *Summary*
- *Review Questions*
- *Further Readings*

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1.0 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- define maintenance management and terotechnology.
- explan maintenance objectives and strategies.
- describe preparation of maintenance planning and scheduling.
- define planned maintenance management system and control.

1.1 MAINTENANCE MANAGEMENT AND TEROTECHNOLOGY: AN OVERVIEW

Production organizations are usually concerned with converting inputs such as raw materials, labor and processes into finished products of higher value at minimum cost satisfying the customer needs. Increased competition for timely delivery of high quality products has forced manufacturers to adopt automation. This has resulted in very high investments in plant and equipment. In order to achieve maximum return on investments the production systems will have to minimize plant downtime, increase productivity, improve quality and deliver orders to customers in a timely fashion. This has brought to the forefront the role of maintenance as a key function in any production system.

Maintenance is a combination of science, art and philosophy. Its execution relies on science, art of maintenance depends on individual aptitude and its philosophy should fit to the operation or organization it serves. The focus of the maintenance function is to insure that all company assets meet and continue to meet the design function of the asset. Maintenance involves a combination of activities by which equipment or system is kept in, or restored to, a state in which it can perform its designated functions. It is an important factor in product quality and can be used as a strategy for successful competition. Many companies consider maintenance as a necessary evil, an expense to the organization, or a non-value-added function. More progressive companies view maintenance as a way to reduce costs of producing their product or providing their services. They are using this cost advantage to lower prices and increase their life cycle profits.

Maintenance management is the management of all the assets owned by a production organization, based on maximizing the return on investment in the assets. This is achieved by applying general management principles of planning, scheduling, organizing and controlling to the maintenance function.

1.2 PLANT MAINTENANCE AND LIFE CYCLE PROFITS

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Life cycle costs are total costs from inception to disposal for equipment and plant. It is the sum of all costs incurred during the lifetime of an item, that is, the total procurement and ownership costs. It is the total cost of ownership. A typical cost element structure is as follows:

Cost Categories

(*a*) **Acquisition costs**

- Research and development
  - Management
  - Engineering
- Design and prototyping
  - Engineering design
  - Fabrication
  - Testing and evaluation
- Production
  - Manufacturing
  - Plant facilities and overhead
  - Marketing and distribution

(*b*) **Operations and support costs**

- Operations
  - Facilities
  - Operators
  - Consumables (energy and fuel)
  - Downtime
- Support
  - Repair resources
  - Supply resources
    - Repairables
    - Expendables
    - Tools, test, and support equipment
  - Failure costs

- Training
- Technical data

(c) **Phase out**

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- Salvage value
- Disposal costs

Life cycle cost = Acquisition costs + operation costs + failure Cost + support cost – net salvage value

Where, Net salvage value = salvage value – disposal cost

To discount monetary values over time, all revenues and costs can be expressed in present day equivalent values.

If P = present value

f = inflation rate

e = annual return on investment rate

i = real, or effective, discount rate

$i \approx e - f$ for small values of e and f

Investment in the plant occurs from its conception to its commissioning. It all goes well the return on the investment begins when the plant comes into use and continues until the plant is finally disposed off. The management objective is to maximize life cycle profits within the constraints imposed by the need for safe operation. The nature of maintenance activity is determined by the manner in which plant and equipment is designed, selected, installed, commissioned, operated, removed and replaced. Best time to influence maintenance and unavailability costs is before the plant comes into use.

The specification for the new plant should include reliability and maintainability (availability) requirements in addition to performance, cost and safety requirements. As far as possible the expected, or useful life of the plant should also be specified. To support this the equipment manuals, drawings, spares needed, spares security of supply and training needs should be specified and included in the contract.

During the design stage in addition to performance due consideration should also be made for reliability, maintainability and useful life. Design stage considerations of reliability and maintainability can also affect the duration and cost of commissioning. At the installation stage, maintainability continues to be an important consideration as it is at this stage that the multidimensional nature of many of the maintenance problem become clear. Similarly many design faults are known and designed out at the commissioning stage of the plant. Failure to do this may cause serious maintenance problems and high unavailability in the beginning of the operational life. Operating equipment past its useful life stage will result in low availability and high maintenance cost.

The total costs to the user throughout the lifetime of the plant can often be many times the initial capital costs. It is essential that the costs of owning plant and equipment are minimized over its working life. To achieve this objective it is necessary to lower the traditional barrier between design, maintenance, operation, finance and other functions. Terotechnology embraces both the aims of life cycle cost optimization and the multifunctional approach to achieve it.

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1.3 TEROTECHNOLOGY

The name Terotechnology is based on the Greek word 'terein', which means to guard or look after. It is defined as — "A combination of management, financial, engineering and other practices applied to physical assets in pursuit of economic life cycle costs. Its practice is concerned with the specification and design for reliability and maintainability of plant , machinery, equipment, buildings and structures, with their installation and replacement, and with the feedback of information on design, performance and costs".

Terotechnology is a multidisciplinary concept and its aim is to achieve the economic life cycle costs. This can only be achieved by a coordinated consideration of reliability, maintainability and performance aspects from the design stage. Terotechnology is concerned with the provisioning and subsequent management of physical assets. Asset-Management is a cradle-to-grave strategy that commences with engineering studies prior to investment and proceeds through design and construction, and ends with operation, maintenance and discarding. During the period of use, operation and maintenance strategies will be applied to give the best performance at least costs.

1.4 PRESENT STATUS OF MAINTENANCE IN INDIAN INDUSTRY

In today's global economy, only those nations that lead in technology will lead the world. India is embarking on a modernization process in which it dreams of becoming an economic an information superpower. Maximum utilization of all forms of assets is an important pre-requisite of this challenge.

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Corrosion phenomenon, which is only a moderate fraction of all failure of plants and equipments, costs India in the region of Rs.24,000/- crores in a year. Recent survey of maintenance, condition monitoring and safety engineering practices of different sectors of Indian Industry by National Productivity Council has indicated that 50% of the maintenance work performed was reactive, 35% preventive periodic, 10% predictive and very few proactive or root-causes based. Average availability of plant and equipment in many industrial sectors range from 40% to 80%, whereas the international best practice benchmark for plant availability is more than 95%.

Similarly, capacity utilization figures of some of our core sector industry hover around 60% to 80%, as compared to a world-class level of 85% to 95%. Role of maintenance becomes significant, as for large systems or pieces of equipment maintenance and support account for as much as 60% to 75% of their overall lifecycle costs. The maintenance has grown from the symbolic spanner and tool-box of the technician to an integrated plant engineering encompassing management systems, human relations, diagnostic engineering techniques, safety engineering etc. The challenge of this millennium would be to harness and further develop this integration so that we can achieve greater results.

1.5 SYSTEMATIC APPROACH TO MAINTENANCE MANAGEMENT

A maintenance system can be viewed as a simple input-output model. The inputs to such a model are labor, management, tools, spares, equipments, plans and schedules; and the output is the equipment that is up, reliable and well configured to achieve the planned operation of the plant. This helps to optimize the resources for maximizing the output of a maintenance system. A typical maintenance system is shown in Figure 1.1.

The basics of preventive maintenance form the foundation of a maintenance management system. Once the preventive maintenance foundation is in place, inventory, work-orders, computerized maintenance management systems, and training of maintenance manpower form the next level. Involving the operator for routine maintenance, along with the predictive and Reliability Centered Maintenance (RCM) techniques, build on this foundation. With the availability of sufficient plant data, the organization can focus on its asset management strategy by Total Productive Maintenance (TPM) and maximize its life cycle profits. Once this level is achieved, the organization should strive for continuous improvement and bench marking.

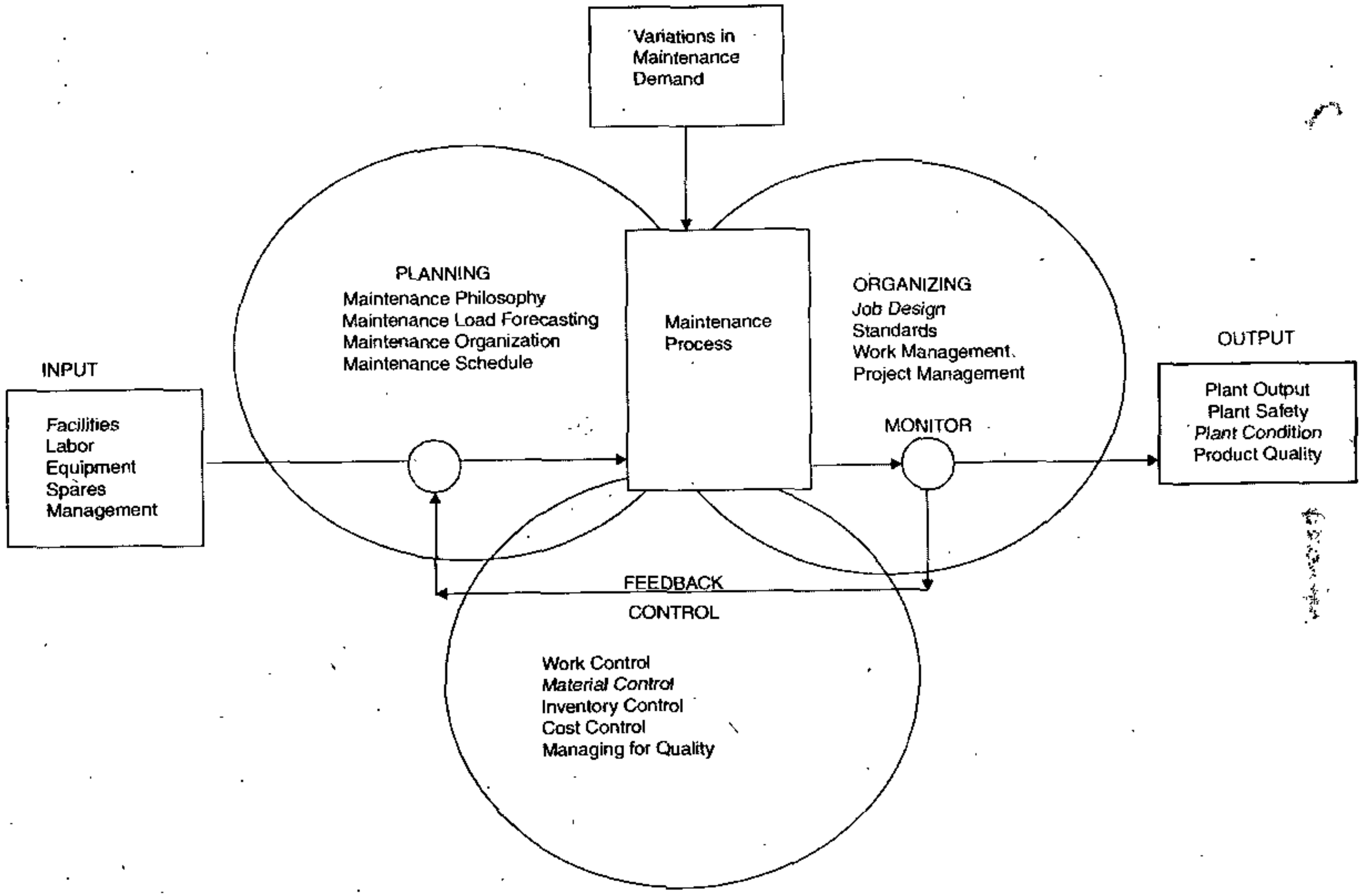

Fig. 1.1. *Typical Maintenance Systems.*

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1.6 MAINTENANCE OBJECTIVES AND STRATEGIES

In recent times industrial plants have come up with large number of automated and sophisticated machinery with complex control systems. With the coming of large size plants, investment costs have increased. Maintenance expenditure forms 3.5% to 5 % of the sales turnover. The poor functioning of many industries is generally because of lack of efficient maintenance of production plant and equipment.

The increased emphasis on equipment availability, performance, quality, environment conditions and safety considerations has made maintenance function very important. Maintenance involves a combination of activities by which equipment or system is kept in, or restored to, a state in which it can perform its designated functions. The rationalization of maintenance function requires a deep insight into what maintenance really is. Raising the efficiency of maintenance does not entail carrying out the wrong kind of work efficiently. Efficient maintenance is a matter of having the right resources at the right place at the right time, to do the right job, in the right way. To achieve this one has to understand the nature of maintenance, its relationship with production, and the functions and objectives of the maintenance department

1.7 FUNCTIONS AND OBJECTIVES OF MAINTENANCE

As discussed earlier industrial maintenance could be considered as a sub-system of an industrial organization enabling the plant to fulfill its specified function for specified time. To enable the plant to achieve this the main functions performed by the maintenance are:

- Cleaning, lubrication and topping up
- Adjustment/Calibration
- Condition assessment
- Repairs and
- Replacements

Maintenance sub-system requires input of resources and information and provides outputs in the form of plant useful-life, availability, performance, quality and safety. Maintenance management finds the most economical ways of performing the desired maintenance functions. Figure 1.2 explains the functions of a maintenance subsystem.

The objective of a production department in any industrial plant is to achieve a planned output in a specified time. This planned output is normally a function of sales demand. It determines the long term and short term production plans fixing the availability requirements of the plant. At any point of time the condition of production units of a plant can be represented as in Figure 1.3. The plant, or some part of it, may be in one of the following states:

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1. In production and only 'running maintenance' can be carried out.
2. Not being used for production and is available for maintenance without any production loss. This is the 'production window' where 'shut down maintenance' will not incur production loss. These production windows may be scheduled or may occur with random incidence. The example of production windows are week ends, night shifts, or during feedstock shortage.
3. Out of production because of scheduled maintenance and will incur production loss.
4. Unexpected breakdown and undergoing emergency maintenance. It incurs production loss and the maintenance is difficult to plan.

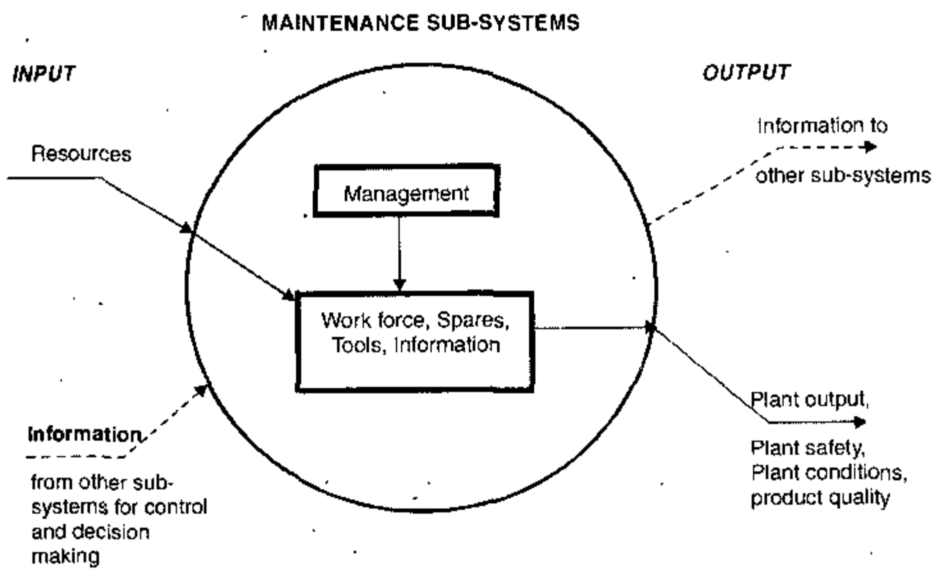

Fig. 1.2. *Functions of a Maintenance sub-System.*

5. Unexpected breakdown and waiting for maintenance because of shortage of maintenance resources. It incurs production loss.

In Fig. 1.3 maintenance is shown as pool of resources (men, spares, tools and information) directed towards achieving desired availability and plant condition following a maintenance plan. To decide on a maintenance plan it is necessary to establish maintenance objectives. These objectives should be compatible with the company objective and must be linked to profitability.

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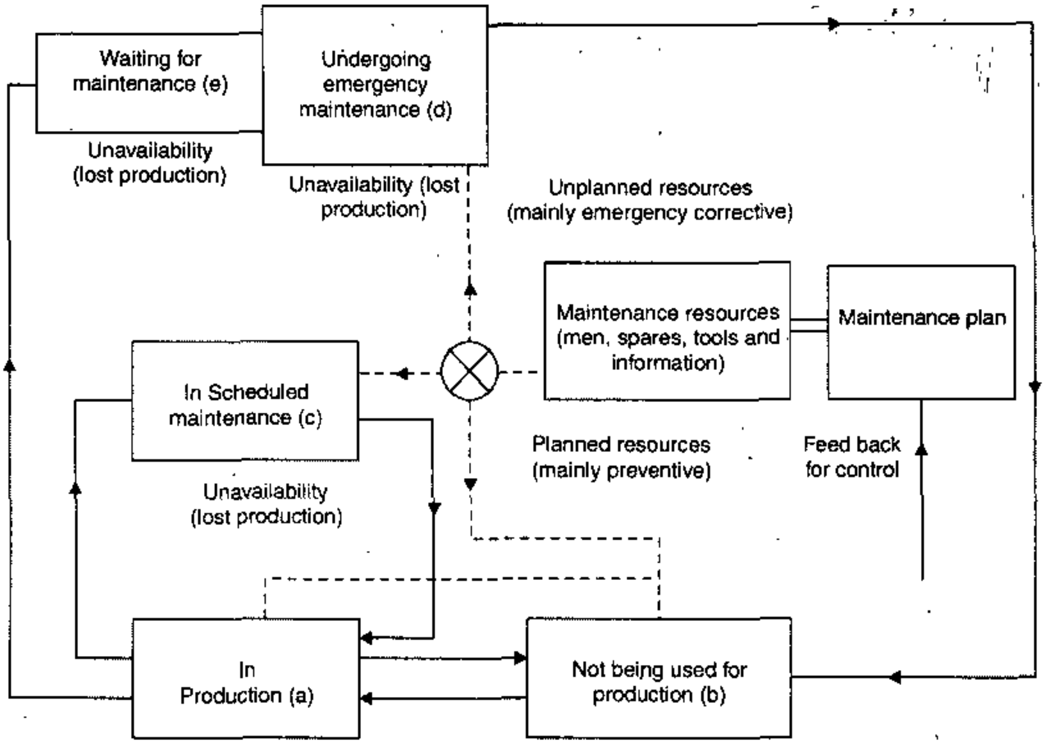

Fig. 1.3. *The Maintenance/Production System.*

Maintenance resources are used to prevent failure or to respond to failure or unacceptable deterioration. Maintenance resource cost (direct cost of maintenance) and un-availability cost (indirect cost of maintenance) affects company profits. In general, greater the level of maintenance resources the lower the level of unavailability and longer the useful life of the plant. Thus the maintenance objective should be to minimize the sum of the direct and indirect costs taking into consideration the long-term effect of maintenance decisions.

Thus the main maintenance objectives can be stated as follows:

1. To enhance overall equipment effectiveness by maximizing availability, performance and quality rates and obtaining maximum return on investments.
2. To extend the useful life of assets by minimizing wear and deterioration.
3. To ensure operational readiness of all equipment at all times and for emergency use.
4. To ensure safety of personnel using facilities and achieve acceptable safety.
5. To provide all this at minimum resource cost.

1.8 MAINTENANCE STRATEGY

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Any industrial plant consists of different functional units. These units are divided into sections and each section may have number of machines. These machines are further sub-divided into sub-assemblies and finally into the lowest level, *i.e.*, components.

Maintenance is generated from component level. When a component is unable to perform its desired function, it is said to have failed. The loss of function could be contained at component level or have consequences at plant level, depending on the design of the plant, *e.g.*, on the amount of interstage storage or redundancy. The loss of function could also have safety consequences.

Many of the machine components are designed with a useful life greater than the longest plant production cycle. In most cases such short life components will have to be identified at the design stage and made easily maintainable at component level without affecting plant availability and safety.

Other machine components will fail for reasons such as poor design, poor maintenance or mal-operation and may be expensive to maintain. It may require replacement of a higher-level assembly. In addition, as the plant ages component and assembly failures may increase. To keep the plant operating at desired level of output and safety proper maintenance strategy is required.

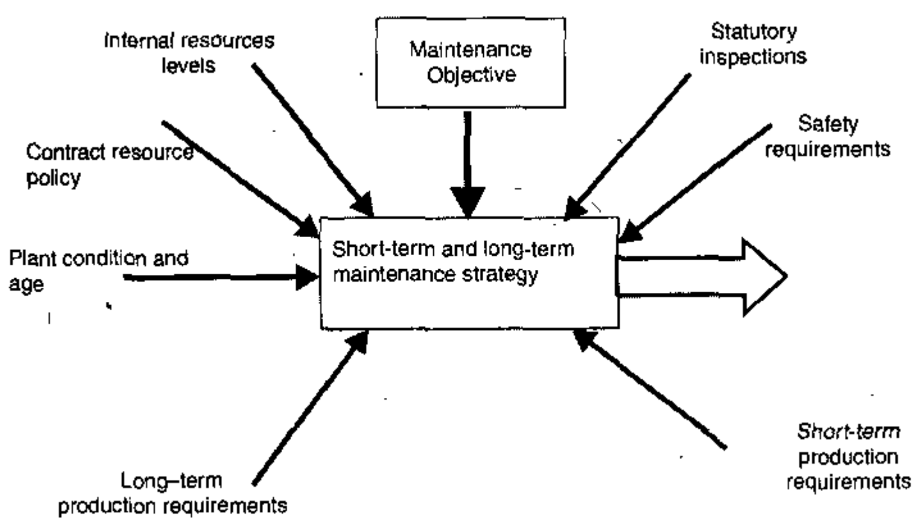

Fig. 1.4. *Factors Affecting Maintenance Strategy.*

Maintenance strategy is concerned with identifying the components of the plant, which might require maintenance, determining the most appropriate maintenance procedure and then listing the procedures in the form of a schedule for a plant.

The maintenance strategy is a function of the production-maintenance relationship and therefore in most situations will be subject to change. The factors that influence the maintenance strategy are shown in Figure 1.4.

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The commonly used maintenance strategies are as follows:

(a) Break-down maintenance/Corrective maintenance

(b) Fixed time maintenance/Preventive maintenance

(c) Condition based maintenance

(d) Opportunistic maintenance

(e) Design-out maintenance

1.9 BREAK-DOWN MAINTENANCE/CORRECTIVE MAINTENANCE

In breakdown maintenance the equipment is allowed to run till it breaks down and then maintaining it and putting back to operation. Here most of the maintenance tasks are reactive to breakdowns or production interruptions and the only focus of these tasks is how quickly the machine or system can be returned to service. The failures may often cause large secondary damages to surrounding machinery before they are discovered.

In breakdown maintenance most of the corrective maintenance work is poorly planned because of the time constraint imposed by production and plant management. As a result, manpower utilization and effective use of maintenance resources are minimal. Breakdown or reactive maintenance may cost three to four times more than the same corrective maintenance work when it is well planned. Another limitation of breakdown maintenance is that it concentrates maintenance work on obvious symptoms of the failure and not on the root cause. As a result, the reliability of the machine or system is severely reduced.

Corrective maintenance is limited to those tasks performed in order to restore the machine or system to acceptable operating condition after a failure has occurred. All corrective maintenance tasks are generally accomplished in four steps:

(i) Fault detection

(ii) Fault isolation

(iii) Fault elimination and

(iv) Verification that the fault has been eliminated.

1.10 FIXED TIME MAINTENANCE/ PREVENTIVE PERIODIC MAINTENANCE

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Here maintenance is carried out at predetermined intervals, or to other prescribed criteria to reduce the likelihood of an equipment or system not meeting an acceptable condition. Other prescribed criteria for determining the intervals could be based on fixed cumulative output, fixed number of cycles of operation or usage hours. Here it is assumed that the mechanical failure and deterioration processes are depending on time in a predictable way. The advantages of this maintenance strategy as compared to breakdown maintenance are:

- Number of unexpected shut-downs are reduced.
- Risk of secondary damages caused by initial failures is reduced.
- Better resource utilization.
- Reduced overtime costs and more economical use of maintenance workers due to working on a scheduled basis instead of a crash basis to repair breakdowns.
- Reduced product rejects, rework, and scrap due to better overall equipment condition.
- Improved safety and quality conditions.

But the actual life span varies from component to component. It depends on several factors like load, lubrication, material quality, environmental conditions etc. The limitations of preventive periodic maintenance are:

- The method does not give full protection from unexpected shut-downs.
- Some of the maintenance actions may not be necessary.
- Periodic maintenance cause increased number of running in failures.
- If incidental failures are predominant, periodic replacement may not have any positive effect on reliability.

The decision regarding the level of preventive maintenance required to bring the plant output factors and the maintenance resource levels under control is important. The various possible strategies ranging from 100% preventive to 100% corrective are possible. The aim is to establish the best strategy to achieve the maintenance objective. Figure 1.5 shows a model describing the relationship between the level of preventive maintenance and the total maintenance cost for any production unit. There is a level of preventive maintenance that minimizes the sum of the resource cost and the lost output.

The optimum level of preventive maintenance is very sensitive to the cost of lost output. As far as possible maintenance work should be carried out in the available 'production windows'.

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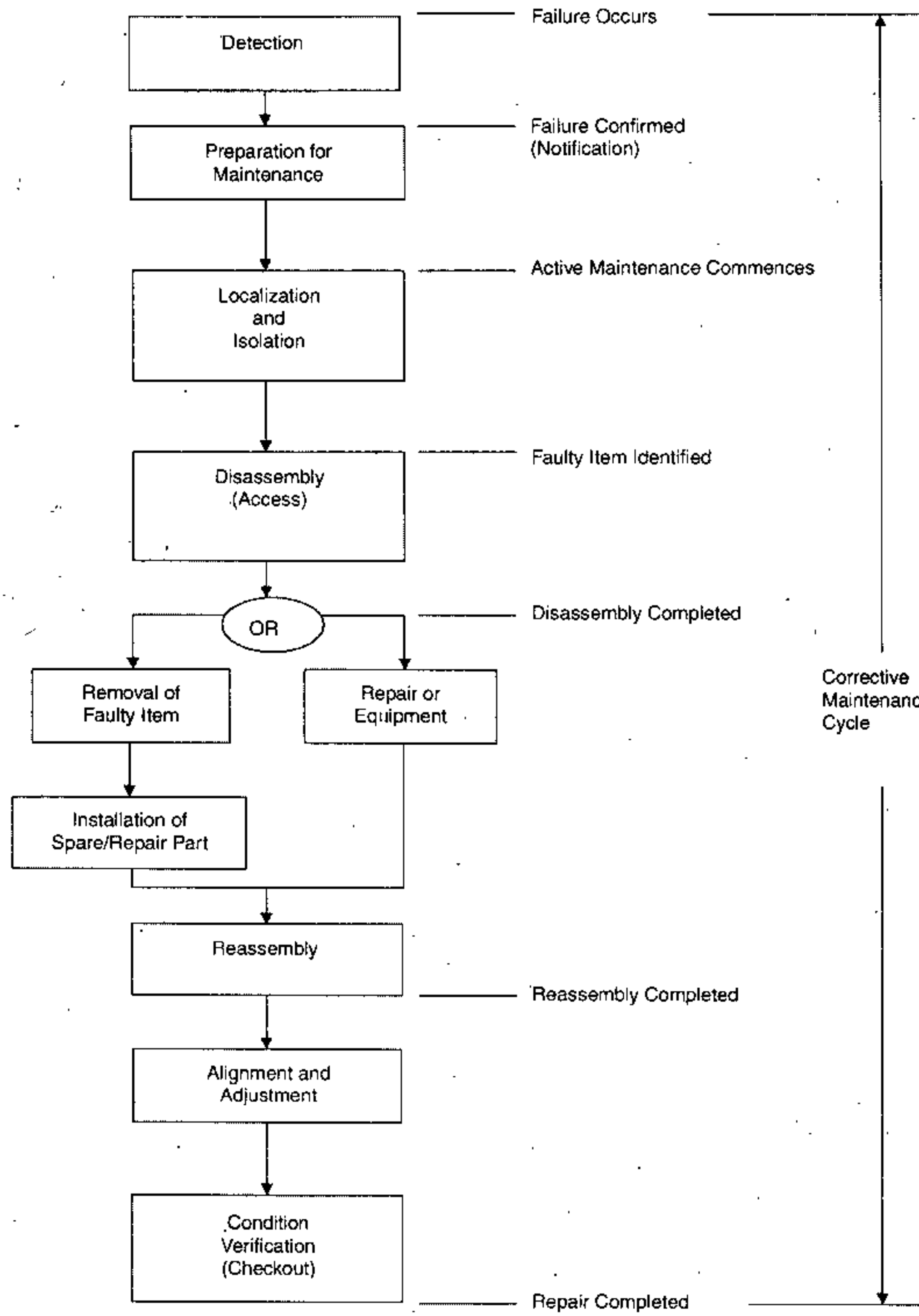

Fig. 1.5. *Corrective Maintenance Cycle.*

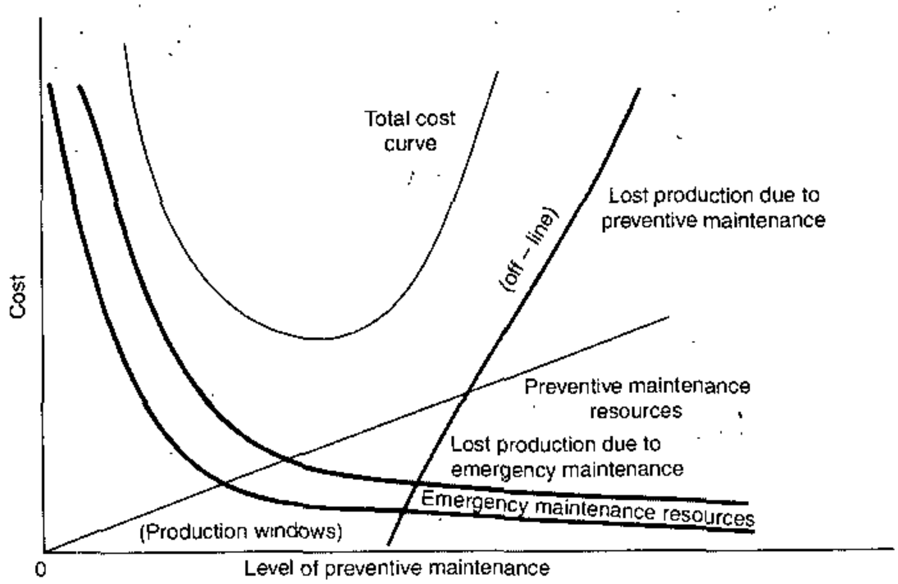

Fig. 1.6. *Possible relationship between level of preventive maintenance and total maintenance cost.*

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1.11 CONDITION BASED MAINTENANCE

In condition based maintenance the equipment is maintained when measurements indicate an incipient failure. The condition of the machine may be determined continuously or at regular intervals by monitoring vibration, wear debris, temperature and performance parameters. Any change in any of these parameters would mean a change in the condition or health of the machine.

Table 1.1: Various methods for conditions monitoring of rotating machinery and their fields of application

Methods → / **Field of Application** ↓	**Over all vibration level**	**Frequency analysis**	**Acoustic emission**	**Kurtosis**	**Crest factor**	**SPM**	**Cepstrum analysis**	**Spectrometric oil analysis**	**Wear particle analysis**	**Particle Counting**	***Magnetic plugs***	**Temperature measurements**	**Shaft alignment**	**Stroboscope**	**Ultrasonic measurements**	**Sound measurement**
Unbalance	1	1	--	--	--	--	--	--	--	--	--	--	x	--	--	--
Misalignment fault	1	1	--	--	--	--	--	--	--	--	--	--	x	x	--	--
Rolling bearing	x	x	0	x	x	1	x	x	x	x	x	x	--	--	x	x

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Sliding bearing	x	x	x	--	--	--	--	x	x	x	x	x	1	--	x	--
Gears	x	1	0	0	0	x	1	x	x	x	x	--	--	--	x	x
Resonance	x	1	--	--	--	--	--	--	--	--	--	--	x	x	1	x
Cavitation	x	x	x	0	0	x	--	--	--	--	--	--	--	--	x	x
Mechanical tolerances	x	x	--	--	--	--	--	--	--	--	--	--	x	x	--	--
Electrical unbalance	1	1	--	--	--	--	--	--	--	--	--	--	x	--	--	--
Bent shaft	1	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Oil whil	x	1	--	--	--	--	--	0	--	--	--	--	1	--	--	--
Friction	x	x	x	--	--	x	--	--	--	--	--	x	x	--	x	x
Faulty driving belts	x	x	--	--	--	--	--	--	--	--	--	--	--	1	--	--
Dirt	1	1	--	--	--	--	--	--	--	--	--	--	x	x	--	--
Contamination of oil	--	--	--	--	--	--	--	1	x	x	x	--	--	--	--	--
Speed of wear	--	--	--	--	--	--	--	x	1	x	x	--	--	--	--	--
Insufficient lubrication	x	x	x	--	0	1	--	x	x	--	--	x	x	--	x	x

1 = Normally applicable

x = Applicable with limitations

o = Requires a case-to-case study

-- = Not normally used

Implementing condition based maintenance involves measurement or monitoring of appropriate physical variables or signatures of the machine using instrumentation and interpretating the signatures to indicate if maintenance of the machine is called for or not.

Flow diagram of the condition monitoring procedure is as shown in Figure 1.6. Table 1.1 gives various methods for condition monitoring of rotating machinery and their fields of application.

The advantages of condition based maintenance are:

- It gives fairly effective protection from unexpected shutdowns.
- The machine is rarely stopped for unnecessary maintenance work compared to that in periodic maintenance.
- Damages may be prevented by reducing stress on the machine in case of incipient failure.
- Condition checking after completion of maintenance helps in checking the quality of maintenance work.

But there is always some degree of subjectivity involved in the interpretation of the measurements and thus there is always a risk of planning maintenance too early or too late. The use of condition based maintenance is justified where benefits prove to be larger than the costs on instrumentation, measurement routines, analysis and follow-up work.

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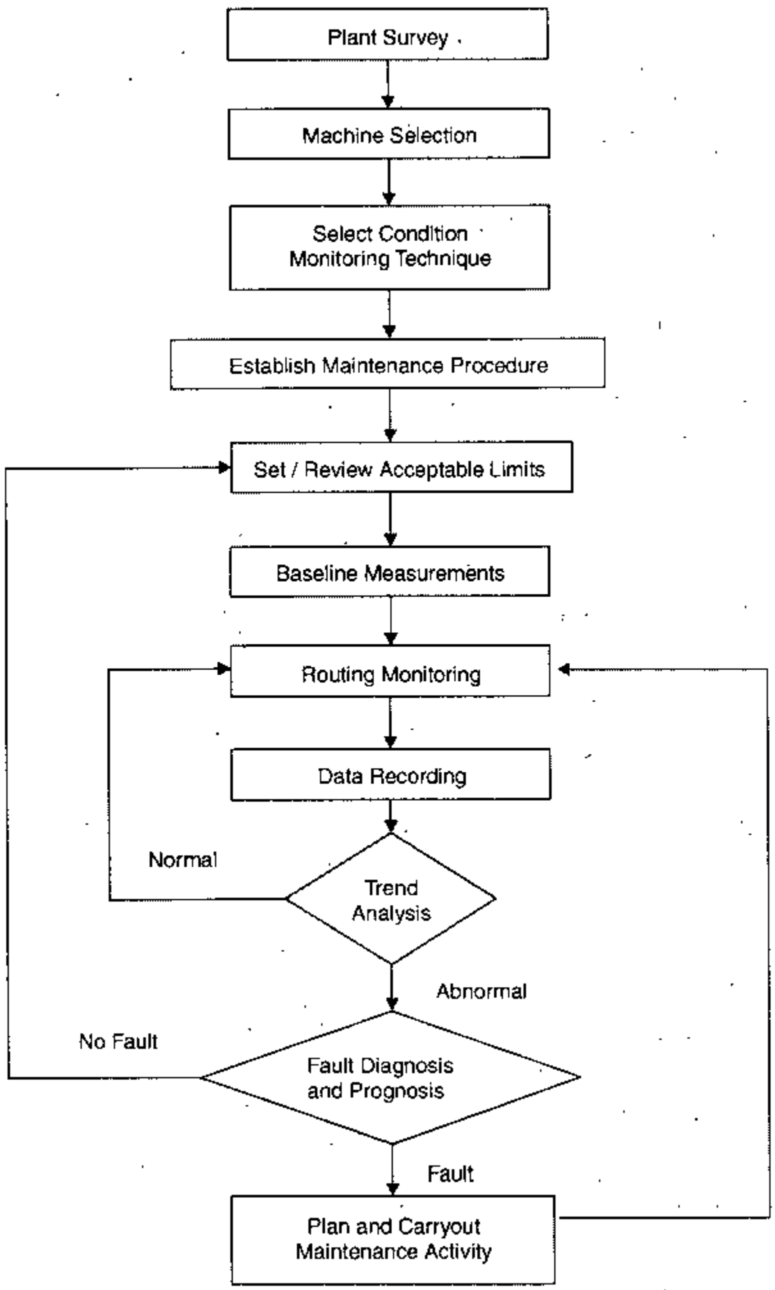

Fig. 1.6. *Flow Diagram of a Condition Monitoring Procedure.*

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1.12 OPPORTUNISTIC MAINTENANCE

Here decision to perform maintenance is taken neither on the basis of condition assessment nor on the basis of elapsed time since the last maintenance, but is carried out in the event of a machine shutdown for maintenance or other reasons (*i.e.*, change of gauge or die). The decision to prepone maintenance to the available opportunity is mostly based on the economics of preponing maintenance to that of sticking to scheduled maintenance and going for another downtime.

1.13 DESIGN-OUT MAINTENANCE

During the design stages of production equipment, designers are primarily concerned with creating mechanisms to carry out set functions. Very often and inadvertently, potential maintenance factors are not fully apparent, otherwise alternative designs would have been incorporated to reduce or eliminate them. These maintenance requirements could become fully apparent during operation, and when highlighted by critical analysis should be viewed with possibility of applying designing-out techniques.

Design-out aims to eliminate the cause of maintenance. This is an engineering design problem but it is often part of maintenance department's responsibility. It is appropriate for items of high maintenance cost where such costs arise either because of poor maintenance, poor design or operation outside design specification. In many cases design-out is aimed at items that were not expected to require maintenance. To effectively implement this policy an information system is required which may help in the identification of such items. The choice is to be made between the cost of re-design plus reduced (or eliminated) maintenance cost and the recurring cost of best maintenance procedure. Important steps involved in design-out maintenance are:

- Identifying the defects causing high maintenance costs
- To look into the possible causes of the defect
- To identify the possible solutions to eliminate the cause
- To suggest the necessary modification eliminating or reducing the effect of the defect
- To compare financial benefits against investments required
- To assess the degree of risk with the new modification.

1.14 GUIDELINES FOR SELECTING BEST MAINTENANCE STRATEGY

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The decision to select the best maintenance strategy for a given item is very important. Selection of strategy is influenced by following factors:

- Deterioration characteristics of item like mean time to failure, nature of deterioration parameter if any.
- Repair characteristics like mean time to repair, time after failure before unit function is affected.
- Economic factors like material cost, repair cost, cost of unexpected failure, cost of replacement prior to failure, monitoring cost.
- Internal, environmental and statutory safety regulations if any.

When the mean life of any item is considerably less than expected the problem boils down to establishing the cause of this and, if possible, designing it out. Often a temporary maintenance procedure is adopted until a more permanent solution is found out. Normally the ranking of the maintenance strategies is in the following order:

1. Condition based maintenance (on-line)
2. Condition based maintenance (off-line)
3. Fixed-time-maintenance
4. Operate-to-failure

1.15 RECENT DEVELOPMENTS IN MAINTENANCE APPROACH

(*a*) Proactive Maintenance

Proactive maintenance is receiving much attention as compared to other conventional maintenance strategies. It is based on the maintenance philosophy, which is 'failure proactive' rather than 'failure reactive' and avoids the underlying conditions that lead to machine faults and degradation. Unlike predictive/preventive maintenance, proactive maintenance commissions corrective actions aimed at failure root causes, not just symptoms. Its central theme is to extend the life of mechanical machinery as opposed to:

1. making repair when often nothing is broken
2. *accommodating failures as routine or normal*, or
3. pre empting crises failure maintenance in favour of scheduled failure maintenance.

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The root causes of machine failure are too many. But it is well accepted that only 10 per cent of the causes of failure are responsible for 90 per cent of occurrences. Most often the symptoms of failure mask the root cause or they are presumed themselves to be the cause.

When a machine is well designed and well manufactured, the causes of failure can generally be reduced to machine misapplication or contamination. And, among these two, contamination is clearly the most common and serious failure culprit. Therefore, the logical first-approach to proactive maintenance is the implementation of rigorous contamination control programs for lubrication fluids, hydraulic fluids, coolants, air, and fuel.

Heat, moisture, air, and particles literally rob fluids and lubricants of life. But with rigid contamination control practices, these fluids and lubricants can last indefinitely which, in turn, prolongs the life of the machine's components and keeps the machine running at the highest level of efficiency. The costs to begin a proactive contamination control program are quickly absorbed in maintenance cost savings. A basic contamination control program could be implemented in three steps:

- Establish the target fluid cleanliness levels for each machine fluid system.
- Select and install filtration equipment (or upgrade current filter rating) and contaminant exclusion techniques to achieve target cleanliness.
- Monitor fluid cleanliness at regular intervals to achieve target cleanliness levels.

(*b*) Reliability Centered Maintenance

Reliability Centered Maintenance approach was initially developed in 1978 to better assure the reliability of the aircraft. It is a systematic approach to determine maintenance requirements of any physical asset in its operating context. It focuses on preserving the functions of equipment not on preserving the equipment itself. By identifying the nature of equipment failures, it specifies actions that reduce the consequences of equipment failure like damaged equipment, possible injury, unnecessary downtime resulting in production loss and, ultimately, reduction in profits.

Implementing reliability centered maintenance requires team effort, especially from operations and maintenance. Operations identify the functions and the performance standards while maintenance identifies the type of failures. Both collaborate on the consequences of identified failures. Maintenance then defines the most appropriate maintenance strategies to predict or prevent each failure and brings them together as a planned maintenance program. Both then cooperate in carrying out the program, often with specific operator tasks. Thus, the implementing team can attain better understanding of how equipment functions and generate quality information for future use. This information is used to monitor progress, measure gains, analyze results and record events to identify new applications and benefits of reliability centered maintenance. The important steps for implementing reliability centered maintenance are as shown in Figure 1.7.

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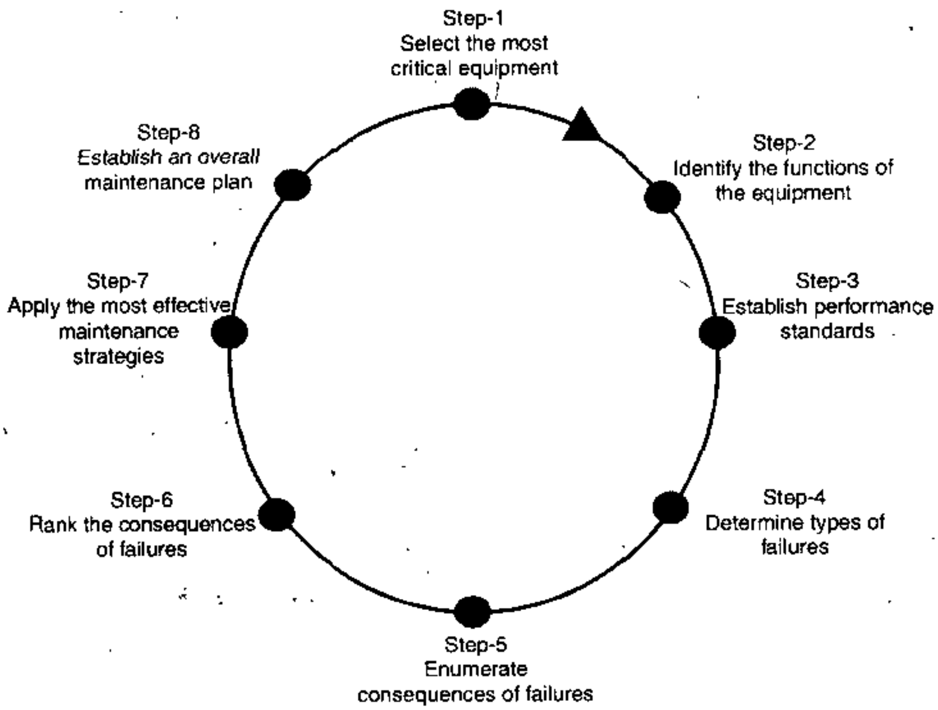

Fig. 1.7. *Important steps in implementing Reliability Centered Maintenance.*

(c) Total Productive Maintenance

Japanese in 1971 introduced the concept of Total Productive Maintenance (TPM), which is in fact productive maintenance implemented by all employees from line operator to top management. Contribution of operation and maintenance cost to life cycle cost of the system is reduced through participative programs designed to increase equipment effectiveness. The term TPM was defined by the Japan Institute of Plant Engineers to include the following five goals:

1. Maximize equipment effectiveness (improve overall efficiency).
2. Develope a system of productive maintenance for the life of the equipment.
3. Involve all departments that plan, design, use, or maintain equipment in implementing TPM.
4. Actively involve all employees-from top management to shop-floor workers.
5. Promote TPM through motivation management: autonomous small group activities.

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The word total in "Total Productive Maintenance" has three meanings related to three important features of TPM:

- Total effectiveness—pursuit of economic efficiency or profitability.
- Total PM—maintenance prevention and activity to improve maintainability as well as preventive maintenance.
- Total participation—autonomous maintenance by operators and small group activities in every department and at every level.

Overall equipment effectiveness is the product of the availability, performance rate and quality rate. It can be maximized and life cycle cost minimized through companywide efforts to eliminate the six big losses that reduce equipment effectiveness:

- Break-downs due to equipment failure.
- Set-up and adjustment (exchange of tools).
- Idling and minor stoppages due to abnormal operation of machine components.
- Reduced speed (discrepancies between designed and actual speed of equipment).
- Defects in process and rework (scrap and quality defects requiring repair).
- Reduced yield between machine start-up and stable production.

First two losses contribute to downtime, third and fourth contribute towards speed losses and the last two contribute towards quality defects. The specific steps necessary to develop a TPM program must be determined for each company individually, adjusted to fit individual requirements and production details.

1.16 PREPARATION OF MAINTENANCE PLANNING AND SCHEDULING

Planning and scheduling are the most important aspects of sound maintenance management. Planning is the process by which elements required to perform a task are determined in advance of the job start time. Scheduling deals with specific time and phasing of planned jobs together with the orders to perform the work, monitoring the work, controlling it, and reporting on job progress. Good planning is a prerequisite for sound scheduling. However, for successful planning, feedback from scheduling is necessary. The principle objectives of planning and scheduling include:

- Minimizing the idle time of maintenance work-force,

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- Maximizing the efficient use of work time, material, and equipment, and
- Maintaining the operating equipment at a level that is responsive to the need of production in terms of delivery schedule and quality.

Effective planning and scheduling contribute significantly to the following:

- Reduced maintenance costs,
- Improved utilization of the maintenance workforce by reducing delays and interruptions,
- Improved quality of maintenance work by adopting the best methods and procedures and assigning the most qualified workers for the job.

An essential part of planning and scheduling is to forecast future work and to balance the workload between different categories. The maintenance management system should aim to achieve over 90% of the maintenance work planned and scheduled in order to reap the benefits of planning and scheduling. Effective planning and scheduling requires consideration of the following aspects:

1. the operational and structural complexity of a large industrial plant
2. the dynamic nature of the relationship between production and maintenance, and
3. the relationship between maintenance strategy, maintenance workload and resource availability.

1.17 MAINTENANCE PLANNING

Planning in the context of maintenance means the process by which all the elements required to perform a task are determined and prepared prior to starting the job (Figure 1.8). Planning is a process of detailed analysis that determines and describes the work to be performed, the sequence of associated tasks, methods to be used for their performance, and the required resources – including skills, crew size, manhours, parts, special tools, and equipment, and an estimate of total cost. It also includes identification of safety precautions, required permits, communication requirement, and reference documents such as drawings and wiring diagrams. It addresses essential preparation, execution and start-up efforts. Work estimates (the setting of job duration and labor estimates) and activation of required procurements, are parts of the planning process.

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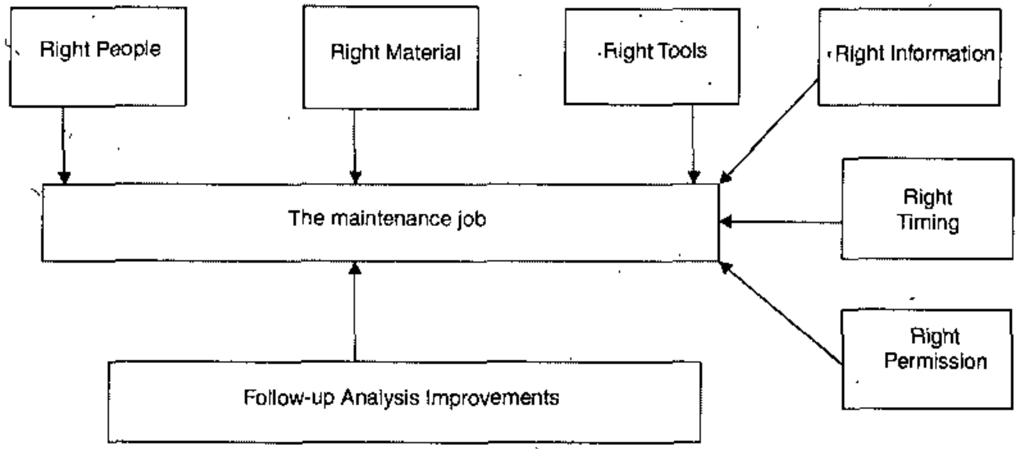

Fig. 1.8. *Role of Planning.*

Basic maintenance planning principles are as follows:

1. The planners are organized into a separate department from the craft maintenance crews to facilitate specializing in planning techniques as well as focusing on future work.
2. The Planning Department concentrates on future work (work that has not been started) in order to provide the Maintenance Department at least one week of work backlog that is planned, approved, and ready to execute. This backlog allows crews to work primarily on planned work. Crew supervisors handle the current day's work and problems. Any problems that arise after commencement of any job are resolved by the craft technicians or supervisors. After every job completion, feedback is given by the lead technician or supervisor to the Planning Department. The feedback consists of any problems, plan changes, or other helpful information so that future work plans and schedules might be improved. The planners ensure that feedback information gets properly filed to aid future work.
3. The Planning Department maintains a simple, secure file system based on equipment tag numbers. The file system enables planners to utilize equipment data and information learned on previous work to prepare and improve work plans, especially on repetitive maintenance tasks. The majority of maintenance tasks are repetitive over a sufficient period of time. File cost information assists making repair or replace decisions. Supervisors and plant engineers are trained to access these files to gather information they need with minimal planner assistance.
4. Planners use personal experience and file information to develop work plans to avoid anticipated work delays and quality or safety problems. As a minimum, planners are experienced, top level technician that are trained in planning techniques.

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5. The Planning Department recognizes the skill of the crafts. In general, the planner's responsibility is "what" and the craft technician's responsibility is "how". The planner determines the scope of the work request including clarification of the originator's intent where necessary.(Work requiring engineering is sent to plant engineering before planning). The planner then plans the general strategy of the work (such as repair or replace). The craft technicians use their expertise to determine how to make the specified repair or replacement. This arrangement does not preclude the planners from being helpful by attaching procedures from the file for reference.
6. Wrench time is the primary measure of workforce efficiency and of planning and scheduling effectiveness. Wrench time is proportion of available-to-work time during which craft persons are not being kept from productively working of a job site by delays such as waiting for assignment clearance, parts, tools, instructors travel, coordination with other crafts or equipment information. Work that is planned before assignment reduces unnecessary delays during jobs and work that is scheduled reduces delays between jobs. The planning process comprises all the functions related to the preparation of the work order, bill of material, purchase requisition, necessary drawings, labor planning sheet, job standards, and all the data needed prior to scheduling and releasing the work order. An effective planning procedure should include the following steps:
   - Determine the job content (may require site visits).
   - Develop a work plan. This gives the sequence of activities in the job and establishing the best methods and procedures to accomplish the job.
   - Establish crew size for the job.
   - Plan and order parts and material.
   - Check if special equipment and tools are needed and obtain them.
   - Assign workers with appropriate skills.
   - Review safety procedures.
   - Set priorities(emergency, urgent, routine and scheduled) for all maintenance work. Table 1.2 explain the priorities used for maintenance work.
   - Assign cost accounts.
   - Complete the work order.
   - Review the backlog and develop plans for controlling it.
   - Predict the maintenance load using an effective forecasting technique.

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Table 1.2: Priorities used for Maintenance Work

Priority Code	Name	Time frame work should start	Type or work
1.	Emergency	Work should start immediately	Work that has an immediate effect on safety, environment, quality, or will shutdown the operation.
2.	Urgent	Work should start within 24 hours	Work that is likely to have an impact on safety, environment, quality, or will shutdown the operation.
3.	Routine	Work should start within 48 hours	Work that is likely to impact the production within a week.
4.	Scheduled	As scheduled	Preventive maintenance and routine, all programmed work.
5.	Postponable	Work should start when resources are available or at shutdown period	Work that does not have an immediate impact on safety, health, environment, or the production operations.

The maintenance work order usually does not provide enough space to perform the details of planning for extensive repairs, overhauls, or large maintenance projects. In such case where the maintenance job is large and requires more than 20 hours, it is useful to complete a maintenance planning sheet (Figure 1.9). In the maintenance planning sheet, the work is broken down into elements. For each element, the crew size and the standard times are determined. Then, the content of the planning sheet is transferred to one or more work orders. In filling out the planning sheet or the work order, the planer must utilize all the expertise available in the maintenance department. Thus, consultations with supervisors, foremen, plant engineers, and workers should be available and very well coordinated. Therefore, the planning and scheduling job requires a person with the following qualifications:

- Full familiarity with the production methods used throughout the plant.
- Sufficient experience to enable him/her to estimate labor, material, and equipment needed to fill the work order.
- Excellent communication skills.
- Familiarity with planning and scheduling tools.
- Preferably with some technical qualification.

The planning office should be centrally located and its organization will depend on the size of the company. The planning process can be divided into three basic levels, depending on the planning horizon:

1. Long range planning (covers a period of 5 years or more).
2. Medium range planning (1-month to 1-year plans).
3. Short range planning (daily and weekly plans).

For long and medium range planning, the planner needs to utilize the following methods:

1. Sound forecasting methods to estimate the maintenance load.
2. Reliable job standard times to estimate staffing requirements.
3. Aggregate planning tools such as linear programming to determine resource requirements.

The long-range plan covers a period of 3 to 5 years and sets plans for future activities and long-range improvements. The medium-range plan covers a period of 1 month to 1 year. The plan will specify how the maintenance workforce will operate and will provide details for major overhauls, construction jobs, preventive maintenance plans, plant shutdowns, and vacation planning. This plan balances the need for staffing over the period covered and estimates required spare parts and material acquisition. Shortrange planning concerns periods of 1 day to 1 week. It focuses on the determination of all the elements required to perform industrial tasks in advance.

Sheet .... of			Filled by		Date	
Equipment Identification No.:			Approval		Priority	
No.	Completion Date	Work Order No.	Unit	Work Description	Crafts	Estimated time

Fig. 1.9. *Maintenance Planning Sheet*

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1.18 MAINTENANCE SCHEDULING

Maintenance scheduling is the process by which jobs are matched with resources and sequenced to be executed at certain points in time. Basic maintenance scheduling principles are as follows:

1. Job plans providing number of persons required, lowest required craft skill level, craft work hours per skill level and job duration information are necessary for advance scheduling.
2. Weekly and daily schedules must be adhered to as closely as possible. Proper priorities must be placed on new work orders to prevent undue interruption of these schedules.
3. A scheduler develops a one week schedule for each crew based on a craft hours available forecast that shows highest skill levels available, job priorities, and information from job plans.
4. The one week schedule assigns work for every available work hour. The schedule allows for emergencies and high priority, reactive jobs by scheduling a sufficient amount of work hours on easily interrupted tasks. Preference is given to completing higher priority work by under-utilizing available skill levels over completing lower priority work.
5. The crew supervisor develops a daily schedule one day in advance using current job progress, the one week schedule and new high priority, reactive jobs as a guide. The crew supervisor matches personnel skills and tasks. The crew supervisor handles the current day's work and problems even to rescheduling the entire crew for emergencies.
6. Wrench time is the primary measure of work force efficiency and of planning and scheduling effectiveness. Work that is planned before assignment reduces unnecessary delays during jobs and work that is scheduled reduces delays between jobs. Schedule compliance is the measure of adherence to the one week schedule and its effectiveness.

A reliable schedule must take into consideration the following:

1. A job priority ranking that reflects the urgency and the criticality of the job
2. Whether all the materials needed for the work order are in the plant (if not, the work order should not be scheduled)
3. The production master schedule and close coordination with operation
4. Realistic estimate and what is likely to happen rather than what scheduler desires
5. Flexibility in the schedule (the scheduler must realize that flexibility is needed, especially in maintenance; the schedule is often revised and updated).

Planning the maintenance work is a prerequisite for sound scheduling. In all types of maintenance work, the following are necessary requirements for effective scheduling:

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1. Written work orders that are derived from a well-conceived planning process. The work order should explain precisely the work to be done, the methods to be followed, the crafts needed, spare parts needed, and priority.
2. Time standards that are based on work measurement techniques
3. Information about craft availability for each shift
4. Stock of spare parts and information on restocking
5. Information on the availability of special equipment and tools necessary for maintenance work
6. Access to the plant production schedule and knowledge about when the facilities will be available for service without interrupting the production schedule
7. Well defined priorities for the maintenance work. These priorities must be developed through close coordination between maintenance and production
8. Information about jobs already scheduled that are behind schedule (backlogs). The scheduling procedure should include the following steps:
   - Sort out backlog work orders by crafts.
   - Arrange orders by priority.
   - Compile a list of completed and carryover jobs.
   - Consider job duration, location, travel distance, and the possibility of combining jobs in the same area.
   - Schedule multi-craft jobs to start at the beginning of every shift.
   - Issue a daily schedule (except for project and construction work).
   - Authorise a supervisor to make work assignments.

The maintenance schedule can be prepared at three levels, depending on the horizon of the schedule:

- The long-range or master schedule, covering a period of 3 months to 1 year,
- the weekly covering one week, and
- the daily schedule covering the work to be completed each day.

The long-range schedule is based on existing maintenance work orders, including blanket work orders, backlog, preventive maintenance, and anticipated emergency maintenance. It should balance long-term demand for maintenance work with available resources. Based on; long-term schedule,

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requirements for spare parts and material could be identified and ordered in advance. The long-range schedule is usually subject to revisions and updating to reflect changes in plans and realized maintenance work.

The weekly maintenance schedule is generated from the long-range schedule and takes into account current operations schedules and economic considerations. The weekly schedule should allow for about 10% to 15% of the workforce to be available for the emergency work. The planner should provide the schedule for the current week and the following week, taking into consideration the available backlog. The work orders that are scheduled for the current week are sequenced based on priority. Critical path analysis and integer programming are techniques that can be used to generate a schedule. In most small and medium sized companies, scheduling is performed based on heuristic rules and experience.

The daily schedule is generated from the weekly schedule and is usually prepared the day before. This schedule is frequently interrupted to perform emergency maintenance. The established priorities are used to schedule the jobs. In some organizations, the schedule is handed to the area supervisor, who assigns the work according to the established priority.

1.19 PLANNED MAINTENANCE MANAGEMENT SYSTEM AND CONTROL

It is well understood that well-planned, properly scheduled and effective communication can accomplish more work, more efficiently, and at a lower cost. Work properly prepared in this fashion disturbs operations less frequently, and is accomplished with higher quality, greater job satisfaction, and higher organizational morale than jobs performed without proper preparation. Planned maintenance refers to maintenance work that is performed with advance planning, foresight, control, and records. It is characterized by the following:

- The maintenance policy has been stated carefully.
- The application of the policy is planned in advance.
- The work is controlled to conform to the original plan.
- Data are collected, analyzed, and used to provide direction for future maintenance policies.

A planned-maintenance system administers the company's maintenance policy by providing the means of technically and financially directing and controlling the maintenance operations with the objective of higher plant maintenance standards and greater cost effectiveness. The successful planned-maintenance systems are those, which are simple to administer and involve shop-floor personnel in the minimum amount of paper work.

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1.20 PLANNED MAINTENANCE SYSTEM

Figure 1.10 explains the working of planned maintenance management system. The steps involved in evolving a successful planned maintenance system are as follows:

1. The first step is to establish what is to be maintained. This involves setting up of a facility record with complete details of all the items in the plant.
2. Next step involves preparation of maintenance schedule for every item of plant or equipment, which requires application of planned preventive maintenance. In the first instance this may be done for critical units of the plant. After gaining experience this can be implemented for all the units in the plant.
3. Detailed job specifications communicating engineers requirements to the tradesman are prepared. They are prepared separately for each trade and frequency of inspection.
4. In order to apply job specification and control their issue, a maintenance program is drawn up. It is convenient to plan preventive maintenance on a weekly basis. This is done in close collaboration with production department. The production planner and planned maintenance controller work very close together. A proper arrangement for plant release for planed maintenance work is an absolute essential requirement.
5. Each week copies of agreed weekly planning program are distributed by the maintenance planning office to the shop-floor production staff and to the maintenance staff, together with the appropriate job specifications listed on the planning program for distribution to the tradesman selected to carryout preventive inspection. The responsibility to select the tradesman to do this work must be that of maintenance supervisor, who knows which of his men are best suited for the job. Plant must be released according to the program and maintenance persons must be made available to carry out maintenance work.
6. A blank inspection report accompanies the job specification. The inspection report is completed by the tradesmen carrying the maintenance job in accordance with the accompanying job specification. Inspection reports are checked and signed by maintenance supervisor before passing it back to the planning office. He can add any pertinent information that might

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be required for the plant-history record. Any fault which is noticed during planned inspections and not attended because of any reasons is reflected on the inspection report. Planning department schedules these jobs depending on the urgency involved.

7. Any emergency work arising at the shop floor is passed on to the maintenance supervision directly by the production supervision in the form of work-order. Work-orders are completed by the tradesmen carrying out the maintenance job. Work-orders are checked and signed by the maintenance supervisor before passing them on to planning office. He can add pertinent information that may be useful for the plant history record:

8. Plant history records are compiled from the inspection reports and maintenance requests after completion of the jobs by the tradesmen. Proper analysis of maintenance reports and designing out maintenance as a result of such an analysis helps in raising the maintenance standards and improve the cost effectiveness. As a result of the analysis if emergency maintenance is found to persist, it will indicate one of the following:

   - Insufficient maintenance.
   - Incorrect maintenance.
   - Inadequate standards of maintenance work.

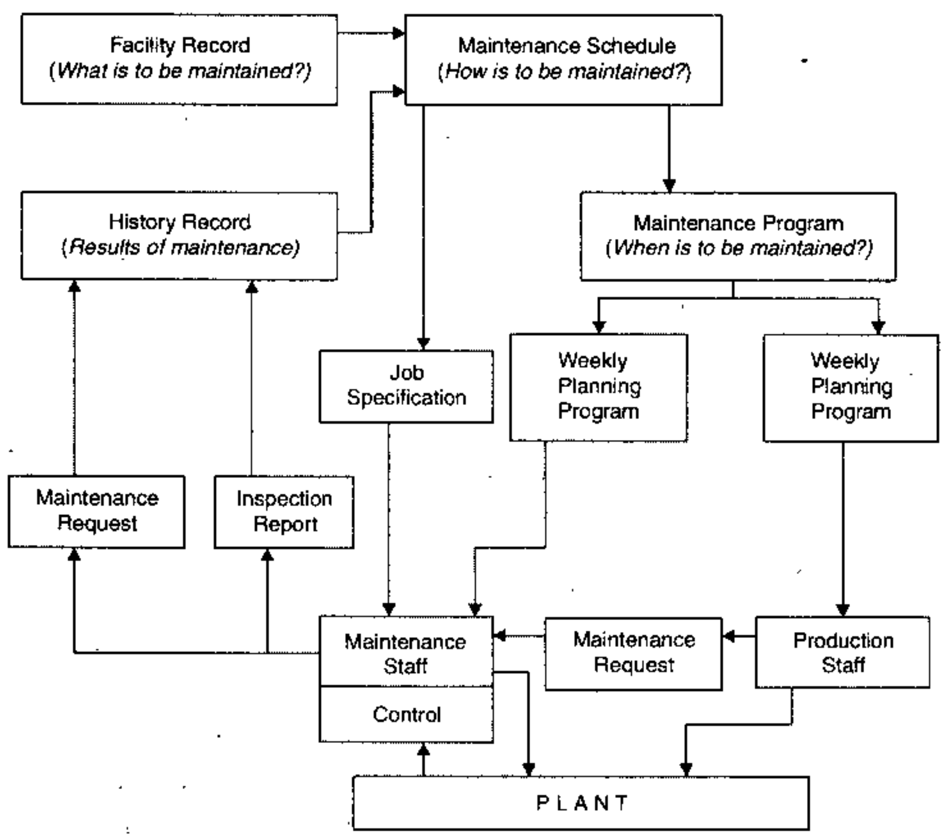

Fig. 1.10. *Planned Maintenance Management System.*

This will mean increasing the frequency of inspections, modifying the schedule to ensure adequate maintenance of those machines, which are causing emergency maintenance, and closer supervision of maintenance workforce. On the other hand, if few or no faults are reported, this may be because of uneconomic over maintenance. It may require decrease in maintenance actions.

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1.21 MAINTENANCE CONTROL

Figure 1.11 depicts the maintenance control cycle, which can be defined as follows:

- The objectives could be plant availability, performance and quality
- Sampling output is to collect data from the work order or equipment history records
- Analyzing the sample to determine if the objective has been met. For example, does the level of quality meet customer satisfaction or does it meet specifications? Also, is equipment availability and performance according to desired targets?
- Corrective action could be revising maintenance policies, changing maintenance schedules, upgrading job specifications, training workers and implementing new maintenance programs and strategies if necessary.

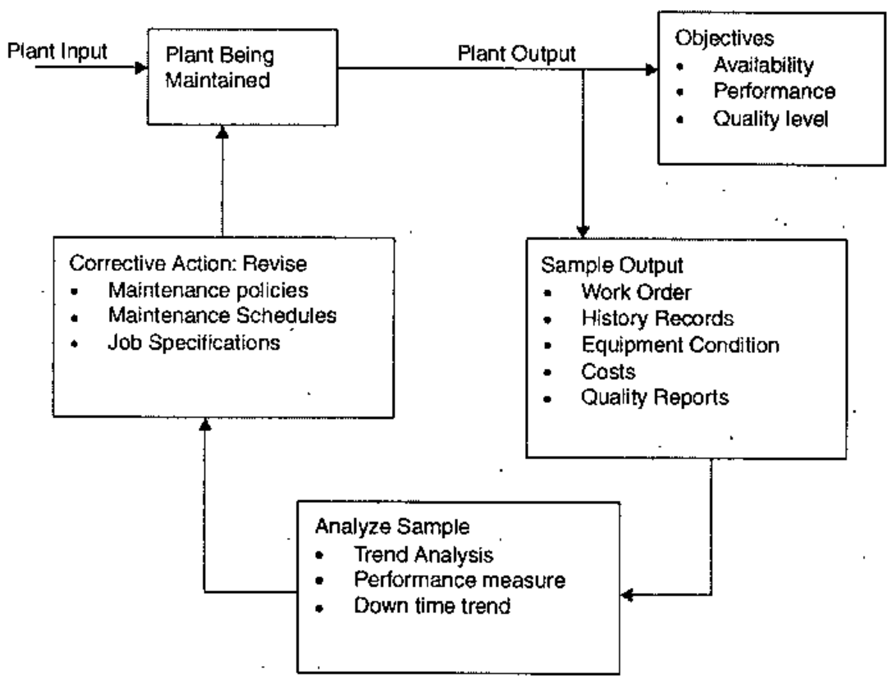

Fig. 1.11. *Maintenance Control Cycle.*

This requires the establishment of procedures and forms for administering maintenance work; standards for data collection and analysis; and means

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for effective reporting of work, equipment condition, and product quality. The later three items are necessary for work control, cost control and plant condition control. Maintenance control comprises the following three important functions:

- Work order coordination and planning.
- Work order processing.
- Information feedback and corrective action.

Work order coordination and planning is concerned with satisfying maintenance demand while meeting the requirements of production and the capacities of maintenance resources. Work order processing is concerned with work order release scheduling and work dispatch. The feedback and control function essentially deals with information gathering and decision making to achieve set goals and objectives.

Information feedback and corrective action is concerned with the collection of data about the status of the work execution, system availability, work backlog and quality of work performed. Then, this information is analyzed and an appropriate course of action is formulated. This course of actions and decisions is aimed at improving the following:

- Work Control
- Cost Control
- Quality Control
- Plant Condition Control.

(*a*) Work Control

This type of control monitors the work status and the accomplished work to investigate if the work has been performed according to standards (quality and time). In this type of control, it is assumed that the maintenance control system includes standards that are assigned in advance of actual maintenance work performed. A set of reports is generated in this category of control. These include a report showing performance according to standard by the trades utilized for the job and their productivity. In this report, it is good practice to indicate what proportion of maintenance work is performed using overtime. Other reports that are useful for work control are backlog percentage of emergency maintenance to planned maintenance and percentage of repair job originated as a result of PM inspection. All these reports reflect some sort of efficiency measures. The backlog report is essential for work control. It is good practice to maintain a weekly backlog report by trade. The report should also indicate the cause of the backlog. It is essential to have a healthy backlog, which generally ranges from 2 to 4 weeks. Too much or too little backlog necessitates a corrective action. In case a downtrend in the backlog is identified, one of the following corrective actions may be necessary:

- Reduce contract maintenance
- Consider transfer between departments
- Downsize maintenance workforce.

If the backlog is increasing and a clear trend is identified, one of the following corrective actions may be necessary:

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- Increase contract maintenance
- Consider transfer between departments
- *Schedule cost-effective overtime*
- Increase maintenance workforce.

The total backlog should be controlled by using statistical process control tools, *specifically control charts.*

(*b*) Cost Control

Maintenance cost consists of the following:

- Direct maintenance cost, which is the cost of labor, spares, material, equipment and tools
- Downtime cost due to breakdown
- Cost of quality due to products being out of specification as a result of machine defects
- Redundancy cost due to equipment backups
- Equipment deterioration cost due to lack of proper maintenance
- Cost of over maintaining.

Almost all information about cost is available on the *work order. A summary* of maintenance costs by work order must be issued monthly. This is utilized to control maintenance costs and develop the cost of manufactured products.

The cost reports will indicate the most *needed* cost reduction programs. Cost reduction should be an ongoing effort in any sound maintenance program. The areas where cost reduction programs can be launched are as follows:

- Considering the use of alternative maintenance materials
- Modifying inspection procedures
- Revising maintenance procedures, particularly making adjustments in the crew size and methods
- Redesigning material handling procedures and the workshop layout.

(*c*) Quality Control

Maintenance has a direct link to the quality of products. Well-maintained equipment produces less scrap than poorly maintained equipment. It is also well known that the condition of machine affects its process capability.

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A monthly report of the percentage of repeat jobs and product rejects may help identify which machines require an investigation to determine the causes of quality problems. Once the machines are investigated, a corrective course of action will be taken to rectify the problem. The action may entail a modification of the current maintenance policy and/or training of a trade force.

(*d*) Plant Condition Control

Plant condition control requires an effective system for recording failures and repairs for critical and major equipment in the plant. This information is usually obtained from the work order and equipment history record. The records in the equipment history file include the time of failure, the nature of the failure, the repairs undertaken, total downtime, and machines and spares used.

A monthly maintenance report should include downtime of critical and major equipment and its availability. If downtime is excessive or the equipment availability and readiness is low, a corrective action must be taken to minimize the occurrence of failure. The corrective action may require the establishment of a reliability improvement program or a planned maintenance program, or both.

1.22 BENEFITS OF PLANNED MAINTENANCE

Following benefits are achieved by implementing planned maintenance in any plant:

1. **Reduction in Emergency Maintenance:** Implementing planned maintenance leads to decreased number of breakdowns, which results in reduction of emergency maintenance work.
2. **Reduction in Downtime:** Planned maintenance helps in better spare parts management, which ultimately leads to reduction in downtimes.
3. **Increased Plant Availability for Production:** Reduction in downtime and number of emergency break-downs results in increased plant availability.
4. **Improved Labor Utilization on Maintenance and Production:** In planned maintenance emergency maintenance standby tradesmen are no longer required and can be more productively employed on planned productive maintenance jobs. Production operatives are no longer idle as they were while their machines were under emergency maintenance.
5. **Extends Duration Between Overhauls:** Raising maintenance standards by regular attention to lubrication, adjustments and replacement of

defective components before they cause extensive damage to other parts of a machine extends the life of machines. The need for a complete overhaul becomes significantly less frequent.

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6. **Reduces Spares Replacement, Assists Stores Control:** Regular inspections ensures regular replacement of defective components before more extensive damage is caused. Inspections provide early warning of impending component failure, providing time for stores control to obtain parts required if they are not stock items. Panic buying becomes a nightmare of the past.
7. **Improves Machine Efficiency:** In planned maintenance machine performance level is checked and maintained to a predetermined and acceptable standard, machine outputs are raised and percentage 'scrap' is reduced.
8. **Provides Reliable Cost and Budgetary Control:** Implementing planned maintenance management system in any plant for reasonably long-time generates realistic cost data and helps in imposing budgetary controls.
9. **Provides Information for Considering Machine Replacement:** Apart from obsolescence, it is difficult to justify on financial grounds the replacement of a machine that is working, unless some reliable operating cost information which includes maintenance is available to management. Worn out machinery that is beyond economical repair ties up maintenance labor and spare parts, and maintenance costs continue to remain high. When it can be clearly shown that a machine is beyond economical repair, then it is time to consider its early replacement.

SUMMARY

- Maintenance is a combination of science, art and philosophy. Its execution relies on science, art of maintenance depends on individual aptitude and its philosophy should fit to the operation or organization it serves.
- The name Terotechnology is based on the Greek word 'terein', which means to guard or look after. It is defined as—A combination of management, financial, engineering and other practices applied to physical assets in pursuit of economic life cycle costs.
- The maintenance has grown from the symbolic spanner and tool-box of the technician to an integrated plant engineering encompassing management systems, human relations, diagnostic engineering techniques, safety engineering etc.
- A maintenance system can be viewed as a simple input-output model. The inputs to such a model are labor, management, tools, spares, equipments,

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plans and schedules; and the output is the equipment that is up, reliable and well configured to achieve the planned operation of the plant.

- Maintenance strategy is concerned with identifying the components of the plant, which might require maintenance, determining the most appropriate maintenance procedure and then listing the procedures in the form of a schedule for a plant.
- In breakdown maintenance the equipment is allowed to run till it breaks down and then maintaining it and putting back to operation.
- The decision to prepone maintenance to the available opportunity is mostly based on the economics of preponing maintenance to that of sticking to scheduled maintenance and going for another downtime.
- Maintenance requirements could become fully apparent during operation, and when highlighted by critical analysis should be viewed with possibility of applying designing-out techniques.
- Planning and scheduling are the most important aspects of sound maintenance management. Planning is the process by which elements required to perform a task are determined in advance of the job start time. Scheduling deals with specific time and phasing of planned jobs together with the orders to perform the work, monitoring the work, controlling it, and reporting on job progress.
- Maintenance scheduling is the process by which jobs are matched with resources and sequenced to be executed at certain points in time.

REVIEW QUESTIONS

1. Define maintenance and its function?
2. What are the life cycle cost components for any plant?
3. Which are the factors affecting life cycle profits of any industrial plant?
4. How can maintenance affect the life cycle profits of any equipment and plant?
5. Explain what do you understand by terotechnology?
6. What are the main components of a maintenance system?
7. What is maintenance objective?
8. What are the functions of a maintenance system?
9. What type of information you will be looking into before deciding for a proper maintenance strategy?
10. Explain the procedure you will recommend for choosing a suitable maintenance strategy?
11. What are the important steps required to accomplish a corrective maintenance task?

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12. What is preventive maintenance? Explain different preventive maintenance tasks?

13. How is the total maintenance cost affected by the level of preventive maintenance?

14. What do you understand by preventive predictive maintenance? How can it be implemented in any plant?

15. What is opportunistic maintenance?

16. What is design-out maintenance? Explain the situations and the steps in which it should be applied?

17. What do you understand by proactive maintenance?

18. What is reliability centred maintenance? What are the important steps involved in implementing it in any plant?

19. What do you understand by total productive maintenance?

20. What is overall equipment effectiveness? How can it be maximized?

21. What do you understand by maintenance planning and scheduling?

22. How can Unit Criticality be classified?

23. What are the maintenance scheduling characteristics?

24. What do you understand by maintenance windows?

25. How can you forecast and analyze the maintenance workload of any plant?

26. What are the basic principles of maintenance planning?

27. What are the steps in effective planning procedure?

28. What should be the qualifications for a good planner and scheduler?

29. Explain the basic levels of planning commonly used?

30. What are the methods used in long and medium range planning?

31. How are the priorities specified for maintenance work?

32. What are the basic principles of scheduling?

33. What are the necessary requirements of effective scheduling?

34. What are the considerations for a reliable schedule?

35. What are the characteristics of planned maintenance?

36. Explain the working of a planned maintenance management system?

37. Visit a plant in your area and design a planned maintenance management system for it?

38. What are minimum documents required to run a planned maintenance management system?

39. What requirements should be met by job specifications?

40. What is work order and how does it help in planned maintenance?

41. What information could be obtained from a well designed work order?

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42. Suggest a suitable format for maintaining the equipment history record?
43. Describe the maintenance control cycle?
44. What are the objectives of maintenance control?
45. Visit two plants in your area and collect samples of their work order. For each point out deficiencies and suggest improved work orders?
46. What are benefits achieved by implementing planned maintenance?

FURTHER READINGS

- **Comprehensive Maintenance Management: Policies, Strategies And Options:** Amit Telang and A.D. Telang, PHI Learning.

NOTES

UNIT II MAINTENANCE RESOURCE MANAGEMENT AND COSTING

★ STRUCTURE ★

2.1 Maintenance Organization
2.2 Goals and Objectives of Maintenance Organization
2.3 Key Issues Affecting Maintenance Organization Structure
2.4 Roles and Responsibilities
2.5 Maintenance Costing and Budgeting
2.6 Maintenance Costing
2.7 Maintenance Budgeting
2.8 Zero Based Budgeting
2.9 Spare Parts Inventory Management
2.10 Types of Spare Parts
2.11 Life Cycle of Spare Parts
2.12 Myths about Spare Parts Management Program
2.13 Spare Parts Management and other Systems
2.14 Benefits of Spare Parts Management
2.15 Cost Control for Spare Parts: Role of Maintenance
2.16 Information Technology (IT) Enabled Maintenance Management
2.17 Benefits of IT Enabled Maintenance
2.18 Conceptual Model of the Maintenance Function
2.19 Maintenance Databases
2.20 CMMS Modules
2.21 Software Selection
2.22 Computerised Maintenance System Implementation
- *Summary*
- *Review Questions*
- *Further Readings*

2.0 LEARNING OBJECTIVES

After going through this unit, you will be able to:

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- describe maintenance organization.
- define maintenance costing and budgeting.
- explain spare parts inventory management.
- define IT enabled maintenance management.

2.1 MAINTENANCE ORGANIZATION

The structure and organization of maintenance in some plants owes more to the origins of the plant, the nature of its business and the 'culture' in which it operates than to any detailed analysis of the maintenance needs of the plant. In most of these cases, efficiency is likely to be problematical. Today, in the early stages of the 21st century, we are surrounded by very high technology systems. Maintenance function in most manufacturing companies has little similarity with those existed earlier. The new mission of maintenance department is to provide excellent support for customers by reducing and eventually eliminating the need for maintenance services. This calls for retooling the traditional roles. On one side, the maintenance must merge with machine and tooling design to integrate maintainability improvements into design. On the other side, routine maintenance activity should be merged into operations. The creed of the new organization is that everyone must add value to the product.

Even a single task such as that shown in Figure 2.1 requires organizing ability of a high order if it is to be carried out successfully at minimum total cost (*i.e.,* sum of downtime cost plus direct maintenance cost). In a large plant the tasks shown in Figure 2.2 may number several hundred each day and it will be clear that this multiplicity of activities must be addressed in a logical fashion, otherwise chaos will result.

A maintenance organization can be considered as being made up of three necessary and inter-related components *i.e.,*

- **Resources:** men, spares and tools, of a particular size, composition and movement
- **Administration:** a hierarchy of authority and responsibility for deciding what, when and how work should be carried out.
- **Work Planning and Control System:** a mechanism for planning and scheduling the work and feeding back the information which is needed if

the maintenance effort is to be correctly directed towards its defined objective. Maintenance organization will need continuous modification to meet the changing requirements of present day production plant.

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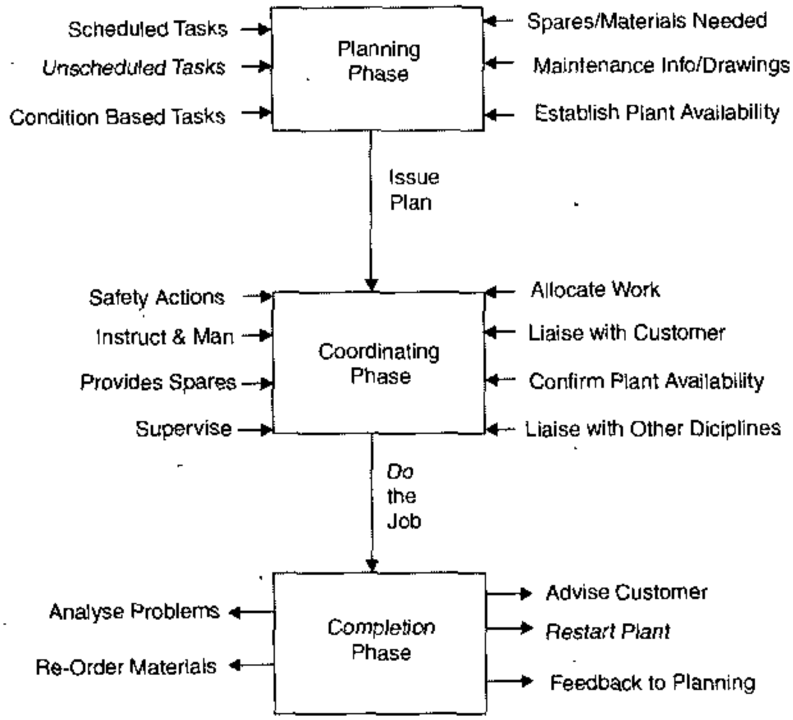

Fig. 2.1. *The Phases of an Engineering Maintenance Task.*

2.2 GOALS AND OBJECTIVES OF MAINTENANCE ORGANIZATION

The typical goals and objectives for a maintenance organization are as follows:

1. Maximum Production or Availability of Facilities at the Lowest Cost and at the Highest Quality and Safety Standards.
2. Maintaining Existing Equipment and Facilities.
3. Equipment and Facilities Inspections and Services.
4. Equipment Installations or Alterations.
5. Identify and Implement Cost Reductions.
6. Provide Accurate Equipment Maintenance Records.
7. Collect Necessary Maintenance Cost Information.
8. Optimize Maintenance Resources.
9. Optimize Equipment Life.

10. Minimize Energy Usage.
11. Minimize Inventory on Hand.

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2.3 KEY ISSUES AFFECTING MAINTENANCE ORGANIZATION STRUCTURE

In large plant, maintenance work will have to be carried out in what is frequently a very rapidly changing environment; which in turn may be due to internal or external pressures upon the company. The maintenance manager may not be in a position to influence that environment to any great extent. He or she should, however, be aware of the forces, which shape this environment. The organization can then be constructed in such a way as to give it the strength and feasibility to change rapidly with minimum loss of efficiency. The factors which can change the 'internal' environment for the maintenance department, and which the maintenance manager must pay some regard to, include.

External Factors:

- Competition
- Loss of market share
- Politics
- Environmental pressures, *i.e.*, green issues
- Legislation—National and International
- Labor mobility and new business in the area.

Internal Factors:

- Industrial relations
- Employee motivation
- Incentive schemes
- Management changes
- New product launches
- Poor communications
- Poor results and economic drive
- Out-dated plant and lack of investment
- Skill shortages
- Lack of training (production operators and tradesmen)
- Resistance to change (management and shop-floor)
- Politics.

The organizational structure for the maintenance department should be such that it can adapt to such changes in the internal environment.

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2.4 ROLES AND RESPONSIBILITIES

Titles, Job Descriptions and Accountabilities

Despite all that has been said about clarity of organizational structure over many years it is still common practice to see 'deputy' or 'assistant' in large organization structures. The reasons given for the existence of such positions and titles are many and usually include:

- Help for overworked manager.
- To enhance the status (and pay) of the assistant or deputy.
- To cover the senior person's absence.

Whatever the motivation for creating these appointments they almost always create confusion as to who is the team leader and therefore the upward and downward authority and accountability. Moreover if one accepts that the structure should contain only whole jobs it is impossible to describe the assistant's job without covering most of the "boss's" job as well. Most people who have to report to such a structure are confused as to who is actually in charge, *i.e.*, if the boss is at work what is the 'deputy' or 'assistant' responsible for? Who do the subordinates report to?

The main organizational evil of such appointments is that they split a real job into two or more parts and as a result no one has sufficient management challenge. This usually results in the deputy or assistant 'making out' or managing a level further down and creating frustration for someone else. If the manager is genuinely overworked then in most cases, it is better to create two real jobs with authority and accountabilities exclusive to them. If a deputy is needed to cover the boss's absence why pay someone all year to duplicate his efforts. Why not appoint subordinates on an ad-hoc basis for absences.

In this way you can:

(*a*) Let the subordinates get a taste of being in charge with minimum risk.

(*b*) Let senior management see how the subordinate performs in the boss's job.

(*c*) Rotate the deputies, and in this way avoid the 'crown prince' syndrome.

Job titles which include the word 'joint' need careful handling and really should be reserved for very short-term training of one of the job holders;

otherwise they smack of indecision and compromise. Permanent positions of this nature inevitably engender the same criticisms as 'deputy this' or 'assistant that'.

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Teams and Leadership

On the assumption that some of the organization will consist of decentralized teams, either a mixed group of single discipline craftsmen or a multi-skill group, it is well to reflect upon what is required of the leader of this group. Question could be asked:

- Is the leader to be a working member of the group or a pure supervisor?
- Does the leader have to technically instruct the group members or is the team sufficiently well trained and motivated that the leaders role is mainly about planning, coordinating and resourcing?
- Is the leader a 'natural' one and hence 'in charge' all the time by common consents or should the nature of work dictate who will lead the team on each occasion?
- Would a self managing group fit in the 'culture' and if so could it be ensured that the essential preventive maintenance was carried out?
- If self managing how will one set objectives, on a team or individual basis?
- How will one appraise performance (everyone needs some kind of feedback)?

This type of decentralized team can be outstandingly effective if the team is fairly small but well balanced, with the right overlapping use of skills and ability, so long as they have clear objectives and at least one natural leader among their ranks. If there is more than one natural leader a close watch on the situation will be needed to ensure that healthy competition does not turn into destructive rivalry (but that, after all, is what management is about).

The Management Team: Authority and Accountability

The final issue is how someone and his management team looks at his roles within the maintenance department. What does the boss expect from his or her maintenance manager? Does the team and the boss accept that the responsibilities within the structure are reciprocal? That is, the team are responsible to the boss for the achievement of their objectives: the boss, in turn, is responsible to them for seeing that:

- They have sufficient training and experience to discharge their accountabilities
- They get a fair deal in return for their efforts
- They get at least as much help from the boss, as the boss expects from them

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- The boss 'cares' and can be seen to care, about them as well as job
- The boss has the courage to deal with offenders in a way which is seen to be 'fair'
- The boss will communicate with them in a way which they understand and will listen to their views
- The boss will let them participate in 'management' to a greater or lesser extent
- That they know 'boss' and 'his' subordinates are there to help them do the 'right' work at the 'right' time and the 'right' cost.

It has been suggested that the usual organization charts should be drawn upside down to bring home to management and workers the inter-dependence of the whole team.

Natural justice would suggest that the degree of authority and accountability must be consistent at each level, *e.g.*, no person should be held accountable for that over which they have no control or authority. The boss can choose to delegate his authority but not his accountability. Those to whom he delegates his authority are accountable to him for the discharge of that authority.

2.5 MAINTENANCE COSTING AND BUDGETING

All the big manufacturing units maintain their own Maintenance and Repair department. To ascertain the exact cost of each maintenance or repair work, a series of service order accounts are opened. Each service order will be given a distinct number, and will be debited with all expenditure on material, labour or other direct charges for repair and maintenance. An addition is also made for works and office indirect expenses on a suitable basis. The total will then be included in factory overheads and is also used for maintenance planning, budgeting and control. In case the repair work is done by an outside agency, there will be no difficulty in ascertaining the exact cost of repair and the same will be included in factory overheads.

Sometimes an expenditure is incurred by the company's own workmen, which give rise to a capital asset. In such cases, the expenses on material and labour are debited to Capital Order Account. A charge is also made for works and office overheads to ascertain the true cost of the work performed. All such expenditures will not be debited to work overhead but be capitalized by passing an appropriate entry in the books of account. In cases major repair is carried out to prolong the life of an asset, cost of such repairs is also spread over the years during which the benefits are expected to come. Thus

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maintenance cost is generally the total cost incurred in doing the maintenance job and keeping a maintenance organization. The treatment of costs associated with other activities like construction, modification, rearrangement and removal of building equipment and assets depend on the nature of job undertaken.

Costs of no maintenance or inadequate maintenance are in the nature of opportunity cost. These lost opportunities includes lower rate of output, poor quality of products, wastage, defectives, damage to equipment, reduction in the useful life of the equipment etc. These costs are not recorded in any of the accounting system and often overlooked while exercising control over maintenance costs. A good maintenance policy should incorporate both the maintenance cost and the cost of lost opportunity due to inadequate maintenance.

2.6 MAINTENANCE COSTING

Costing is the technique of ascertaining costs. It consists of analyzing, recording, classifying and appropriate allocation of expenditure for the determination of the costs of products or services, comparing against standards or budgets, reporting and recommending. It renders information for the guidance of the management for proper planning, operation, control and decision making. The costing of maintenance department involves three steps:

1. Collection and classification of maintenance costs
2. Departmentalization of maintenance cost
3. Absorption of maintenance cost

Collection and Classification of Maintenance Costs

The maintenance costs include cost incurred on large number of activities. Some of these activities are as follows:

- Cost of manpower and facilities dedicated to maintenance department for repair and maintenance.
- Cost of preventive maintenance to improve the availability of the assets.
- Cost of resources like equipment and other facilities for condition monitoring and diagnostic maintenance.
- Cost of materials like spares lubricants and other consumables, tools etc.
- Cost of purchase and stores department looking after the activities of maintenance including salaries of clerk etc.
- Cost of stationery, printing of formats, computer and accessories etc.

- Cost of subcontracting maintenance work to outside agencies.
- Cost of training of maintenance personnel

Maintenance costs may be classified according to their nature, function and a number of other characteristics. A typical chart showing the classification of maintenance costs is given in Figure 2.2. The classification can be summarized as follows:

According to Nature

- Material: - Cost of spare parts, lubricating oil. Cotton waste etc.
- Labour: - Salary paid to the maintenance manager and other officers
  - Wages to Maintenance workers and supervisors including contributions to provident fund and other perquisites.
  - Overtime wages
- Overheads: - Those costs of the maintenance department which cannot be directly allocated to a specific job, but which must be absorbed by apportioning a share to all jobs and operations.
  - Store expenses including salaries of storekeepers and other expenses in handing of spare parts and other stores related to maintenance.
  - Cost of training new employees.

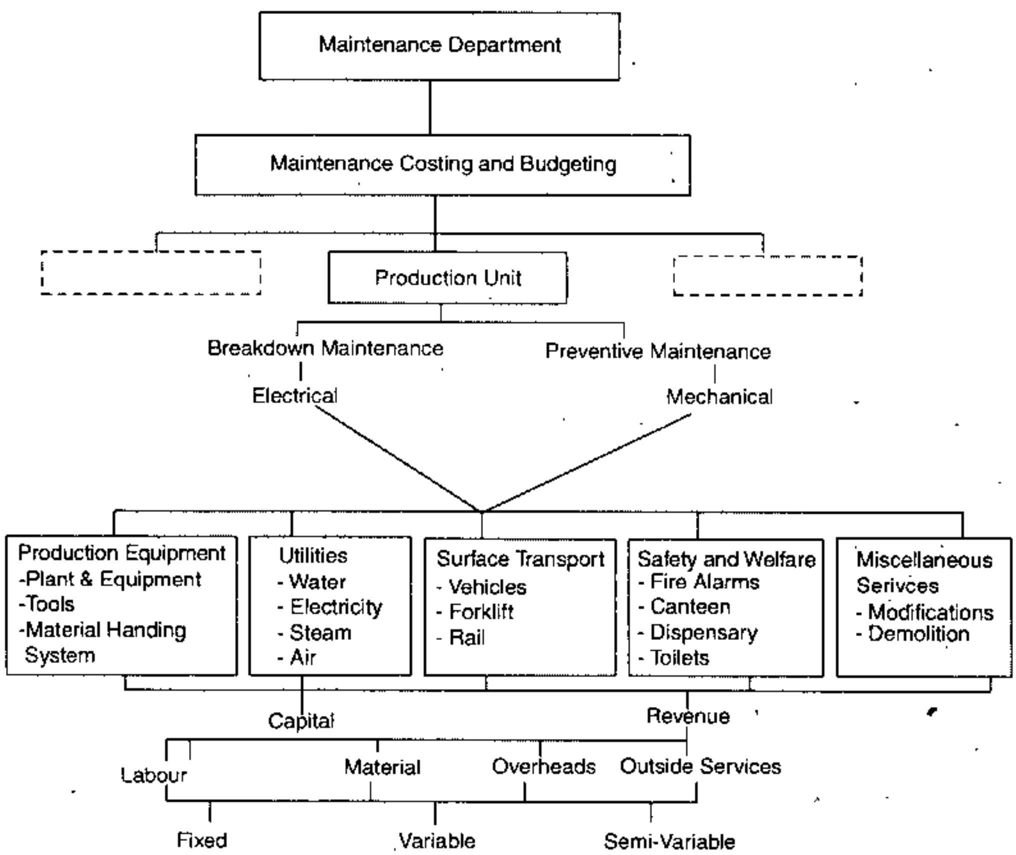

Fig. 2.2. *Classification of Maintenance Costs for a Typical Organization.*

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- **Outside Services:** External labour and supervisory services engaged in addition to the resources of the activity concerned, the costs of which include the provider's overheads. Engineering services and hire of mobile plant, tools and equipment are also included. The services of central workshop may also be included in common with the services of external firm.

According to Normality

- Normal maintenance cost
- Abnormal maintenance cost

Normal maintenance cost refers to the cost, which is expected to be incurred. This is unavoidable.

According to Type of Maintenance Action

- Breakdown maintenance activity
- Preventive/planned maintenance activity.

According to Controllability

- Controllable cost
- Uncontrollable cost.

According to Behaviour

- Fixed cost
- Variable cost
- Semi variable cost.

According to Impact of Maintenance

- *Direct maintenance cost:* The cost incurred to keep the equipment and systems operable.
- Cost of standby equipment
- Opportunity cost due to under repair.

According to the type of Budget

- Revenue cost
- Capital cost.

Revenue costs include those expenditures, which are covered by revenue budget allocated for various normal maintenance activities. Capital costs are covered by capital budget, which are specifically sanctioned for specific job on specific equipment generally for improving the features or the life of the equipment. After classification of maintenance costs, cards are maintained for every service order. Entries in the card are made periodically from purchase journal, stores requisitions, petty cash book, wage analysis book etc. The details regarding the source of information is recorded in the remarks column.

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2.7 MAINTENANCE BUDGETING

A budget is a detailed plan of operations for some specific future period. It is an estimate prepared in advance of the period to which it applies. Different types of budgets are prepared by an industrial concern for different purposes. The maintenance budget is an estimate of its requirements for spare parts, manpower, consumable and other expenses. It is prepared to bring efficiency and economy in the maintenance activities. Since the importance of the maintenance costs lies in their influence on production costs, the budgets must therefore portray them in production terms, and must result from discussions between the maintenance department, the production department and the financial control. The maintenance management provides information relating to expenditure under the various maintenance classifications. The production management gives information relating to production targets, and plant, equipment and service requirements. The finance control completes and correlates the information, prepares the budget statement and issue the periodic returns and statistics relating to actual performance against forecasted performance.

2.8 ZERO BASED BUDGETING

A zero based budget breaks the overall demand for maintenance services into its constituents, that is, assets or areas. In addition to the unit or asset list, a zero based budget has allocations for certain areas that are hard to define as assets such as electrical system on pavement. All these maintenance activities can be traced back to one of the following eight demands. A demand is a categorization of where maintenance labour or materials are expended.

(*a*) **Preventive Maintenance:** Based on the facility and equipment size, use, construction and the standard times of the preventive maintenance (PM) activities, the total time for PM activities is calculated. In a Total Productive Maintenance (TPM) shop, some of the PM hours will come from shop floor workers. Materials used for each service are also added. Some time for the short repairs that the machine will get is also included. Since PM has flexibility in scheduling, the PM can be considered as a level demand activity throughout the year.

(*b*) **Corrective Maintenance:** The deficiencies in the facility or equipment found during PM are recorded separately and taken up as scheduled maintenance. These are considered schedule work so long they don't interrupt job in process. Previous years data can be used to know this demand.

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(c) **User Maintenance:** User maintenance (UM) is the maintenance based on the requests received from the user department. This includes both routine as well as breakdown maintenance requests. Previous year data can be used to budget this exercise.

(d) **Seasonal Maintenance:** Review of roofing, checking of air conditioners before summer are seasonal maintenance (SM). Some percentage of seasonally driven emergencies are also included in this list. Budgets are based on history

(e) **Replacement/Rehabilitation Maintenance:** This type of maintenance is also called capital improvement maintenance. This is required either at the end of useful life or to improve the performance of the equipment.

(f) **Social Demand:** These activities include preparation for visiting dignitaries, or work on non organization equipment and facilities (charity work). Estimate the hours and material on these activities.

(g) **Expansion:** Any expansion in the size of facility, size of work force, addition of scope of control will expand the overall budget requirements. New facilities disrupt the current activities as well as taking direct time. Estimation of additional time and other resources is to be made.

(h) **Catastrophes:** Every part of the country has characteristic catastrophes. This can include flood, hurricane, fire etc. Add some labour hours and materials to the budget.

2.9 SPARE PARTS INVENTORY MANAGEMENT

Margins are narrowing down, budgets are stretched and operational expenditures are rising. One must find ways to maximize revenues and reduce the operating costs. Knowing what is in your inventory is the first step. Optimal spares conditioning is a necessity for the entire types of maintenance tasks, such as inspections, protective maintenance, and repairs. With the exception of protective activities, spare parts for maintenance tasks are usually required at random intervals. Thus, the rapid and safe coordination of the demand for spare parts with the supply of spare parts at the required time is a vital factor for the prompt execution of the maintenance process.

Missing materials are one of the most frequently cited rationales for the interruption in completion of maintenance tasks. As spare parts for equipment are frequently of very high quality, merely increasing warehouse stock cannot solve this problem. A maintenance planner should know about potentially essential parts and their accessibility. Effective maintenance management results in higher productivity, better quality and reduced cost of operations. Spare parts play a vital role in these.

2.10 TYPES OF SPARE PARTS

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Spare parts, maintenance and operating supplies comprises of all variety of parts and materials essential to uphold the production assets in acceptable operating condition so as to accomplish desired production results in terms of quality, quantity and time. The three basic types of spares parts are:

(*a*) **PM Spares:** Those replaced during preventive or opportunity maintenance,

(*b*) **Repair Parts (Breakdown Spares):** those required to replace parts that fail during service, and

(*c*) **Overhaul (Shutdown) Parts:** Those required during planned overhaul or shutdown of the plant.

The quantity and the time of requirement cannot be predicted for the repair parts. Only, the chance of their requirement can sometimes be predicted. Statistical methods are needed for their inventory control.

2.11 LIFE CYCLE OF SPARE PARTS

Spare parts go through the following six stages in their life cycle:

1. Design and specifications (The right spare)
2. *Determination of initial requirements* (*The right quantity*)
3. Procurement (The right Price)
4. Storage and preservation (Minimum custodial and inventory carrying cost)
5. Issue and replenishment-(Minimum-downtime cost through inventory control)
6. Disposal of damaged, surplus and obsolete spares (Minimum damage and maximum disposal value).

2.12 MYTHS ABOUT SPARE PARTS MANAGEMENT PROGRAM

There are certain misconceptions which could deviate the reader from understanding the concepts with respect to spare parts management, the below mentioned myth can facilitate in getting rid of it:

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Table 2.1: Myths about Spares Parts Management Program

S.No.	Myth	Fact
1	Spare parts management is a blockage	Spare parts management process facilitates and supports real-time part selections, providing cost-effective design decisions.
2	Spare Parts management is difficult task	Usage of computerized systems allows real-time analysis and makes available decision-support tools for recognizing the right spare parts.
3	Spare Parts management is a cost driver	Spare Parts management gets hold of money and reduces logistics support and parts redundancy costs.
4	Service provider logistics support nullifies the importance of spare parts management	Service provider should administer parts to stay competitive and develop logistics readiness.
5	It restricts design flexibility and restrains the introduction of new parts	An efficient program integrates system design, and parts management personnel. Spare Parts management facilitates with reviewing new parts procedure.

One should clearly understand the truths about spare parts so that the real benefits of spare parts management can be visualized.

2.13 SPARE PARTS MANAGEMENT AND OTHER SYSTEMS

Spare parts management involves numerous business processes that require application support and data from diverse classes of applications. A spare parts management system needs to interact with the following systems:

- **ERP Systems (Enterprise Resource Planning):** systems is a broad set of activities supported by multi-module application software that facilitate the organization in product planning, parts purchasing, maintaining inventory, interacting with supplier & customer, tracking order etc. The core task of this category of system is to manage transactions such as procurement, inventory transactions, returns, etc.
- **MES Systems (Manufacturing Execution Systems):** Systems that accommodates maintenance planning and implementation, capture of service history, etc. moreover time attendant systems, quality control systems, production scheduling systems, etc.),
- **SCM Systems (Supply Chain Management):** Systems for advanced planning and scheduling capabilities, the elements that affect your supply

chain efficiency, including inventory reduction, supplier relationships and IT strategy. Supply Chain Management systems are an overturn of prior practices where manufacturers supplied spare parts to customers they required them. Now customers tell suppliers how and when they want their spare parts delivered. The driver behind Supply Chain Management is to eradicate inefficiencies, excess costs and excess inventories from the *supply pipeline, which extends from the customer* back all the way through his suppliers and his suppliers' suppliers and so on. By having the program driven by the customer, it is anticipated that inventories, caused by uncertainties and sluggish response, will be appreciably eliminated.

- ***MIS Systems (Management Information Systems):*** The MIS for spare parts is similar to that for other materials and has the same aims. Typical reports generated by the MIS are:
  - Stock and consumption status report
  - Pending indents report
  - Pending purchase orders report
  - Stock-out report (also dangerously low stock position report)
  - Over-stock/ Under-stock report
  - ABC analysis- separately for repair items and overhaul items.

In addition, the computer should automatically adjust the inventory parameters, such as ROL, SS, LT for routine indenting. Special' 'alerts' may be build *into the system to identify deviations from expectations e.g., sudden* rise/fall of consumption rates of spares. Typically, a sudden increase in the usage rate of a component may be due to related increase in failure rate, which in turn could be due to poor quality for latest supplier. If the drop in consumption of a part is accompanied by sudden rise in the consumption of the assembly into which is goes, evidently for some reason maintenance had started replacing assemblies instead of parts. The range of spare parts is so vast that computers have to be sued for getting replies to the numerous queries that will arise in managing spare parts.

2.14 BENEFITS OF SPARE PARTS MANAGEMENT

Merger of economic, technological & market forces have made it critical for companies to promote it sales service and particular service parts supply. Spare Parts Management is a constructive way for implementing a robust in-house parts management. The supply of spare parts have turn out to be increasingly *fundamental for companies wishing to stay ahead of competition* This section defines the essential elements of a spare parts management

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process, including establishing an in-house parts management board, developing a preferred parts list or corporate parts baseline, establishing a process for selecting and authorizing parts and establishing a process for qualifying parts etc.

- **Condensed Acquisition Lead-Time:** When preferred spare parts are used, the government and industry keep away from the expenses and delays of designing and developing parts and the issue of acquiring a new item with no obtainable history or documentation. Using preferred spare parts diminishes the time between the purchase request and the receipt of the part.
- **Cost Savings:** Spare Parts management facilitates save design and life-cycle costs of equipment by encouraging the application of frequently used or preferred parts. Standardization of parts, replacing numerous similar parts with one universal part, results in larger part-type buys because the general parts are used in multiple applications. Larger part-type buys permit both the contractor and the customer to promote from the economies of scale. Part standardization also diminishes the contractor's cost of maintaining technical data and storing, tracking, and distributing multiple parts.
- **Enlarged Supportability and Safety of Systems and Equipment:** Preferred parts diminish risk and enhance the chances that equipment will accomplish reliably. Preferred parts have a history of established reliability; enduring rigorous testing and performing at stated levels. Their use decreases the number of part failures, reducing the number of maintenance actions and potentially precluding failures that could cause mission breakdown or loss of life.
- **Improved Logistics Readiness and Interoperability:** When items or systems allocate general components, repair time is shorter because parts are more possible to be on hand and technicians use up less time solving individual problems. Moreover, using regular components simplifies logistics support and augments substitutability because fewer parts are stocked. This translates to savings in procuring, testing, warehousing, and transporting parts.

2.15 COST CONTROL FOR SPARE PARTS: ROLE OF MAINTENANCE

Cost due to end of spare parts occurs as:

(*a*) Cost due to non-availability when required for the machine,

(*b*) Consumption value,

(*c*) Inventory carrying cost, and

(*d*) Capital cost of non-moving items.

To minimize the need for troublesome repair parts, operations must prevent failures, and maintenance must ensure that maintenance is done on time and is of high quality. Maintenance must give top *priority to eliminate failures* requiring the high cost items that are also critical. Worn parts can often be rebuilt at a fraction of the price of new parts. Standard parts, low LT, purchase from OEM/reliable suppliers will reduce cost. Simple procedures, using computer for scientific analysis and updating of inventory parameters will reduce the operating cost of the spare parts system. Maintenance must assist in identification, preservation, and inspection of spare parts.

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2.16 INFORMATION TECHNOLOGY (IT) ENABLED MAINTENANCE MANAGEMENT

Maintenance management and engineering function has to position it to achieve the corporate objectives and strategies in general and the operational strategies in particular. In the process, it needs to interface with different functions, within and external to the enterprise.

Information generation, processing and usage are major requirements for the maintenance function to efficiently manage its resources. Many of the earlier maintenance systems suffered from crude and conventional methods of data processing and information exchange. The result of this had been that many a times decisions were made purely based on intuitions and guess works. The efficacy and efficiency of such decisions were obviously questionable and led to loss of productivity.

Information technology (IT), the new buzzword for the use of electronic, communication and convergence technologies has made tremendous difference to our way of functioning in all walks of life. IT has made deep inroads into possibly every facet of economical functioning of organizations. Terminologies like e-business, e-commerce, enterprise resource planning (ERP), Customer Relations Management (CRM) etc. have become common parlance in the management circles. Though the use of IT has been adopted quite lately for maintenance functions compared to other functions like finance, personnel, materials etc., tremendous progress has been achieved in the use of IT in *both the maintenance management and engineering functions*. We would have a brief coverage on this in the following paragraphs.

2.17 BENEFITS OF IT ENABLED MAINTENANCE

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Use of IT in many organizations has resulted in many benefits over the conventional manual systems. Some of these benefits have been indicated below:

- Reduction in downtime costs
- Reduction in maintenance costs
- Reduction in materials costs
- Reduction in life cycle costs of machinery
- Increased availability of plant and equipment
- Reduction in the breakdowns
- Increased and extended usage life of plant and equipment
- Improved diagnosis of machine problems
- Availability of machine, operation and maintenance information in right time and in right perspective
- Proper planning, scheduling and control of preventive, predictive and corrective maintenance
- Efficient control of backlogs
- Better utilization of maintenance resources, men, materials and logistics.
- Availability of History of machines to enable decision making
- Ensure efficacy and efficiency of reporting systems
- Better interface amongst maintenance and other functions like operation, materials, quality, safety etc.
- Reduction in unnecessary paper works, in essence, improvement in the overall productivity and profitability of the organisation.

2.18 CONCEPTUAL MODEL OF THE MAINTENANCE FUNCTION

Though, many benefits of use of IT in maintenance has been delineated in the previous section, it should be recognized that computers are basically tools in the hands of managers to achieve their objectives. As the famous saying regarding computers 'Garbage in, Garbage out' signifies, sufficient amount of preparatory and systematic analysis would be required, if computerization efforts are to succeed. Indeed, there have also been number of cases where improper use of computers have added to the misery of maintenance managers. Some of the benefits mentioned above have not accrued but exactly the opposite has happened in those companies. Hence the necessity to completely visualize the maintenance function in a systematic fashion and then go for use of computers to achieve the pre conceived benefits.

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The Figure 2.3 explains the conceptual model through which the maintenance function can achieve its objectives on a sustained basis.

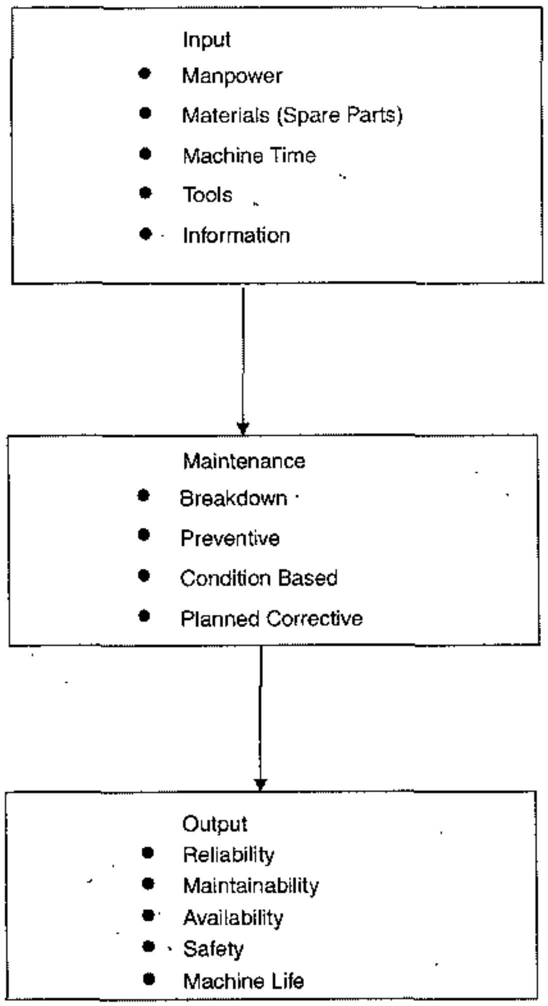

Fig. 2.3. *Inputs Maintenance Output Model.*

2.19 MAINTENANCE DATABASES

In order to enable information technology processing to help the maintenance function, input data has to be collected and entered in the master databases. In this section, we would see the types of master databases that are required to be maintained.

Equipment Master: The equipment master would have all the static information about all the equipment in the plant. Some of the illustrative information are the equipment code, equipment description,

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manufacturer/supplier details, purchase data, warranty/insurance information, drawings, major specifications, details and specifications of sub-assemblies, details of spare parts etc. This master information can be maintained in the data base in different forms.

Corrective Maintenance Master: This master database maintains the information regarding the standard corrective maintenance activities to be performed on the equipment. Some examples of corrective maintenance activities are balancing a fan rotor, replacement of pump impeller, relining a cement kiln refractory wall etc. For each of these activities information like activity code, description of the activity, normal frequency of execution, resource requirements like manpower, materials, tools, standard downtime, activity restriction like safety permits etc. are stored in the database. It could be visualized that some corrective maintenance activities would be standard activities applicable to a large number of equipment, whereas some of them would be equipment specific. The master database can also keep this information as to whether a particular activity is standard or equipment specific.

Preventive Maintenance Master: Similar to corrective maintenance master, information about the preventive maintenance activities are separately maintained in the preventive maintenance master data base. Some examples of preventive maintenance activities are regular lubrication (both topping up and change of oil), scheduled replacement of consumables like bearings, v-belts, oil seals etc.; overhaul of gear boxes, engines etc. The data base would contain details like activity code, description of the activity, normal frequency of execution, resource requirements like manpower, materials, tools, standard downtime, activity restriction like safety permits etc. The frequency of execution of preventive maintenance activities can be based on different logics. For example, the v-belt of a fan can be changed on the basis of elapse of calendar time since last replacement, completion of pre determined number of running hours, indication of an abnormal symptom of condition monitoring parameter measured through predictive maintenance etc. The database can contain a logic indicator as to which particular or a combination of these triggers has to be employed to schedule a particular preventive maintenance activity. Like in the case of corrective maintenance, preventive maintenance activities can also be standard activities or equipment specific.

Predictive Maintenance Master: The predictive maintenance master database would contain information regarding the predictive maintenance activities, which are mostly standard activities. Some of these activities are measurement of vibration levels or spectrum, oil contamination levels, temperature, pressure and other monitoring parameters. Nowadays the predictive maintenance instrument suppliers combine their measurement

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equipment with computerized portable data collector and analysis software. In such cases, the predictive maintenance master database resides within the respective hardware/software. The results of the predictive maintenance have always to trigger one or more of the other types of maintenance, namely, corrective, preventive or emergency maintenance. Hence the logic for the same also needs to be maintained in the master database. One example of such a linkage is the requirement of greasing of an anti friction bearing in case the high frequency vibration levels increases more than alarm levels on the bearing casings.

Spare Parts/Materials Master: The information regarding the maintenance materials is normally maintained in this master database. Ideally, this information would also be required for materials management function and hence would be part of that system. The type of information that would be maintained are item code, item description, specifications, cost, lead time, vendor details, ordering quantity, classification etc. The database may also keep this information regarding other types of maintenance resources like tools, sub assemblies, rotable spares etc.

Latest maintenance management softwares have capability to store both the text characters as well as images. Thus the above master data bases can also retain information like equipment figures and drawings, lubrication diagrams, instructions for preventive maintenance etc. in the computer medium.

2.20 CMMS MODULES

Having studied the basic features of the planning and scheduling of the various types of maintenance activities, we shall now study the common modules present in the computerized maintenance management system (CMMS) software.

Machinery Information and Preventive Maintenance Module

This module normally contains the following facilities:

- Enable querying and printing static equipment information
- PM work order scheduling by calendar or metered usage & printing of PM work orders
- Scheduling of multi crafts for performing the PM
- Scheduling PM based on prior completion of PM, request of Maintenance Planning, predictive maintenance results etc.,
- Balance PM work load over the scheduling period
- Forward planning to inform production function in advance in case PM requires equipment shutdown.

The preventive maintenance work orders would basically track maintenance labour and materials utilized so that these costs can be calculated and monitored. In addition, the downtime due to preventive maintenance and the corrective maintenance requirement also collected for compilation and analysis. Normally the PM software module has the ability to print the work orders in a specific sorted order, the key for which could be the craft, department, priority, etc independently or in combination. The module also produces various types of reports and queries, some of which are, past due work orders, back log of non-completed work orders, equipment history, equipment wise down time, cost of preventive maintenance, type and number of defects observed and corrected etc.

Pre-requisites and Operation of the PM Software Module

The initial step would be to compile a list of equipment to be covered under the computerized system and collect both basic data as well as PM requirements of each of this equipment. This information would be available from manufacturer's manuals for operation and maintenance, which may need suitable modification based on the operating experience of the plant personnel. An example of the type of data that would be keyed in the equipment and PM master database are given the Figure 8.2. Based on the estimations made about the down time and labour time required for completion of the identified preventive maintenance activities and material availability, the computer program schedules the preventive maintenance activities, normally every week and prints out the corresponding work orders.

Corrective Maintenance and Work Order Module: The execution of corrective maintenance activities through a well-structured work order system helps a maintenance department with higher availability and reduced costs. Ideally, the work order system should produce enough information to enable the maintenance manager take proper decision regarding allocation of the resources to achieve overall improvement in the productivity. Normally the corrective maintenance and work order module has the following features:

- Track labour and material utilization and costs thereof
- Assign different crafts for different works
- Identify work orders separately for equipment under warranty
- Track contracted out maintenance separately
- Facilitate use of special tools and materials
- Enable obtaining special permits like safety/electrical lock out etc.
- Enable scheduling based on various logics like priority of equipment, priority of jobs, material availability, craft etc.
- Permit input of information related emergency maintenance, which are not scheduled, after they are completed

- Just like the PM module, the corrective maintenance module is also capable of producing various types of reports, the most important of which are:
- Active and Pending work orders report
- History of equipment
- Downtime of equipment
- *Cost of Corrective Maintenance.*

Pre-requisites and Operation of the CM Software Module

The CM module basically operates through the central point of recognition of work order numbers. There should be a unique and specific maintenance work order number for each of the corrective maintenance carried out. The work order numbers can be manually entered into the module, or it can also be automatically generated by a programmed logic. The CM master database would have information about CM activities, which are amenable for planning in advance, and the increased use of planning, helps the corrective maintenance to achieve improved performance in terms of reduced downtime, lesser consumption of materials and effective utilization of maintenance manpower. On the other hand, increased dependence on emergency and unplanned maintenance increases the workload and results in higher costs and lower morale.

The various reports that can emanate from a CM module are as follows:

- Maintenance History Report
- Maintenance Costs Report
- Work Order Backlog Report
- Material Consumption Report
- Downtime Report

Spare Parts Control Module: This module is very similar to a materials management module, which helps in classifying maintenance materials, purchase, inward goods inspection, issue and receipt. It also tracks consumption and controls inventory. The main difference between a materials management computerized software and a spare parts control module would be that of difference in numbers and types and the logics and models used for inventory controls. There could also be renewable spares (also called rotable spares) whose position need to be tracked separately in the spare parts control module. Some of the features of a computerized spare parts module are given below:

- Predictable materials are included in the work orders and their need communicated to stores
- Matching of parts required to availability automatically
- Automatic reordering based on inventory control/ purchase logic

- Accumulation of material costs in the history of equipment
- Linking of equipment data to spare parts data
- Performance reporting on consumption, inventory, stock outs etc.

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Condition Monitoring Module: The modern day computerized software systems for maintenance have a condition monitoring module which can receive equipment performance characteristics like vibration signals, temperature, pressure, lubrication oil condition etc directly from the sensors mounted on the critical equipment. These information would be suitably trended and various corrective action like issue of alarms, tripping of the equipment, carrying out diagnostics to suggest preventive/corrective maintenance etc can be performed by the software. Since this type of on-line condition monitoring would be quite expensive and may not be feasible for all types of equipment, there are also alternative portable data collector and analyzer systems which can be used independently to manually collect the condition monitoring data and analyze through a dedicated software.

2.21 SOFTWARE SELECTION

Broadly there are two alternatives to a maintenance department, either internal development of the software or purchase of a standard software. The merits and demerits of internally developed software are:

- Flexibility in developing the software
- Can be designed to exactly suit the internal requirements
- Greater acceptability
- Long development time and special skills requirements
- Higher cost of development and maintenance

Alternatively ready-made software has the following features:

- Relatively lower cost
- Less preparatory time
- Can get the latest technology software
- Integrated systems like ERP (Enterprise Resource Planning) software, which has maintenance as one of the modules thus enabling interlinking with other functions of the organization.
- Sometimes may not meet all special requirements of the plant
- Difficulty in maintenance and up gradation.

While selecting particular software, the following factors need to be considered so that maximum use can be made by the company:

Ease of Use: The software should preferably have in-built features like help menus, tool tips etc., for making the user comfortable with the operation of the software. In case of sophisticated softwares, detailed user training would be essential by the software vendor and during the training; the actual data pertaining to the company can be used to understand the process better.

Ease of Implementation: Depending upon the sophistication in the software, installation, testing and commissioning of the software is performed either by the user himself or the vendor or a third party implementer. As far as possible, the users are to be associated with these processes. This would help in identifying any possibly bugs at this stage itself, which can be corrected before going for full-fledged implementation.

System Support: The software should be aptly supported with technical and system supports for provision of upgrades; fixing errors and integration of both hardware and software with the factory network systems, intranet and Internet.

Hardware and Software System Requirements: The requirements in terms of hardware features in terms of processor speed, memory and hard disk capacity, applicable drive systems etc., are to be understood before selection of the software. Similarly the software system requirements like operation system, RDBMS environment are also important.

Documentation: The extent of documentation provided by the vendor is to be critically analyzed, as this is an important requirement for continuous reference whenever problems are encountered in operation. It should also ensure whether details of source code etc would be available or accessible in case of future requirements.

2.22 COMPUTERISED MAINTENANCE SYSTEM IMPLEMENTATION

Most of the enterprises have priority for computerization for functions other than maintenance, like finance, personnel, operation etc. Even today, many companies operate their maintenance function through manual systems and procedures. Hence the implementation of computerized maintenance system, many a times, has to start with an effort to justify the investment in a CMMS software. This needs to be done by identifying the benefits of computerized maintenance systems over a period of time and the cost trade offs such a system implementation would provide to the company. As in preventive maintenance, the results of the implementation take a considerable period to show in the improvement of the bottom lines. Hence the justification has to be worked out as rate of return on investment over a sufficiently

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longer period of time. Once the CMMS software is acquired, the implementation efforts have to be carried out through the following steps:

1. Motivation of all level of personnel to obtain support for implementation
2. Installation of the computer hardware/software
3. Training of the personnel
4. Creation of the Master Data bases
5. Creating Security system for the files/transactions
6. Phase wise/Department wise adaptation
7. Follow Up/Back up of Files

SUMMARY

- The structure and organization of maintenance in some plants owes more to the origins of the plant, the nature of its business and the 'culture' in which it operates than to any detailed analysis of the maintenance needs of the plant.
- Costing is the technique of ascertaining costs. It consists of analyzing, recording, classifying and appropriate allocation of expenditure for the determination of the costs of products or services, comparing against standards or budgets, reporting and recommending.
- A budget is a detailed plan of operations for some specific future period. It is an estimate prepared in advance of the period to which it applies.
- Spare parts, maintenance and operating supplies comprises of all variety of parts and materials essential to uphold the production assets in acceptable operating condition so as to accomplish desired production results in terms of quality, quantity and time.
- Spare parts management involves numerous business processes that require application support and data from diverse classes of applications.
- Spare Parts Management is a constructive way for implementing a robust in-house parts management.
- Maintenance management and engineering function has to position it to achieve the corporate objectives and strategies in general and the operational strategies in particular.
- Most of the enterprises have priority for computerization for functions other than maintenance, like finance, personnel, operation etc. Even today, many companies operate their maintenance function through manual systems and procedures.

REVIEW QUESTIONS

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1. What are the important components of a maintenance organization?
2. What are the goals and objectives of a maintenance organization?
3. Name the key issues affecting the maintenance organization structure.
4. Give the factors, which can influence the internal environment of a maintenance department?
5. Explain what is meant by cost absorption and cost apportionment? Illustrate each with two examples from maintenance department. Discuss the methods of cost absorption and state which method do you consider to be the best and why?
6. What are the main sources of collection of maintenance cost? State the procedure with examples for collection of data from these sources.
7. What is the importance of maintenance budgeting? Give the advantages of Zero Based Budget.
8. What is the aim of spare parts inventory management? In what way does it influence the different stages of the life cycle of spare parts?
9. What are the different types of spare parts, and when are they used?
10. What is EOQ? Why is the EOQ formula not useful for spare parts?
11. What is Pareto's Law? In what ways is it used for spare parts?
12. What is VED analysis and how is it used?
13. Which problems are unique to spare parts that other materials do not exhibit? Why do these problems occur?
14. How is the maintenance function related to other functions of an enterprise?
15. 'Timely and Relevant information is a main requirement of productivity' – State reasons.
16. In your opinion, what is the cause of late adoption of Information Technology (IT) for maintenance compared to other functions?
17. What cost improvements are possible in maintenance with IT applications?
18. 'IT application is not panacea for all the ills of the maintenance function' – Justify this statement.
19. What intangible benefits can be expected from IT enabled maintenance operations?
20. Why should one understand the total concept of the maintenance system's functioning before attempting to use IT enablers?
21. What are the major objectives of maintenance function?
22. Explain the steps involved in the execution cycle of any maintenance activity.
23. 'IT can be used only for pre-planning oriented maintenance activities like preventive and predictive maintenance' – True or False? Give Reasons.

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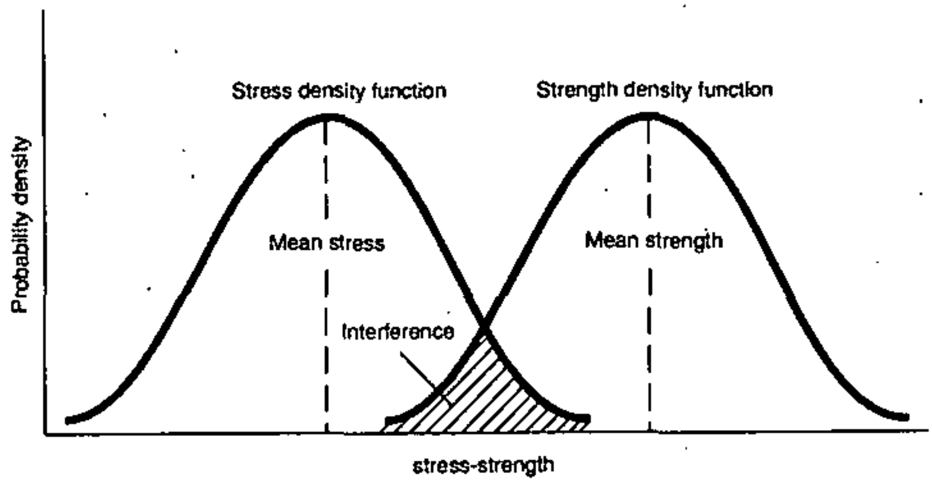

Fig. 3.3. *Stress/strength diagram.*

A stress/strength interference diagram is shown in Fig. 3.3. The darkened area in the diagram represents the *interference* area. Besides such graphical presentation, it is also necessary to define the differences between stress and strength.

Stress is defined as "*the load which will produce a failure of a component or device*". The term *load* may be identified as mechanical, electrical, thermal or environmental effects.

Strength is defined as "*the ability of a component or device to accomplish its required function satisfactorily without a failure when subject to external load*".

Stress–strength *interference reliability* is defined as "*the probability that the failure governing stress will not exceed the failure governing strength*".

In mathematical form, this can be stated as

$$R_C = P(s < S) = P(S > s),$$

where:

R_C = the reliability of a component or a device,

P = the probability,

S = the strength,

s = the stress.

Equation above can be rewritten in the following form

$$R_C = \int_{-\infty}^{+\infty} f_2(s)\left[\int_{s}^{\infty} f_1(s)\, dS\right] ds,$$

where:

$f_2(s)$ is the probability density function of the stress, s

$f_1(S)$ is the probability density function of the strength, S.

Models employed to predict failure in predominantly mechanical systems are quite elementary. They are based largely on techniques developed many years ago for electronic systems and components. These models can be employed effectively for analysis of mechanical systems but they must be used with caution, since they assume that extrinsic factors such as the frequency of random shocks to the system (for example, power surges) will determine the probability of failure—hence, the assumption of Poisson distribution processes and constant hazard rates.

In research conducted into mechanical reliability, it is shown that intrinsic degradation mechanisms such as fatigue, creep and stress corrosion can have a strong influence on system lifetime and the probability of failure. In highly stressed equipment, cumulative damage to specific components will be the most likely cause of failure. Hence, a review of the factors that influence degradation mechanisms such as *maintenance practice* and *operating environment* becomes a vital element in the evaluation of likely reliability performance. To predict the probability of *system* failure, it becomes necessary to identify the various degradation mechanisms, and to determine the impact of different maintenance and operating strategies on the expected lifetimes, and level of maintainability, of the different assemblies and components in the system. The load spectrum generated by different operating and maintenance scenarios can have a significant effect on system failure probability.

When these distributions are well separated with small variances (low-stress conditions), the *safety margin* will be large and the failure distribution will tend towards the constant hazard rate (random-failure) model. In this case, the system failure probability can be computed as a function of the hazard rates for all the components in the system. For highly stressed equipment operating in hostile environments, the load and strength distributions may have a significant overlap because of the greater variance of the load distribution and the deterioration in component strength with time. Carter shows that the safety margin will then be smaller, and the tendency will be towards a weakest-link model. The probability of failure in this case can then depend on the resistance of one specific component (the weakest link) in the system.

Carter's research has been published in a number of papers and is summarised in his book *Mechanical reliability* (Carter 1986). Essentially, this work relates failure probability to the effect of the interaction between the system's *load* and *strength* distributions, as indicated in Fig. 3.3. Carter's research work also relates reliability to design.

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System Reliability Modelling Based on System Performance

The techniques for *reliability prediction* have been selected to be appropriate during conceptual design. However, at both the conceptual and preliminary design stages, it is often necessary to consider only *systems*, and not *components*, as most of the system's components have not yet been defined. Although reliability is generally described in terms of probability of failure or a mean time to failure of items of *equipment* (*i.e.*, *assemblies* or *components*), a distinction is sometimes made between the *performance* of a *process* or *system* and its *reliability*. For example, process performance may be measured in terms of output quantities and product quality. However, this distinction is not helpful in process design because *it allows for omission of reliability prediction* from conceptual design considerations, leaving the task of evaluating reliability until detail design, when most of the equipment has been specified.

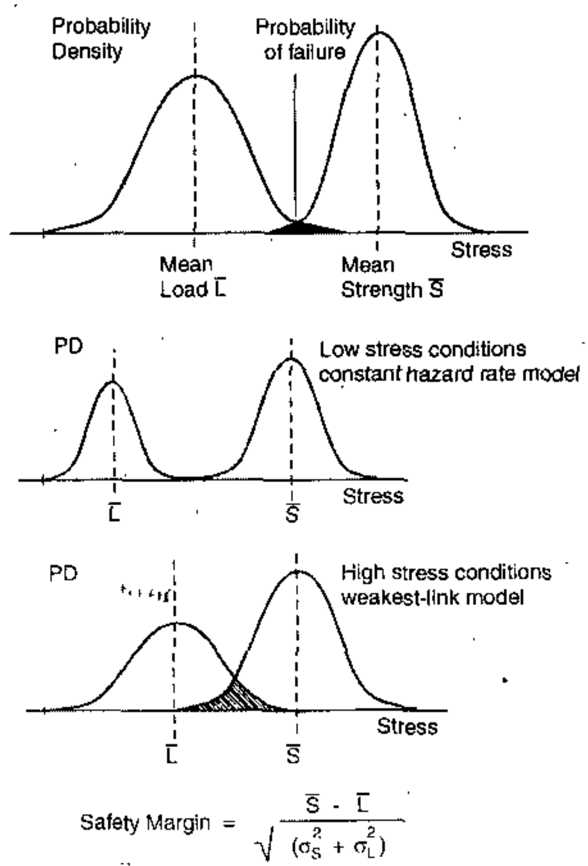

Fig. 3.4. *Interaction of load and strength distributions.*

3.3 AVAILABILITY AND MAINTAINABILITY IN ENGINEERING DESIGN

Availability in engineering design has its roots in *designing for reliability* as well as *designing for maintainability*, in which a 'top-down' approach is adopted, predominantly from the design's systems level to its equipment level (*i.e.*, assembly level), and constraints on systems *operational* performance are determined. Availability in engineering design was initially developed in defence and aerospace design (Conlon et al. 1982), whereby availability was viewed as a measure of the degree to which a system was in an operable state at the beginning of a mission, whenever called for at any random point in time.

Traditional reliability engineering considered *availability* simply as a special case of *reliability* while taking the *maintainability* of equipment into account. Availability was regarded as the parameter that translated system reliability and maintainability characteristics into an index of system *effectiveness*. Availability in engineering design is fundamentally based on the question 'what must be considered to ensure that the equipment will be in a working condition when needed for a specific period of time'?

The ability to answer this question for a particular system and its equipment represents a powerful concept in engineering design integrity, with resulting additional side-benefits. One important benefit is the ability to use availability analysis during the engineering design process as a platform to support design for reliability and design for maintainability parameters, as well as trade-offs between these parameters.

Availability is intrinsically defined as "*the probability that a system is operating satisfactorily at any point in time when used under stated conditions, where the time considered includes the operating time and the active repair time*" (Nelson et al. 1981).

While this definition is conceptually rather narrow, especially concerning the *repair* time, the thrust of the approach of *availability in engineering design* is to initially consider *inherent availability* in contrast to *achieved* and *operational availability* of processes and systems. A more comprehensive approach would need to include a measure for the quantification of *uncertainty*, which involves considering the concept of availability as a decision analysis problem. This results in identifying different options for improving availability by evaluating respective outcomes with specific criteria such as *costs* and *benefits*, and quantifying their likelihood of occurrence. Economic incentive is the primary basis for the growing interest in more deliberate and systematic availability analysis in engineering design.

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Ensuring a proper analysis in the determination of *availability in engineering design* is one of the few alternatives that design engineers may have for obtaining an increase in process and/or systems capacity, without incurring significant increases in capital costs. From the definition, it is evident that any form of availability analysis is time-related.

Figure 3.5 illustrates the breakdown of a total system's equipment time into time based elements on which the analysis of availability is based. It must be noted that the time designated as 'off time' does not apply to availability analysis because, during this time, system operation is not required. It has been included in the illustration, however, as this situation is often found in complex integrated systems, where the reliability concept of 'redundancy' is related to the availability concept of 'standby'.

The basic relationship model for availability is:

$$\text{Availability} = \frac{\text{Up Time}}{\text{Total Time}} = \frac{\text{Up Time}}{\text{Up Time + Down Time}}$$

Analysis of availability is accomplished by substituting the time-based elements defined above into various forms of the basic relationship, where different combinations formulate various definitions of availability.

Designing for availability predominantly considers whether a design has been configured at *systems* level to meet certain *availability* requirements based on specific process or systems *operating* criteria. Designing for availability is mainly considered at the design's systems and higher equipment level (*i.e.,* assembly level, and *not* component level), whereby availability requirements based on expected systems performance are determined, which eventually affects all of the items in the systems hierarchy. Similar to *designing for reliability*, this approach does not depend on having to initially identify all the design's components, and is suitable for the conceptual or preliminary design stage

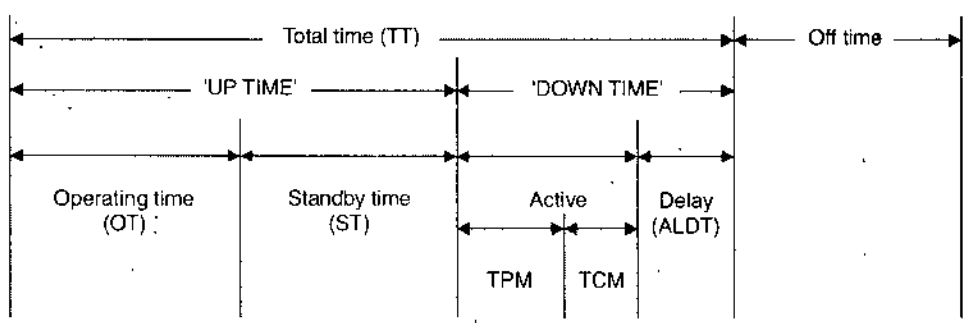

Fig. 3.5. *Breakdown of total system's equipment time where UP TIME = operable time, DOWN TIME = inoperable time, OT = operating time, ST = standby time, ALDT = administrative and logistics downtime, TPM = total preventive maintenance and TCM = total corrective maintenance.*

However, it is observed practice in most large continuous process industries that have complex integrations of systems, particularly the power-generating industry and the chemical process industries, that the concept of availability is closely related to reliability, whereby many 'availability' measures are calculated as a 'bottom-up' *evaluation*. In such cases, *availability in engineering design* is approached from the design's lower levels (*i.e.*, assembly and/or component levels) *up* the systems hierarchy to the design's higher levels (*i.e.*, system and process levels), whereby the collective effect of all the equipment availabilities is determined. Clearly, this approach is feasible only once all the design's equipment have been identified, which is well into the detail design stage.

In order to establish the most applicable methodology for determining the integrity of engineering design at different stages of the design process, particularly with regard to the development of *designing for availability*, or to the assessment of *availability in engineering design* (*i.e.*, 'top-down' or 'bottom-up' approaches in the systems hierarchy respectively), some of the basic availability analysis techniques applicable to either of these approaches need to be identified by definition and considered for suitability in achieving the goal of this research.

Furthermore, it must also be noted that these techniques do *not* represent the total spectrum of availability analysis, and selection has been based on their application in conjunction with the selected reliability techniques, (reliability prediction, assessment and evaluation), in order to determine the integrity of engineering design at the relative design phases.

The definitions of availability are qualitative in distinction, and indicate significant differences in approaches to the determination of designing for availability at different levels of the systems hierarchy, such as:

- *prediction of inherent availability* of systems based on a *prognosis of systems operability* and *systems performance* under conditions subject to various *performance criteria*;
- *assessment of achieved availability* based on *inferences of equipment usage with respect to downtime and maintenance*;
- *evaluation of operational availability* based on *measures of time that are subject to delays*, particularly with respect to anticipated values of administrative and logistics downtime.

Maintainability in engineering design is described as 'Designing and developing maintainable products and systems' as "*the relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at* *each prescribed level of maintenance and repair. In this context, it is a function of design".*

Maintainability refers to the measures taken during the design, development and manufacture of an engineered installation that reduce the required maintenance, repair skill levels, logistic costs and support facilities, to ensure that the installation meets the requirements for its intended use. A key consideration in the maintain ability measurement of a system is its active *downtime, i.e.,* the time required to bring a failed system back to its operational state or capability. This active downtime is normally attributed to *maintenance* activities.

An effective way to increase a system's *availability* is to improve its maintainability by minimising the downtime. This minimised downtime does not happen at random; it is *designed* to happen by actively ensuring that proper and progressive consideration be given to *maintainability* requirements during the conceptual, schematic and detail design phases. Therefore, the inherent maintainability characteristics of the system and its equipment must be assured. This can be achieved only by the implementation of specific design practices, and verified and validated through maintainability assessment and evaluation methods respectively, utilizing both analyses and testing.

The following topics cover some of these assurance activities:

- Maintainability analysis
- Maintainability modelling
- Designing for maintainability.

Maintainability analysis includes the *prediction* as well as the *assessment* and *evaluation* of maintainability criteria throughout the engineering design process, and would normally be implemented by a well-defined program, and captured in a maintainability program plan (MPP). Maintainability analysis differs significantly from one design phase to the next, particularly with respect to a *systems-level* approach during the early conceptual and schematic design phases, in contrast to an *equipment-level* approach during the later schematic and detail design phases. These differences in approach have a significant impact on *maintainability in engineering design* as well as on contractor/ manufacturer responsibilities. Maintainability is a design consideration, whereas *maintenance* is a consequence of that design. However, at the early stages of engineering design, it is important to identify the maintenance concept, and derive the initial system maintainability requirements and related design attributes. This constitutes maintainability analysis.

Maintainability, from a maintenance perspective, can be defined as *"the probability that a failed item will be restored to an operational effective condition within a given period of time"*.

This restoration of a failed item to an operational effective condition is normally when *repair action*, or *corrective action* in *maintenance* is performed in accordance with prescribed standard procedures. The item's operational effective condition in this context is also considered to be the item's *repairable condition*. Maintainability is thus the *probability* that an item will be restored to a *repairable condition* through *corrective maintenance action*, in accordance with prescribed standard procedures, within a given period of time.

Corrective maintenance action is the *action* to rectify or set right defects in the equipment's *operational* and *physical conditions*, on which its functions depend, in accordance with a standard. Similarly, it can also be discerned, from the description of *corrective maintenance action* in maintenance, that *maintainability* is achieved through restorative *corrective maintenance action* through some or other *repair action*.

This *repair action* is, in fact, action to rectify or set right defects in accordance with a standard. The *repairable condition* of equipment is determined by the *mean time to repair (MTTR)*, which is a measure of its *maintainability*. *Maintainability is thus a measure of the repairable condition of an item that is determined by MTTR, and is established through corrective maintenance action.*

Maintainability modelling for a repairable system is, to a certain extent, a form of applied probability analysis, very similar to the probability assessment of uncertainty in reliability. It includes Bayesian methods applied to Poisson processes, as well as Weibull analysis and Monte Carlo simulation, which is used extensively in availability analysis. Maintainability modelling also relates to *queuing theory*. It can be compared to the problem of determining the occupancy, arrival and service rates in a queue, where the service performed is repair, the server is the maintenance function, and the patrons of the queue are the systems and equipment that are repaired at random intervals, coincidental to the random occurrences of failures. Applying maintainability models enhances the capability of designing for maintainability through the appropriate consideration of design criteria such as *visibility*, *accessibility*, *testability* and *interchangeability*. Using maintainability prediction techniques, as well as specific quantitative maintainability analysis models relating to the operational requirements of a design can greatly enhance not only the integrity of engineering design but also the confidence in the operational capabilities of a design. Maintainability predictions of the operational requirements of a design during its conceptual design phase can aid in design decisions where several design options need to be considered. Quantitative maintainability analysis during the schematic and detail design phases

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consider the assessment and evaluation of maintainability from the point of view of *maintenance* and *logistics support* concepts.

Designing for maintainability requires a product that is *serviceable* (must be easily repaired) and *supportable* (must be cost-effectively kept in, or restored to, a usable condition). If the design includes a *durability* feature related to *availability* (degree of operability) and *reliability* (absence of failures), then it fulfils, to a large extent, the requirements for engineering design integrity. Maintainability is primarily a design parameter, and designing for maintainability defines how long the equipment is expected to be down. *Serviceability* implies the speed and ease of maintenance, whereby the amount of time expected to be spent by an appropriately trained maintenance function working within a responsive supply system is such that it will achieve minimum downtime in restoring failed equipment. In designing for maintainability, the *type of maintenance* must be considered, and must have an influential role in considering *serviceability*.

For example, the stipulation that a system should be capable of being isolated to the component level of each circuit card in its control sub-system may not be justified if a faulty circuit card is to be replaced, rather than repaired. Such a design would impose added developmental cost in having to accommodate a redundant feature in its functional control.

Supportability has a design subset involving *testability*, a design characteristic that allows verification of the operational status to be determined and faults within the system's equipment to be isolated in a timely and effective manner. This is achieved through the use of built-in-test equipment, so that an installed item can be monitored with regard to its status (operable, inoperable or degraded).

Designing for maintainability also needs to take cognisance of the item's operational *durability* whereby the period (downtime) in which equipment will be down due to unavailability and/or unreliability needs to be considered. Unavailability in this context occurs when the equipment is down for periodic maintenance and for repairs. Unreliability is associated with system failures where the failures can be associated with unplanned outages (corrective action) or planned outages (preventive action). Relevant criteria in designing for maintainability need to be verified through maintainability *design reviews*. These design reviews are conducted during the various design phases of the engineering design process, and are critical components of modern design practice. The primary objective of maintainability design reviews is to determine the relevant progress of the design effort, with particular regard to designing for maintainability, at the completion of each specific design phase. As with design reviews in general (*i.e.*, design reviews concerned with designing for reliability, availability, maintainability and safety), maintainability design reviews fall into three distinct categories: initial or

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conceptual design reviews, intermediate or schematic design reviews, and final or detail design reviews (Hill 1970).

Initial or *conceptual design reviews* need to be conducted immediately *after* formulation of the conceptual design, from initial process flow diagrams (PFDs). The purpose is to carefully examine the functionality of the intended design, feasibility of the criteria thatmust bemet, initial formulation of design specifications at process and systems level, identification of process design constraints, existing knowledge of similar systems and/or engineered installations, and cost-effective objectives. Intermediate or *schematic design reviews* need to be conducted immediately *after* the schematic engineering drawings are developed from firmed-up PFDs and initial pipe and instrument diagrams (P&IDs), and when primary specifications are fixed. This is to compare formulation of design criteria in specification requirements with the proposed design. These requirements involve assessments of systems performance, reliability, inherent and achieved availability, maintainability, hazardous operations (HazOps) and safety, as well as cost estimates.

Final or *detail design reviews*, referred to as the *critical design review*, are conducted immediately *after* detailed engineering drawings are developed for review (firmed PFDs and firmed P&IDs) and most of the specifications have been fixed. At this stage, results from preceding design reviews, and detail costs data are available. This review considers evaluation of design integrity and due diligence, hazards analyses, value engineering, manufacturing methods, design producibility/constructability, quality control and detail costing. The essential criteria that need to be considered with *maintainability design reviews* at the completion of the various engineering design phases include the following:

- Design constraints and specified systems interfaces
- Verification of maintainability prediction results
- Evaluation of maintainability trade-off studies
- Evaluation of FMEA results
- Maintainability problem areas and maintenance requirements
- Physical design configuration and layout schematics
- Design for maintainability specifications
- Verification of maintainability quantitative characteristics
- Verification of maintainability physical characteristics
- Verification of design ergonomics
- Verification of design configuration accessibility
- Verification of design equipment interchangeability
- Evaluation of physical design factors

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- Evaluation of facilities design dictates
- Evaluation of maintenance design dictates
- Verification of systems testability
- Verification of health status and monitoring (HSM)
- Verification of maintainability tests
- Use of automatic test equipment
- Use of Built-In-Test (BIT) methods
- Use of onboard monitoring and fault isolation methods
- Use of online repair with redundancy
- Evaluation of maintenance strategies
- Selection of assemblies and parts kits
- Use of unit (assembly) replacement strategies
- Evaluation of logistic support facilities.

3.4 SAFETY AND ENVIRONMENTAL ASPECTS IN MAINTENANCE MANAGEMENT

Management of the modern business enterprise is not just the culmination of producing products and services to sell to the customers and make profit. Due to the intrinsic network of various stakeholders of an enterprise starting from the shareholders to the general public at large, a management has to not only look for immediate results like profitability but also take care of long term goals like customer satisfaction, public image and goodwill etc. The assiduously built reputation of a company can be destroyed by a single incident of accident in its premises. A recent example was the accident in Bhopal in the Union Carbide factory, which sullied its reputation worldwide. Similarly, Governments and the general public are demanding safeguards for environmental performance of the products and processes of a production operation. In view of these requirements, safety and environmental issues have assumed priority over many other requirements for a business enterprise.

The earlier thinking in the safety assurance of an operation system was to stress on creation of a separate safety specialization, which had been primarily made responsible for the safety of men and machines. Such attempts have often been found to be inadequate due to non-participation of the grass root level personnel of the plant. The modern concept of safety assurance tries to stress the importance of involvement of all the people, right from the top most owner of the company to the lower most workers in the safety and environment movement of the company. Terminologies like 'Total Safety

Management', 'Sustainable Development' etc., are the result of such modern thinking to bring a holistic view into the subject. The analysis of the causes of many safety and environmental accidents, have invariably identified 'improper maintenance' as one of the major reasons. While simple preventive maintenance activities like inspections, timely replacements etc would be quite économical, the neglect of the same has been the reason for enormous loss of revenue running to million of rupees as a result of the accidents emanating from such causes, not to speak of the invaluable loss of precious lives.

Needless to emphasize, safety and environmental issues need to be made an integral part of the maintenance management function, without which the basic objective of the maintenance function of assurance of plant availability is not complete. This unit tries to bring out the important facets of the interlinkage between safety and environmental issues and maintenance management.

3.5 THE COMPONENTS OF SAFETY AND ENVIRONMENTAL ASPECTS AND THEIR RELATION TO MAINTENANCE MANAGEMENT

There are various aspects concerned with the safety and environmental performance of an enterprise. Each of these aspects has also linkage with the operation and maintenance management functions. These are briefly described below:

Corporate Objectives and Goals: The top management of the organizations is expected to clearly specify the corporate objectives and goals it would like to practice in terms of environment and safety assurance. Many a times, this is done through a widely publicized policy statement. The policy and objectives of the operation and maintenance functions are expected to dovetail them into the corporate safety and environmental objectives. For example, a policy of strict environmental cleanliness in terms of carbon dioxide emission norms may mean operation and maintenance policy practice of alternate use of clean fuels or the requirement for more frequent preventive maintenance overhauling.

Documentation of Process and Equipment: Another important requirement for the safety and environmental assurance for the company is the meticulous documentation of the vital specifications of the process and equipment in terms of their compliance to safety and environmental standards, statutory or otherwise. This documentation can be either independently

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prepared or integrated into the operation and maintenance manuals of the plant processes or equipment.

Risk Management: As it may not be possible to totally eliminate the risks to zero level, specifically in case of large complex process plants, it would be required to scientifically analyze the risks involved and prepare plans to mitigate them. Risk management involves use of multi disciplinary knowledge and participation to identify all possible hazards and also identify solutions to keep their risks at acceptable levels. The contribution of operation and maintenance in risk management is to contribute to the analysis process through inputs regarding various hazards of operation and maintenance processes. For example, many of the accidents in chemical process plants are due to typical maintenance operations like structure welding, catalyst change, overhauling etc. Hence the maintenance functions having intrinsic knowledge of these processes need to contribute in the process of study of these risks.

Change Management: In process plants, many of the environmental and safety failures arise from the failure to manage changes, both in the technology applications or systems. The Flixborough accident happened due to the failure to manage properly the change required in terms of providing a bypass line to a reactor during shut down of a reactor. Hence process safety guidelines insist on well laid out procedures for change management. As maintenance activities are the most prominent examples of unknown changes, due to their unique nature each time, these requirements are mainly applicable to the maintenance function.

Human Factors: The untrained or improperly placed worker is likely to commit mistakes, which may lead to safety or environmental consequences. Apart from this, there are other human factors like attitude, ergonomics, work culture etc, which have great bearing on the safety and environmental performance. Nurturing the human factors to enable achievement of best safety results is equally applicable to all plant functions, including operation and maintenance.

Investigation of Incidents: There is requirement, statutory or otherwise, to intensely investigate incidents, so that underlying causes can be found out and corrective actions for future improvements can be prescribed. The role of operation and maintenance personnel are important in such investigations, as they have to provide the correct sequence of activities before, during and after the incident to the investigating team and also implement the suggestions emanating from such investigations.

Safety and Environmental Audits: As already explained in another unit, there is increasing tendency to integrate the safety and environment audit requirements in the maintenance audits. The audits are mainly to identify whether the existing systems, techniques and procedures comply with the stated and required standards and suggest improvements wherever required. The maintenance executive is an important team member of the safety and environment audit team in many process plants.

3.6 MAINTENANCE TECHNIQUES FOR SAFETY AND ENVIRONMENTAL IMPROVEMENTS

The primary function of maintenance management is to ensure the availability of the plant and equipment. However, intrinsic to this requirement is the necessity to also provide maximum reliability and safety. Hence maintenance management needs to integrate their techniques to simultaneously improve safety and environmental aspects of operation and maintenance of plant and equipment. In this portion we would see what are the maintenance management techniques that can contribute in this direction.

Classification of Plant and Equipment: It is normally required for the maintenance management function to classify the equipment into various categories so that resource allocation can be facilitated according to their criticality. A factorization method is sometimes used to rank the equipment in term of their criticality. Apart from the conventional broad factors of Operational Criticality, Maintenance intensiveness, *Quality of Products, it is* emphasized that Safety and Environmental factor is also considered in such classifications. The sub-factors under this category could be the accident potential and severity, emission of pollutants, extent of exposure of human elements to the equipment etc.

Preventive and Predictive Maintenance Scheduling: Regular checklists and preventive maintenance schedules should include important safety and environmental checkpoints. Nowadays preventive maintenance is often supported by instrumentoriented measurements called Condition Monitoring. Many of these monitoring instruments can be used as dual purpose techniques, for example, measurement of thickness of reactor wall thickness using ultrasonic gauges not only predicts wear and tear from maintenance replacement angle but also identifies potential dangerous situations of excessive material deterioration, cracks etc. Similarly, thermograph can identify both insulation wear and thermal breakdowns in high temperature *reformers, furnaces etc.*

Shutdown Maintenance Planning: Long shutdowns for annual turnarounds and major overhauls are important requirements of many process plants and heavier and complex equipment. Due to the tight time schedule under which such shutdown maintenance are executed, there are many

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possibilities of compromises on safety and environmental features and standards. Hence the planning process of such activities needs to meticulously include the steps required to ensure safety and environmental standards.

Communication between Maintenance and other Departments: Many safety and environmental hazards have emanated from improper communication between maintenance and other departments, especially the operations department. Proper information systems like log book entries, work order systems, work permit systems, lock out systems in case of electrical hazards etc are some of the requirements to ensure communication, thus enabling safety.

Maintenance Training: All maintenance personnel working in plant facility should be trained in the basic understanding of the process and mechanical hazards. The training should include mechanical skills, theory, on-the-job/ apprentice training, safe work practices training and specialized craft training. Maintenance staff often forgets after a period, thus the company often loses valuable work information. Several accidents have occurred due to such 'corporate memory lapses'. The techniques useful under such circumstances are:

- Refresher training of all staff
- Use of incident investigation in training
- Publicity campaigns on safety
- Close supervision of new staff
- Continuous updation of maintenance instructions
- Safety compliance audits
- Counseling poorly performing staff.

3.7 HUMAN RESOURCE DEVELOPMENT IN MAINTENANCE MANAGEMENT

In the olden times an employee, especially a worker was treated more like a mindless machine than as a human being. Other than basic technical skills that he/she had to have, he/she was not given any training and was left to his/her own to improve himself. It was a case of survival of the fittest (as seen by his superiors) that dictated his/her career path. This process never brought out the full creative potential even amongst the best of employees. Often, it brought out one's cunning ability to step on others for one's own success. There was no conscious or organized attempt towards developing talents, and attitudes, and relationships that could contribute to achievement of significantly higher level of performance of the individual and through him, the organization. Artificial methods of increasing output such as purely financial incentives and fear of dismissal had to be used.

The enterprise, therefore, did not get the most out of its workforce. Managing such a workforce was quite stressful to the managers. Conditions have changed a great deal in recent years. Global competition has forced management to look into ways and means of increasing productivity and reduce costs. At all levels technological advances have placed greater demands on the thinking process rather than just the physical side of work. The tremendous difference made to organization efficiency, morale of workforce, and relatively stress-free gain in productivity by companies that invested in the development of their employees has convinced most management that human resource development (HRD) is the fundamental and probably the most important responsibility/duty of the organization.

3.8 MATCHING OF EXPECTATIONS

To understand the meaning of HRD, one must ask what does the management of an organization want from the workforce and what do the individuals that make up the workforce want from their job. Once these matters are clear, the manner and method of HRD for a given organization will become clear. At this stage, it is important to recognize that HRD is a function and not a department exclusively dealing with this topic. As such, its activity and responsibility stretches across many parts of the organization and at many levels.

Expectations of the Organization

The explicit or implicit expectations of an organization from its employees are:

- **Skill of the job:** A machine tool operator should handle the machine skillfully, safely and without damage, and should produce error-free product. A vehicle driver should drive smoothly at the right speed, practice good road discipline and laws and also take care of the vehicle. A clerk should know the related procedure, type fast and file documents correctly. A mechanic should correctly diagnose a fault in a machine, and repair it quickly and fully in minimum time etc.
- **Commitment:** The employee should show some responsibility to the task and not find excuses to shirk from work. He/she should show initiative

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and interest and solve minor work-related problems himself. He/she should also report to the superior, upcoming difficulties or growing problems that are outside his/her ability or authority to tackle.

- **Versatility:** Complexities of modern machines and workplace demand higher degree of specialization on the part of the work force than ever before. Yet, in many work areas tasks of different skills overlap. The employee must stretch his/her hand to take on a part of such 'gray' areas of work and achieve close coordination to save time. Also, sometimes there is a need for a person to do more than one task. In many cases, it is not even economical to employ a full time specialist for jobs that cannot load him/her fully. A versatile employee can be easily trained to take on new roles that are inevitable in the rapidly changing industrial scenario.
- **Team spirit:** More and more of today's work is teamwork. A cooperative and mutually supportive attitude, willingness to go with others or take others with oneself, tolerance for different viewpoints, and having a sense of ownership about the team rather than glorifying oneself at the cost of the team, are the best indicators of team spirit. These can be inculcated but the individual must also be amenable to it.
- **Discipline:** An organization has to have procedures and rules of conduct in order to ensure predictability and to avoid chaos. This involves some restraints on everybody. Constantly rebelling against the rules simply to emphasize one's own independence is disastrous to the functioning of any group, department or even a whole organization. In this sense, the organization has a right to expect disciplined behavior from the employees.

From the managers, the organization has some additional expectations. These will naturally change according to the size and nature of the organization, but broadly these are:

- Professional knowledge of the business/industry/technology
- Skills of planning, coordinating and controlling work
- Resourcefulness and problem solving ability
- Being innovative
- Leadership qualities (including decision making)

Expectations of the Employees

The expectations of managers and other employees from the organization are:

- Adequate monetary compensation
- Job satisfaction (Pride that his/her skills had been well utilized)
- Social interaction at workplace

- Fairness and justice in dealing by their superiors in particular and by the organization at large
- Opportunities for growth
- Stress free work culture
- Recognition by superiors
- Freedom to share/express his/her opinions and thoughts about work

These fit into Abraham Maslow's 'hierarchy of needs'. In the old days, the attitude of slavery at work prevented expression of the needs. With our enlightened society, protective labour laws, and fast communications, the modern employee has become aware and more vocal about them.

3.9 ROLE OF HUMAN RESOURCE DEVELOPMENT

HRD can now be seen as 'developing the workforce in such a way as to match the organizational needs and the needs of its work force'. Implicit in this approach is the recognition that the work force is its most important instrument of growth. It is worth noting that in the Indian Army 'man management' has always been given the highest priority – even greater than professional competence and weaponry.' Man is to machine (weapon) as three is to one'-is the refrain in leadership, administration and training.

How can an organization grow unless its most important instrument itself grows? The term 'growth' applied to an individual in an organization means developing his qualities that make him more useful to the organization. Behavioral scientists have discovered that the individual's growth for self also contributes to the growth of the organization. A constructive look at the areas where the personal and the organizational expectations and needs could match or be complimentary, will help bring out ways and means to develop the human being as a resource. Some expectations are common to all, but other will vary to some extent with the job. For instance, the expectations of/from a research scientist would be different of/from a worker in a coalmine. Expectations of/from a machine tool/crane operator would be different from that of/from an accounts or stores clerk or a maintenance technician. This paper deals with HRD for maintenance, where the specific needs of maintenance have been considered.

3.10 INTRODUCING HRD FOR MAINTENANCE

The starting point for HRD is the senior most maintenance engineer/manager talking to his colleagues and subordinates and to take the following steps:

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- Identify the short and long-term goals for maintenance; typically, reducing downtime of selected machines to a lower (specified) level; reducing cost on spares; increasing part rebuilding.
- For each goal undertakes a series of brainstorming sessions with related (interdepartmental) persons at mixed levels, levels, on 'deterrents that come in the way of achieving that goal'.
- Prioritize these and select a few (usually five to eight) key deterrents and carry out further brainstorming to identify why these deterrents existed.
- After this stage the major problem areas will become clear-as perceived by the participants of the brainstorming session. These will fall into five main classes: knowledge; skill; attitudes; workload; and organization.
- These problems must now be solved step by step, again involving personnel at all levels. These steps (such as developing excellence through various types of training, leadership, stress management, team building etc.,) have been discussed earlier.

An attitudinal change takes place in this process as employees get deeply involved and begin to 'own' the problem.. Problem solving by mixed teams will further strengthen the process. Training needs is clearly brought out in this way. Knowledge will be improved by training, both on the job and off the job. HRD will have to be a continuous and concurrent process in the twin areas of technical competence and human attitudes and relationships. HRD is a non-stop process.

3.11 TQM AND MAINTENANCE MANAGEMENT

TQM is *the* way of managing for the future, and is far wider in its application than just assuring product or service quality — it is a way of managing people and business processes to ensure complete customer satisfaction at every stage, internally and externally. TQM, combined with effective leadership, results in an organisation doing the right things right, first time.

The core of TQM is the ***customer-supplier*** interfaces, both externally and internally, and at each interface lie a number of ***processes***. This core must be surrounded by ***commitment*** to quality, ***communication*** of the quality message, and recognition of the need to change the ***culture*** of the organisation to create total quality. These are the foundations of TQM, and they are supported by the key management functions of ***people***, ***processes*** and ***systems*** in the organisation.

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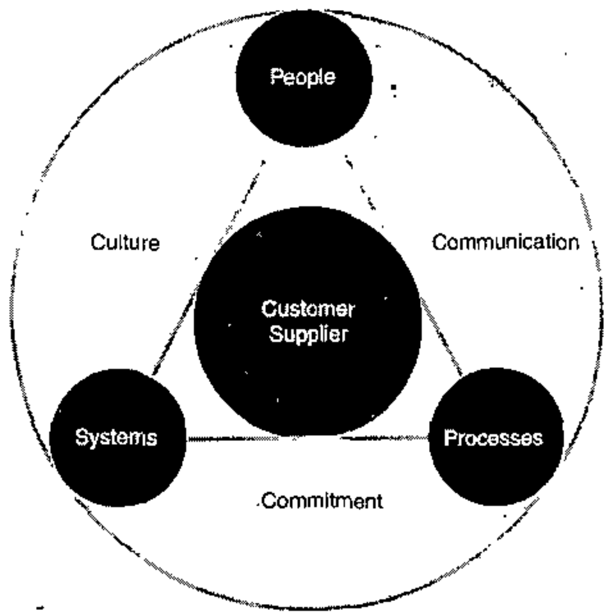

Fig. 3.5

This section discusses each of these elements that, together, can make a total quality organisation. Other sections explain people, processes and systems in greater detail, all having the essential themes of commitment, *culture* and *communication running through them.*

3.12 WHAT IS QUALITY?

A frequently used definition of quality is *"Delighting the customer by fully meeting their needs and expectations"*. These may include performance, appearance, availability, delivery, reliability, maintainability, cost effectiveness and price. It is, therefore, imperative that the organisation knows what these needs and expectations are. In addition, having identified them, the organisation must understand them, and measure its own ability to meet them. Quality starts with market research – to establish the true requirements for the product or service and the true needs of the customers. However, for an organisation to be really effective, quality must span all functions, all people, all departments and all activities and be a common language for improvement. The cooperation of everyone at every interface is necessary to achieve a total quality organisation, in the same way that the Japanese achieve this with company wide quality control.

The failure to address the culture of an organisation is frequently the reason for many management initiatives either having limited success or failing altogether. Understanding the culture of an organisation, and using that

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knowledge to successfully map the steps needed to accomplish a successful change, is an important part of the quality journey.

The culture in any organisation is formed by the beliefs, behaviours, norms, dominant values, rules and the "climate". A culture change, e.g, from one of acceptance of a certain level of errors or defects to one of right first time, every time, needs two key elements:

- Commitment from the leaders.
- Involvement of all of the organisation's people.

There is widespread recognition that major change initiatives will not be successful without a culture of good teamwork and cooperation at all levels in an organisation, as discussed in the section on People.

The building blocks of TQM: processes, people, management systems and performance measurement.

Everything we do is a Process, which is the transformation of a set of inputs, which can include action, methods and operations, into the desired outputs, which satisfy the customers' needs and expectations.

In each area or function within an organisation there will be many processes taking place, and each can be analysed by an examination of the inputs and outputs to determine the action necessary to improve quality. In every organisation there are some very large processes, which are groups of smaller processes, called key or core business processes. These must be carried out well if an organisation is to achieve its mission and objectives. The section on Processes discusses processes and how to improve them; and Implementation covers how to prioritise and select the right process for improvement.

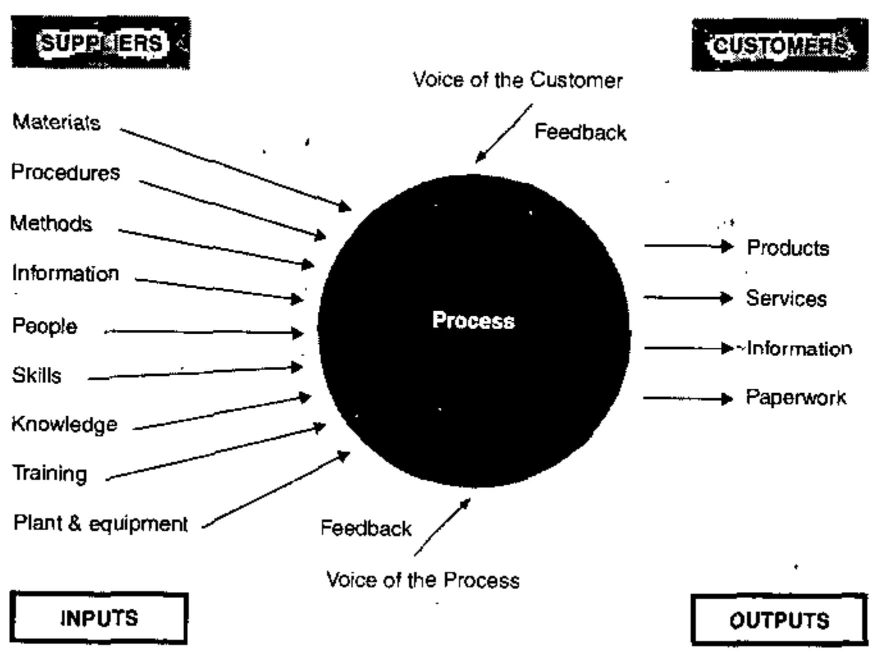

Fig. 3.6

The only point at which true responsibility for performance and quality can lie is with the **People** who actually do the job or carry out the process, each of which has one or several suppliers and customers. An efficient and effective way to tackle process or quality improvement is through teamwork. However, people will not engage in improvement activities without commitment and recognition from the organisation's leaders, a climate for improvement and a strategy that is implemented thoughtfully and effectively. The section on People expands on these issues, covering roles within teams, team selection and development and models for successful teamwork.

An appropriate documented **Quality Management System** will help an organisation not only achieve the objectives set out in its policy and strategy, but also, and equally importantly, sustain and build upon them. It is imperative that the leaders take responsibility for the adoption and documentation of an appropriate management system in their organisation if they are serious about the quality journey. The Systems section discusses the benefits of having such a system, how to set one up and successfully implement it.

Once the strategic direction for the organisation's quality journey has been set, it needs **Performance Measures** to monitor and control the journey, and to ensure the desired level of performance is being achieved and sustained. They can, and should be, established at all levels in the organisation, ideally being cascaded down and most effectively undertaken as team activities.

3.13 TYPES OF MAINTENANCE PROGRAMS

What is maintenance and why is it performed? Past and current maintenance practices in both the private and Government sectors would imply that maintenance is the actions associated with equipment repair after it is broken. The dictionary defines maintenance as follows: "the work of keeping something in proper condition; upkeep." This would imply that maintenance should be actions taken to prevent a device or component from failing or to repair normal equipment degradation experienced with the operation of the device to keep it in proper working order.

Unfortunately, data obtained in many studies over the past decade indicates that most private and Government facilities do not expend the necessary resources to maintain equipment in proper working order. Rather, they wait for equipment failure to occur and then take whatever actions are necessary to repair or replace the equipment. Nothing lasts forever and all equipment has associated with it some predefined life expectancy or operational life.

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For example, equipment may be designed to operate at full design load for 5,000 hours and may be designed to go through 15,000 start and stop cycles.

The design life of most equipment requires periodic maintenance. Belts need adjustment, alignment needs to be maintained, proper lubrication on rotating equipment is required, and so on. In some cases, certain components need replacement, *e.g.*, a wheel bearing on a motor vehicle, to ensure the main piece of equipment (in this case a car) last for its design life. Anytime we fail to perform maintenance activities intended by the equipment's designer, we shorten the operating life of the equipment. But what options do we have? Over the last 30 years, different approaches to how maintenance can be performed to ensure equipment reaches or exceeds its design life have been developed in the United States. In addition to waiting for a piece of equipment to fail (reactive maintenance), we can utilize preventive maintenance, predictive maintenance, or reliability centered maintenance.

Reactive Maintenance

Reactive maintenance is basically the "run it till it breaks" maintenance mode. No actions or efforts are taken to maintain the equipment as the designer originally intended to ensure design life is reached. Studies as recent as the winter of 2000 indicate this is still the predominant mode of maintenance in the United States. The referenced study breaks down the average maintenance program as follows:

- >55% Reactive
- 31% Preventive
- 12% Predictive
- 2% Other.

Note that more than 55% of maintenance resources and activities of an average facility are still reactive. Advantages to reactive maintenance can be viewed as a double-edged sword. If we are dealing with new equipment, we can expect minimal incidents of failure. If our maintenance program is purely reactive, we will not expend manpower dollars or incur capitol cost until something breaks.

Since we do not see any associated maintenance cost, we could view this period as saving money. The downside is reality. In reality, during the time we believe we are saving maintenance and capitol cost, we are really spending more dollars than we would have under a different maintenance approach. We are spending more dollars associated with capitol cost because, while waiting for the equipment to break, we are shortening the life of the equipment resulting in more frequent replacement. We may incur cost upon failure of the primary device associated with its failure causing the failure of a secondary device. This is an increased cost we would not have experienced if our maintenance program was more proactive.

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Our labor cost associated with repair will probably be higher than normal because the failure will most likely require more extensive repairs than would have been required if the piece of equipment had not been run to failure. Chances are the piece of equipment will fail during off hours or close to the end of the normal workday. If it is a critical piece of equipment that needs to be back on-line quickly, we will have to pay maintenance overtime cost. Since we expect to run equipment to failure, we will require a large material inventory of repair parts. This is a cost we could minimize under a different maintenance strategy.

Advantages

- Low cost.
- Less staff.

Disadvantages

- Increased cost due to unplanned downtime of equipment.
- Increased labor cost, especially if overtime is needed.
- Cost involved with repair or replacement of equipment.
- Possible secondary equipment or process damage from equipment failure.
- Inefficient use of staff resources.

Preventive Maintenance

Preventive maintenance can be defined as follows: Actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level.

Depending on the facilities current maintenance practices, present equipment reliability, and facility downtime, there is little doubt that many facilities purely reliant on reactive maintenance could save much more than 18% by instituting a proper preventive maintenance program. While preventive maintenance is not the optimum maintenance program, it does have several advantages over that of a purely reactive program. By performing the preventive maintenance as the equipment designer envisioned, we will extend the life of the equipment closer to design. This translates into dollar savings. Preventive maintenance (lubrication, filter change, etc.,) will generally run the equipment more efficiently resulting in dollar savings. While we will not prevent equipment catastrophic failures, we will decrease the number of failures. Minimizing failures translate into maintenance and capitol cost savings.

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Advantages

- Cost effective in many capital intensive processes.
- Flexibility allows for the adjustment of maintenance periodicity.
- Increased component life cycle.
- Energy savings.
- Reduced equipment or process failure.
- Estimated 12% to 18% cost savings over reactive maintenance program.

Disadvantages

- Catastrophic failures still likely to occur.
- Labor intensive.
- Includes performance of unneeded maintenance.
- Potential for incidental damage to components in conducting unneeded maintenance.

Predictive Maintenance

Predictive maintenance can be defined as follows: Measurements that detect the onset of a degradation mechanism, thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration in the component physical state. Results indicate current and future functional capability.

Basically, predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the machine rather than on some preset schedule. You will recall that preventive maintenance is time-based. Activities such as changing lubricant are based on time, like calendar time or equipment run time. For example, most people change the oil in their vehicles every 3,000 to 5,000 miles traveled. This is effectively basing the oil change needs on equipment run time. No concern is given to the actual condition and performance capability of the oil. It is changed because it is time. This methodology would be analogous to a preventive maintenance task. If, on the other hand, the operator of the car discounted the vehicle run time and had the oil analyzed at some periodicity to determine its actual condition and lubrication properties, he/she may be able to extend the oil change until the vehicle had traveled 10,000 miles. This is the fundamental difference between predictive maintenance and preventive maintenance, whereby predictive maintenance is used to define needed maintenance task based on quantified material/equipment condition.

The advantages of predictive maintenance are many. A well-orchestrated predictive maintenance program will all but eliminate catastrophic equipment failures. We will be able to schedule maintenance activities to minimize or delete overtime cost. We will be able to minimize inventory and order parts, as required, well ahead of time to support the downstream maintenance needs. We can optimize the operation of the equipment, saving energy cost and increasing plant reliability. Past studies have estimated that a properly functioning predictive maintenance program can provide a savings of 8% to 12% over a program utilizing preventive maintenance alone. Depending on a facility's reliance on reactive maintenance and material condition, it could easily recognize savings opportunities exceeding 30% to 40%. In fact, independent surveys indicate the following industrial average savings resultant from initiation of a functional predictive maintenance program:

- Return on investment: 10 times
- *Reduction in maintenance costs: 25% to 30%*
- Elimination of breakdowns: 70% to 75%
- Reduction in downtime: 35% to 45%
- *Increase in production: 20% to 25%.*

On the down side, to initially start into the predictive maintenance world is not inexpensive. Much of the equipment requires cost in excess of $50,000. Training of in-plant personnel to effectively utilize predictive maintenance technologies will require considerable funding. Program development will require an understanding of predictive maintenance and a firm commitment to make the program work by all facility organizations and management.

Reliability Centered Maintenance

Reliability centered maintenance (RCM) magazine provides the following definition of RCM: "a process used to determine the maintenance requirements of any physical asset in its operating context." Basically, RCM methodology deals with some key issues not dealt with by other maintenance programs. It recognizes that all equipment in a facility is not of equal importance to either the process or facility safety. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from different degradation mechanisms than others. It also approaches the structuring of a maintenance program recognizing that *a facility does not have unlimited financial and personnel resources* and that the use of both need to be prioritized and optimized. In a nutshell, RCM is a systematic approach to evaluate a facility's equipment and resources to best mate the two and result in a high degree of facility reliability and cost-effectiveness. RCM is highly reliant on predictive maintenance but also recognizes that maintenance activities on equipment that is inexpensive and unimportant to facility reliability may best be left to a reactive maintenance approach. The following maintenance program breakdowns of continually

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top-performing facilities would echo the RCM approach to utilize all available maintenance approaches with the predominant methodology being predictive.

- <10% Reactive
- 25% to 35% Preventive
- 45% to 55% Predictive.

Because RCM is so heavily weighted in utilization of predictive maintenance technologies, its program advantages and disadvantages mirror those of predictive maintenance. In addition to these advantages, RCM will allow a facility to more closely match resources to needs while improving reliability and decreasing cost.

Advantages

- Can be the most efficient maintenance program.
- Lower costs by eliminating unnecessary maintenance or overhauls.
- Minimize frequency of overhauls.
- Reduced probability of sudden equipment failures.
- Able to focus maintenance activities on critical components.
- Increased component reliability.
- Incorporates root cause analysis.

Disadvantages

- Can have significant startup cost, training, equipment, etc.
- Savings potential not readily seen by management.

How to Initiate Reliability Centered Maintenance?

The road from a purely reactive program to a RCM program is not an easy one. The following is a list of some basic steps that will help to get moving down this path.

1. Develop a Master equipment list identifying the equipment in your facility.
2. Prioritize the listed components based on importance to process.
3. Assign components into logical groupings.
4. Determine the type and number of maintenance activities required and periodicity using:
   (*a*) Manufacturer technical manuals
   (*b*) Machinery history
   (*c*) Root cause analysis findings - Why did it fail?
   (*d*) Good engineering judgement

5. Assess the size of maintenance staff.
6. Identify tasks that may be performed by operations maintenance personnel.
7. Analyze equipment failure modes and effects.
8. Identify effective maintenance tasks or mitigation strategies.

NOTES

The references and resources provided below are by no means all-inclusive. The listed organizations are not endorsed by the authors of this guide and are provided for your information only. To locate additional resources, the authors of this guide recommend contacting relevant trade groups, databases, and the world-wide web.

SUMMARY

- Reliability and performance prediction in this context is considered in the *conceptual design* phase of the engineering design process. The most applicable methodology for reliability and performance prediction in the conceptual design phase includes basic concepts of mathematical modelling.
- *Availability in engineering design* has its roots in *designing for reliability* as well as *designing for maintainability*, in which a 'top-down' approach is adopted, predominantly from the design's systems level to its equipment level (*i.e.,* assembly level), and constraints on systems *operational* performance are determined.
- Hence maintenance management needs to integrate their techniques to simultaneously improve *safety* and *environmental aspects of operation* and maintenance of plant and equipment.
- HRD can now be seen as 'developing the workforce in such a way as to match the organizational needs and the needs of its work force'.
- Quality is *"Delighting the customer by fully meeting their needs and expectations"*. These may include performance, appearance, availability, delivery, reliability, maintainability, cost effectiveness and price.
- Maintenance is the actions associated with equipment repair after it is broken. The dictionary defines maintenance as follows: "the work of keeping something in proper condition; upkeep." This would imply that maintenance should be actions taken to prevent a device or component from failing or to repair normal equipment degradation experienced with the operation of the device to keep it in proper working order.

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REVIEW QUESTIONS

1. What do you understand by reliability?
2. What do you understand by availability?
3. What do you understand by maintainability?
4. What are the different methods of reliability analysis in engineering design?
5. illustrate the basic concepts of mathematical modelling:
   - Total cost models for design reliability.
   - Interference theory and reliability modelling.
   - System reliability modelling based on system performance.
6. Write the short notes on System Reliability Modelling Based on System Performance.
7. Why are safety and environmental issues important for a manufacturing concern?
8. What do you understand by the term 'Total Safety Management'?
9. "Improper Maintenance is a major cause of Accidents"- Give your arguments in favour and against this statement.
10. What are major components of safety and environmental issues of an enterprise?
11. How do the maintenance goals and objectives take care of safety goals of an organization?
12. What types of maintenance documentation do you think are important from safety and environmental point of view?
13. How classification of plant and equipment help safety? Give an example.
14. What safety checks are possible in preventive and predictive maintenance – give some examples
15. How can the communication between maintenance and other functions can be enhanced?
16. What types of training techniques are available for preparing maintenance personnel to enhance safety and environmental performance?
17. What are the basic expectations of the organization from all the employees? List these.
18. What are the expectations of all employees from the organization?
19. What are the aspects and activities of the maintenance function?
20. Many organizations have standing conflicts amongst maintenance and production/operations employees. Describe the nature of these conflicts. What are the main causes?
21. What can be done to improve the negative image and low self-concept of maintenance?

22. What is the difference between maintenance technology and maintenance engineering?
23. What steps are needed to introduce and sustain HRD, Specifically for maintenance, in an organization?
24. What do you understand by TQM?
25. What is quality?
26. What are different types of Maintenance Programs?

FURTHER READINGS

- **Comprehensive Maintenance Management: Policies, Strategies And Options:** Amit Telang and A.D. Telang, PHI Learning.

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UNIT IV ANALYTICAL METHODS IN MAINTENANCE MANAGEMENT

★ STRUCTURE ★

4.1 Failure Statistics, Data Analysis and Methods of Qualitative Analysis
4.2 Theoretical Overview of Reliability Assessment in Preliminary Design
4.3 Theoretical Overview of Reliability Evaluation in Detail Design
4.4 Economics of Repair and Replacement of Equipment
4.5 Economic Life Models
4.6 Planning and Scheduling Plant and Overhauling Shutdowns
4.7 Planning
4.8 Scheduling
4.9 Planning and Scheduling of Plant Shutdowns
- *Summary*
- *Review Questions*
- *Further Readings*

4.0 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain failure statistics, data analysis and methods of qualitative analysis.
- define economic of repair and replacement of equipment.
- describe planning and scheduling of plant and overhauling shut-down.

4.1 FAILURE STATISTICS, DATA ANALYSIS AND METHODS OF QUALITATIVE ANALYSIS

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The fundamental understanding of the concepts of reliability, availability and maintainability (and, to a large extent, an empirical understanding of safety) has in the main dealt with statistical techniques for the measure and/ or estimation of various parameters related to each of these concepts, *based on obtained data*. Such data may be obtained from current observations or past experience, and may be complete, incomplete or censored. Censored data arise from the cessation of experimental observations prior to a final conclusion of the results. These statistical techniques are predominantly couched in probability theory.

The usual meaning of the term *reliability* is understood to be *'the probability of performing successfully'*. In order to assess reliability, the approach is based upon available test data of successes or failures, or on field observations relative to performance under either actual or simulated conditions. Since such results can vary, the estimated reliability can be different from one set of data to another, even if there are no substantial changes in the physical characteristics of the item being assessed. Thus, associated with the reliability estimate, there is also a measure of the significance or accuracy of the estimate, termed the 'confidence level'. This measure depends upon the amount of data available and/or the results observed. The data are normally governed by some parametric probability distribution. This means that the data can be interpreted by one or other mathematical formula representing a specific statistical probability distribution that belongs to a family of distributions differing from one another only in the values of their parameters. Such a family of distributions may be grouped accordingly:

- Beta distribution
- Binomial distribution
- Lognormal distribution
- Exponential (Poisson) distribution
- Weibull distribution.

Estimation techniques for determining the level of confidence related to an assessment of reliability based on these probability distributions are the methods of *maximum likelihood*, and *Bayesian estimation*.

In contrast to reliability, which is typically assessed for *non-repairable systems*, *i.e.*, without regard to whether or not a system is repaired and restored to service after a failure, *availability* and *maintainability* are principally assessed

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for *repairable systems*. Both availability and maintainability have the dimensions of a probability distribution in the range zero to one, and are based upon time-dependent phenomena. The difference between the two is that availability is a measure of total performance effectiveness, usually of systems, whereas maintainability is a measure of effectiveness of performance during the period of restoration to service, usually of equipment.

Reliability assessment based upon the family of statistical probability distributions considered previously is, however, subject to a somewhat narrow point of view— success or failure in the function of an item. They do not consider situations in which there are some means of backup for a failed item, either in the form of *replacement* or in the form of *restoration*, or which include multiple failures with standby reliability, *i.e.*, the concept of *redundancy*, where a redundant item is placed into service after a failure. Such situations are represented by additional probability distributions, namely:

- Gamma distribution
- Chi-square distribution.

Availability, on the other hand, has to do with two separate events—failure and repair. Therefore, assigning confidence levels to values of availability cannot be done parametrically, and a technique such as Monte Carlo simulation is employed, based upon the estimated values of the parameters of time-to-failure and time-to repair distributions. When such distributions are exponential, they can be reviewed in a Bayesian framework so that not only the time period to specific events is simulated but also the *values* of the parameters. Availability is usually assessed with Poisson or Weibull time-to-failure and exponential or lognormal time-to-repair. *Maintainability* is concerned with only one random variable—the repair time for a failed system. Thus, assessing maintainability implies the same level of difficulty as does assessing reliability that is concerned with only one event, namely the failure of a system in its operating condition. In both cases, if the time to an event of failure is governed by either a parametric, Poisson or Weibull distribution, then the confidence levels of the estimates can also be assigned parametrically.

(*a*) Designing for Reliability

In an elementary process, *performance* may be measured in terms of input, throughput and output quantities, whereas *reliability* is generally described in terms of the probability of failure or a mean time to failure of equipment (*i.e.*, assemblies and components). This distinction is, however, not very useful in engineering design because it omits the assessment of *system reliability* from preliminary design considerations, leaving the task of evaluating

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equipment reliability during detail design, when most equipment items have already been specified. A closer scrutiny of reliability is thus required, particularly the broader concept of *system reliability*.

System reliability can be defined as *"the probability that a system will perform a specified function within prescribed limits, under given environmental conditions, for a specified time"*.

An important part of the definition of system reliability is the ability to perform within prescribed limits. The boundaries of these limits can be quantified by defining constraints on acceptable performance. The constraints are identified by considering the *effects of failure* of each identified performance variable. If a particular performance variable (designating a specific required duty) lies within the space bounded by these constraints, then it is a feasible design solution, *i.e.,* the design solution for a chosen performance variable does not violate its constraints and result in unacceptable performance. The best performance variable would have the greatest variance or *safety margin* from its relative constraints. Thus, a design that has the highest safety margin with respect to all constraints will inevitably be the most reliable design.

(*b*) Designing for Availability

Designing for availability, as it is applied to an item of equipment, includes the aspects of *utility* and *time*. Designing for availability is concerned with equipment *usage* or *application* over a period of *time*. This relates directly to the equipment (*i.e.*, assembly or component) being able to perform a specific function or duty within a given time frame, as indicated by the following definition: *Availability* can be simply defined as *"the item's capability of being used over a period of time"*, and the measure of an item's availability can be defined as *"that period in which the item is in a usable state"*. Performance variables relating availability to reliability and maintainability are concerned with the measures of time that are subject to equipment failure. These measures are mean time Between Failures (MTBF), and mean downtime (MDT) or mean time to Repair (MTTR). As with designing for reliability, which includes all aspects of the ability of a system to perform, designing for availability includes reliability and maintainability considerations that are integrated with the performance variables related to the measures of time that are subject to equipment failure. Designing for availability thus incorporates an assessment of *expected performance* with respect to the performance measures of MTBF, MDT or MTTR, in relation to the performance capabilities of the equipment. In the case of MTBF and MTTR, there are no limits of capability.

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(c) Designing for Maintainability

Maintainability is that aspect of maintenance that takes *downtime* into account, and can be defined as *"the probability that a failed item can be restored to an operational effective condition within a given period of time"*. This restoration of a failed item to an operational effective condition is usually when *repair action*, or *corrective maintenance action*, is performed in accordance with prescribed standard procedures.

The item's operational effective condition in this context is also considered to be the item's *repairable condition. Corrective maintenance action* is the *action* to rectify or set right defects in the item's *operational* and *physical conditions*, on which its functions depend, in accordance with a standard. Maintainability is thus the *probability* that an item can be restored to a *repairable condition* through *corrective action*, in accordance with prescribed standard procedureswithin a given period of time. It is significant to note that maintainability is achieved not only through restorative corrective maintenance action, or repair action, in accordance with prescribed standard procedures, but also within a given period of *time*. This *repair action* is in fact determined by the mean time to repair (MTTR), which is a measure of the performance of maintainability.

A fundamental principle is thus identified:

Maintainability is a measure of the repairable condition of an item that is determined by the mean time to repair (MTTR), established through corrective maintenance action.

Designing for maintainability fundamentally makes use of maintainability prediction techniques as well as specific quantitative maintainability analysis models relating to the operational requirements of the design. Maintainability predictions of the operational requirements of a design during the conceptual design phase can aid in design decisions where several design options need to be considered. Quantitative maintainability analysis during the schematic and detail design phases considers the assessment and evaluation of maintainability from the point of view of *maintenance* and *logistics support* concepts. Designing for maintainability basically entails a consideration of design criteria such as *visibility, accessibility, testability, repairability* and *inter-changeability*. These criteria need to be verified through *maintainability design reviews*, conducted during the various design phases. Designing for maintainability at the *systems* level requires an evaluation of the *visibility, accessibility* and *repairability* of the system's equipment in the event of failure. This includes integrated systems shutdown during planned maintenance.

4.2 THEORETICAL OVERVIEW OF RELIABILITY ASSESSMENT IN PRELIMINARY DESIGN

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Reliability assessment attempts to estimate the expected reliability and criticality values for each individual *system* or *assembly* at the upper systems levels of the systems breakdown structure (SBS). This is done without any difficulty, not only for relatively simple initial system configurations but for progressively more complex integrations of systems as well. Reliability assessment ranges from estimations of the reliability of relatively simple systems with series and parallel *assemblies*, to estimations of the reliability of multi-state systems with random failure occurrences and repair times (*i.e.*, constant failure and repair rates) of inherent independent assemblies.

Reliability assessment in this context is considered during the *preliminary* or *schematic design* phase of the engineering design process, with an estimation of the probability that items of *equipment*will perform their intended function for specified intervals under stated conditions.

The most applicable methods for reliability assessment in the preliminary design phase include concepts of mathematical modelling such as:

- Markov modelling: To estimate the reliability of multi-state *systems* with constant failure and repair rates of inherent independent *assemblies*.
- The binomial method: To assess the reliability of simple *systems* of series and parallel *assemblies*.
- Equipment aging models: To assess the aging of *equipment* at varying rates of degradation in engineered installations.
- Failure modes and effects analysis/criticality analysis: A step-by-step procedure for the assessment of failure effects and criticality in *equipment* design.
- Fault-tree analysis: To analyse the causal relationships between *equipment* failures and *system* failure, leading to the identification of specific critical *system* failure modes.

Markov Modelling (Continuous Time and Discrete States)

This method can be used in more cases than any other technique (Dhillon 1999a). Markov modelling is applicable when modelling assemblies with dependent failure and repair modes, and can be used for modelling multi-state systems and common cause failures without any conceptual difficulty.

The method is more appropriate when system failure and repair rates are constant, as problems may arise when solving a set of linear algebraic equations for large systems where system failure and repair rates are variable.

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The method breaks down for a system that has non-constant failure and repair rates, except in the case of a few special situations that are not relevant to applications in engineering design. In order to formulate a set of Markov state equations, the rules associated with transition probabilities are:

1. The probability of more than one transition in time interval Δt from one state to the next state is negligible. The transitional probability from one state to the next state in the time interval λt is given by λt, where is the *constant failure rate* associated with the Markov states.
2. The occurrences are independent.

A system state space diagram for *system* reliability is shown in Fig. 4.1. The state space diagram represents the transient state of a system, with system transition from state 0 to state 1. A state is transient if there is a positive probability that a system will not return to that state.

As an example, an expression for *system* reliability of the system state space shown in Fig. 4.1 is developed with the following equations

$$P_0(t + \Delta t) = P_0(t)\ [1 - \lambda\ \Delta t] \qquad ...(4.1)$$

where:

$P_0(t)$ is the probability that the system is in operating state 0 at time t.

λ is the constant failure rate of the system.

$[1 - \lambda\ \Delta t]$ is the probability of no failure in time interval Δt when the system is in state t.

$P_0(t + \Delta t)$ is the probability of the system being in operating state 0 at time $t + \Delta t$.

Similarly,

$$P_1(t + \Delta t) = P_0(t)\ [\lambda\ \Delta t] + P_1(t) \qquad ...(4.2)$$

$P_0(t)$ denotes the probability that the system is in failed state 0 in time Δt. In the limiting case, Eqs. (4.1) and (4.2) become

$$\lim_{\Delta t \to 0} \frac{P_0(t + \Delta t) - P_0(t)}{\Delta t} = \frac{dP_0(t)}{dt} = \lambda\ P_0(t) \qquad ...(4.3)$$

The initial condition is that when

$$\lim_{\Delta t \to 0} \frac{P_1(t + \Delta t) - P_1(t)}{\Delta t} = \frac{dP_1(t)}{dt} = \lambda\ P_0(t) \qquad ...(4.4)$$

where: $t = 0$, $P_0(0) = 1$, and $P_1(0) = 0$.

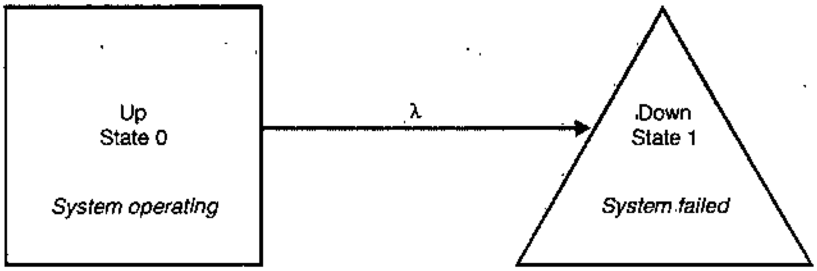

Fig. 4.1. *System transition diagram.*

Solving Eqs. (4.3) and (4.4) by using Laplace transforms

$$P_0(s) = \frac{1}{s+\lambda} \qquad ...(4.5)$$

and

$$P_1(s) = \frac{\lambda}{s+\lambda}. \qquad ...(4.6)$$

By using the inverse transforms, Eqs. (4.5) and (4.6) become

$$P_0(t) = e^{-\lambda t},$$

$$P_1(t) = 1 - e^{-\lambda t}, \qquad ....(4.7)$$

Markov modelling is a widely used method to assess the reliability of systems in general, when the system's failure rates are constant. For many systems, the assumption of constant failure rate may be acceptable. However, the assumption of a *constant repair rate* may not be valid in just as many cases.

The Binomial Method

This technique is used to assess the reliability of relatively simple systems with series and parallel *assemblies*. For reliability assessment of such *equipment*, the *binomial method* is one of the simplest techniques. However, in the case of complex systems with many configurations of assemblies, the method becomes a trying task. The technique can be applied to systems with independent identical or non-identical assemblies.

Various types of quantitative probability distributions are applied in reliability analysis. The binomial distribution specifically has application in combinatorial reliability problems, and is sometimes referred to as a Bernoulli distribution. The binomial or Bernoulli probability distribution is very useful in assessing the probabilities of outcomes, such as the total number of failures that can be expected in a sequence of trials, or in a number of equipment items. The mathematical basis for the technique is the following:

$$\prod_{i=1}^{k}(R_i + F_i) \qquad ...(4.8)$$

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where:

k is the number of non-identical assemblies

R_i is the ith assembly reliability

F_i is the ith assembly unreliability.

This technique is better understood with the following examples: Develop reliability expressions for (*a*) a series system network and (*b*) a parallel system network with two non-identical and independent assemblies each. Since $k = 2$, from Eq. (4.8) one obtains

$$(R_1 + F_1)(R_2 + F_2) = R_1R_2 + R_1F_2 + R_2F_1 + F_1F_2 \qquad \text{...(4.9)}$$

(*a*) Series Network

For a series network with two assemblies, the reliability R_S is

$$R_S = R_1R_2 \qquad \text{...(4.10)}$$

Equation (4.10) simply represents the first right-hand term of Eq. (4.9).

(*b*) Parallel Network

Similarly, for a parallel network with two assemblies, the reliability R_P is

$$R_P = R_1R_2 + R_1F_2 + R_2F_1.$$

Since $(R_1 + F_1) = 1$ and $(R_2 + F_2) = 1$, the above equation becomes

$$R_P = R_1R_2 + R_1(1 - R_2) + R_2(1 - R_1). \qquad \text{...(4.11)}$$

By rearranging

$$R_P = R_1R_2 + R_1 - R_1R_2 + R_2 - R_1R_2$$

$$R_P = R_1 + R_2 - R_1R_2$$

$$R_P = 1 - (1 - R_1)(1 - R_2). \qquad \text{...(4.12)}$$

This progression series can be similarly extended to a k assembly system. The binomial method is fundamentally a statistical technique for establishing estimated reliability values for series or parallel network systems. The confidence level of *uncertainty* of the estimate is assessed through the *maximum-likelihood* technique. This technique finds good estimates of the parameters of a probability distribution obtained from available data.

Properties of maximum-likelihood estimates include the concept of *efficiency* in its comparability to a 'best' estimate with minimum variance, and *sufficiency* in that the summary statistics upon which the estimate is based essentially contains sufficient available data. This is a problem with many preliminary designs where the estimates are not always unbiased, in that the sum of the squares of the deviations from the mean is, in fact, a biased estimate.

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Equipment Aging Models

A critical need for high reliability has particularly existed in the design of weapons and space systems, where the lifetime requirement (5 to 10 years) has been relatively short compared to the desired lifetime for systems in process designs such as nuclear power plant (up to 30 years). In-service aging due to stringent operational conditions can lead to simultaneous failure of redundant systems, particularly safety systems, with an essential need for functional operability in high-risk processes and systems, such as in nuclear power plants (IEEE Standard 323–1974). Because it is the most prevalent source of potential *common failure mechanisms*, *equipment aging* merits attention in reviewing reliability models for use in *designing for reliability* and in qualifying equipment for use in *safety systems*.

Although it is acknowledged that *random failures* are not likely to cause simultaneous failure of redundant safety systems, and this type of failure does not automatically lead to rejection of the equipment being tested, great care needs to be taken in understanding *random failure* in order to provide assurance that it is, in fact, not related to a deficiency of design or manufacture. Aging occurs at varying rates in engineering systems, from the time of manufacture to the end of useful life and, under some circumstances, it is important to assess the aging processes.

Accelerated aging is the general term used to describe the simulation of aging processes in the short time. At present, no well-defined accelerated aging methodology exists that may be applied generally to all process equipment. The specific problem is determining the possibility of a link between aging or deterioration of a component, such as a safety-related device, and operational or environmental stress. If such a link is present in the redundant configuration of a safety system, then this can result in a *common failure mode*, where the common factor is aging.

Figure 4.2 below illustrates how the risk of *common failure mode* is influenced by stress and time (EPRI 1974). The risk function is displayed by the surface, 0*t*PS. As both stress and time-at-stress increase, the *risk* increases. P is the point of maximum *common failure mode* risk, which occurs when both stress and time are at a maximum. However, the risk occurring in and around point P cannot be evaluated by either reliability analysis or high-stress exposure tests alone. In this region, it may be necessary to resort to accelerated aging followed by design criteria conditions to evaluate the risk. This requires an understanding of the basic aging process of the equipment's material.

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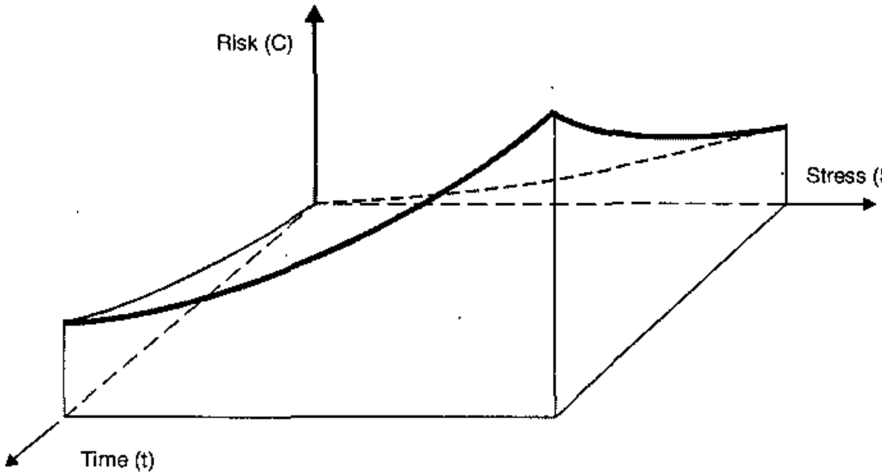

Fig. 4.2. *Risk as a function of time and stress.*

Generally, aging information is found for relatively few materials. Practical methods for the simulation of accelerated aging are limited to a narrow range of applications and, despite research in the field, would not be practically suited for use in *designing for reliability*.

Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effect Analysis (FMEA): It is a powerful reliability assessment technique developed by the USA defence industry in the 1960s to address the problems experienced with complex weapon-control systems. Subsequently, it was extended for use with other electronic, electrical and mechanical equipment. It is a step-by step procedure for the assessment of failure effects of potential failure modes in equipment design. FMEA is a powerful design tool to analyse engineering systems, and it may simply be described as an analysis of each *failure mode* in the system and an examination of the results or effects of such failure modes on the system. When FMEA is extended to classify each potential failure effect according to its *severity* (this incorporates documenting catastrophic and critical failures), so that the criticality of the *consequence* or the severity of failure is determined; the method is termed a *failure mode effects and criticality analysis (FMECA)*. The strength of FMEA is that it can be applied at different systems hierarchy levels. For example, it can be applied to determine the performance characteristics of a gas turbine power-generating *process* or the functional failure probability of its fire protection *system*, or the failure-on-demand probability of the duty of a single pump *assembly*, down to an evaluation of the failure mechanisms associated with a pressure switch *component*. By the analysis of individual failure modes, the *effect* of each failure can be determined on the operational functionality of the relevant systems hierarchy level. FMEAs can be performed in a variety of different ways depending on the objective of the assessment, the extent of systems definition and development, and the information available on a system's assemblies and components at the time of the analysis. A different FMEA focus may dictate a different worksheet format in each case; nevertheless, there are two basic approaches for the application of FMEAs in engineering design:

- **The functional FMEA:** which recognises that each *system* is designed to perform a number of *functions* classified as outputs. These outputs are identified, and the losses of essential inputs to the item, or of internal failures, are then evaluated with respect to their effects on *system* performance.
- **The equipment FMEA:** which sequentially lists individual *equipment* items and analyses the effect of each *equipment failure mode* on the performance of the system. In many cases, a combination of these two approaches is employed. For example, a functional analysis at a major *systems* level is employed in the initial functional, 'broad-brush' analysis during the preliminary design phase, which is then followed by more detailed analysis of the *equipment* identified as being more sensitive to the range of uncertainties in meeting certain design criteria during the detail design phase.

4.3 THEORETICAL OVERVIEW OF RELIABILITY EVALUATION IN DETAIL DESIGN

Reliability evaluation determines the reliability and criticality values for each individual item of equipment at the *lower* systems levels of the systems breakdown structure. Reliability evaluation determines the failure rates and failure rate *patterns* of components, not only for functional failures that occur at random intervals but for wear-out failures as well.

Reliability evaluation is considered in the *detail design* phase of the engineering design process, to the extent of determination of the frequencies with which failures occur over a specified period of time based on *component* failure rates. The most applicable methodology for reliability evaluation in the detail design phase includes basic concepts of mathematical modelling such as:

- The hazard rate function.

  (To represent the failure rate *pattern* of a component by evaluating the ratio between its probability of failure and its reliability function.)
- The exponential failure distribution.

  (To define the probability of failure and the reliability function of a component when it is subject only to *functional failures* that occur at *random* intervals.)

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- The Weibull failure distribution.

  (To determine component criticality for wear-out failures, rather than random failures.)
- Two-state device reliability networks.

  (A component is said to have two states if it either operates or fails.)
- Three-state device reliability networks.

  (A three-state component derates with one operational and two failure states.)

However, it is essential to understand how *component reliability* is determined, specifically from two important *failure distributions*, namely:

- Exponential failure distribution.
- *Weibull failure distribution.*

The Exponential Failure Distribution

When a component is subject only to *functional failures* that occur at *random* intervals, and the expected number of failures is the same for equally long periods of time, its *probability density function* and its *reliability* can be defined by the exponential equation:

Probability density function:

$$f(t, \theta) = \frac{1}{\theta} e^{-t/\theta} \quad \text{...(4.13)}$$

Reliability:

$$R(t, \theta) = e^{-t/\theta} \quad \text{...(4.14)}$$

or, if it is expressed in terms of the *failure rate*, λ

$$f(t, \lambda) = \lambda e^{-\lambda t} \quad \text{...(4.15)}$$

and the reliability function is

$$R(t, \lambda) = e^{-\lambda t} \quad \text{...(4.16)}$$

where:

$f(t, \lambda)$ = probability density function of the Poisson process in terms of time t and failure rate λ.

$R(t, \lambda)$ = reliability of the Poisson process.

t = operating time in the 'useful life period'.

θ = mean time between failures (MTBF).

λ = $1/\theta$, the failure rate for the component.

This equation is applicable for determining *component reliability*, as long as the component is in its 'useful life period'. This is the period during which the *failure rate is constant*, and *failure occurrences* are predominantly *chance or random failures*. The 'useful life period' is considered to be the time after which 'early failures' no longer exist and 'wear-out' failures have not begun. Note that is λ the distribution *scale* parameter because it scales the exponential function. In reliability terms, λ is the failure rate, which is the reciprocal of the mean time between failure. Because λ is constant for a Poisson process (exponential distribution function), the probability of failure at any time *t* depends only upon the elapsed time in the component's 'useful life period'.

In complex electro-mechanical systems, the *system failure rate* is effectively constant over the 'useful life period', *regardless of the failure patterns of individual components*. An important point to note about Eqs. (4.17) and (4.18), with respect to *designing for reliability*, is that reliability in this case is a function of *operating time* (*t*) for the component, as well as the measure of *mean time to failure (MTTF)*.

The Weibull Failure Distribution

Although the determination of *equipment reliability* and corresponding *system reliability* during the period of the equipment's useful life period is based on the *exponential failure distribution*, the *failure rate* of the equipment may *not* be constant throughout the period of its use or operation. In most engineering installations, particularly with the integration of complex systems, the purpose of determining equipment criticality, or combinations of critical equipment, is predominantly to *assess the times to wear-out failures, rather than to assess the times to chance or random failures*.

In such cases, the *exponential failure distribution* does *not* apply, and it becomes necessary to substitute a general failure distribution, such as the *Weibull distribution*. The Weibull distribution is particularly useful because it can be applied to *all three of the phases* of the *hazard rate curve*, which is also called the equipment 'life characteristic curve'. The equation for the two-parameter *Weibull cumulative distribution function (c.d.f.)* is given by

$$F(t) = \int_0^1 f(t|\beta\mu)\, dt \qquad \text{...(4.17)}$$

The equation for the two-parameter *Weibull probability density function (p.d.f.)* is given by

$$f(t) = \frac{\beta t^{(\beta-1)} e^{-t/\mu^{\beta}}}{\mu^{\beta}} \qquad \text{...(4.18)}$$

where:

t = the *operating time* for which the *reliability* $R(t)$ of the component must be determined.

β = parameter of the Weibull distribution referred to as the *shape parameter*.

μ = parameter of the Weibull distribution referred to as the *scale parameter*.

4.4 ECONOMICS OF REPAIR AND REPLACEMENT OF EQUIPMENT

Businesses require equipment in order to function and deliver their outputs. In the global, competitive environment, this equipment is critical to success. However, equipment generally degrades with age and usage, and investment is required to maintain the functional performance of equipment. For example, in mass urban transportation, annual expenditure on equipment replacement for the Hong Kong underground is of the order of $50 million, and further, the Hong Kong underground network is a fraction of the size of that in London, Paris or New York. Where equipment replacement impacts significantly on the bottom line of a corporation and decision-making about such expenditure is under the control of the company executive, the modelling of such decision making is within the scope of this chapter. Capital equipment investment projects are typically driven by operating cost control, technical obsolescence, requirements for performance and functionality improvements, and safety. That is, rational decision-making about capital equipment replacement will take account of engineering, economic, and safety requirements.

In this unit we will assume that the engineering requirements concerning replacement will define certain choices for equipment replacement. For example, engineers would normally propose a number of options for providing the continuity of equipment function: retain the current equipment as is, refurbish the equipment in order to improve operation and functionality, or replace the equipment with new improved technology. We will further assume that safety requirements are addressed when these options are analysed by engineers. Consequently, we argue that rational choice between the defined replacement options is an economic question. Thus, a logistics corporation may be considering replacement of certain assets in its road transportation fleet. The organisation may have to raise capital to fund such replacement. There is the expectation that engineers for the corporation will offer a number of choices for replacement (*e.g.,* buy tractors from company X or Y, buy tractors now or in N years time, or scrap or retain existing tractors as spares) that meet future functional and safety requirements. In this way, decision making about replacement then necessarily considers the costs of the replacement options over some suitable planning horizon. As capital equipment replacement potentially incurs significant costs, the cost of capital is a factor in the decision problem and models to support decision making typically take account of the time value of capital through discounting.

Capital equipment is a significant asset of a business. It consists of necessarily complex systems and a business would typically own or operate a fleet of equipment: the Mass Transit Railway Corporation Limited of Hong Kong operates hundreds of escalators; Fed Ex Express, the cargo airline corporation operates more than 600 aircraft; electricity distribution systems comprise thousands of kilometres of cable and hundreds of thousands of items such as transformers and switches; water supply networks are on a similar scale. We can appeal to the law of large numbers and assume with some justification that the economic costs that enter capital equipment replacement decisions are deterministic. Consequently, we consider deterministic models in this chapter and model rational decision making throughout using net present value techniques.

4.5 ECONOMIC LIFE MODELS

A Simple Model for Individual Plant

Early economic life models such as Eilon et al. (1966) considered an idealized equipment replaced at age T, that is, replacement every T time units, in perpetuity. In this idealised framework, for T small, frequent replacement leads to high replacement or capital costs. Infrequent replacement (large T), on the other hand, results in high operating or revenue costs (assuming that operating costs increase with the age of equipment). Trading-off capital costs against revenue costs leads to an optimum age at replacement, T*, the so-called *economic life. The decision criterion is typically* the total cost per unit time or the annuity—this latter term has been called the rent by Christer (1984). In the case without discounting, the total cost per unit time, c(T), and the annuity are equivalent and

$$c(T) = \left\{\int_0^T m_0(t)dt + R\right\} \Big/ T \qquad \text{...(4.1)}$$

Where $m_0(t)$ is the operating cost rate and R is the replacement cost, and assuming no residual value. From Equation 14.1, *it follows that* T* is the solution of

$$\int_0^{T^*} m_0(t)dt + R = T^* m_0(T^*) \qquad \text{...(4.2)}$$

provided it exists. In its discrete time form the total cost per unit time is $c(T) = \left\{\sum_{i=1}^{T} m_{0i} + R\right\} \Big/ T$, where m_{0i} is the operating cost in time period i.

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With a discount factor v, discounting to year end, and a residual value function S(T), the net present value (NPV) of all future costs in perpetuity is

$$C_{NPV}(T) = \left(1 + v^T + v^{2T} + \ldots\right)\left\{\sum_{i=1}^{T} m_{0i}v^i + v^T\left[R - S(T)\right]\right\}$$

$$= \left(1 - v^T\right)^{-1}\left\{\sum_{i=1}^{T} m_{0i}v^i + v^T\left[R - S(T)\right]\right\} \qquad \ldots(4.3)$$

An objection to this criterion is that as $n \to l$, $C_{NPV}(T) \to \infty$, Consequently, we recommend the annuity or rent (the amount paid annually and in perpetuity that is necessary to meet the total discounted cost) given by

$$(1 + v + v^2 + \ldots)\, c_{rent}(T) = (1 + v^T + v^{2T} + \ldots)\left\{\sum_{i=1}^{T} m_{0i}v^i + v^T\left[R - S(T)\right]\right\} \qquad \ldots(4.4)$$

Hence,

$$= \frac{(1 - v)}{\left(1 - v^T\right)}\left\{\sum_{i=1}^{T} m_{0i}v^i + v^T\left[R - S(T)\right]\right\} \qquad \ldots(4.5)$$

Notice that as $v \to l$, $c_{rent}(T) \to c(T)$, the total cost per unit time. The economic life can be obtained by minimizing $c_{rent}(T)$, typically using a spreadsheet by considering a range of values of T.

Analysing Technological Change Using a Two-cycle Model

The economic life model can be adapted to consider technological change in a number of ways. One can consider economic factors for new models of equipment (future operating costs) in a parametric fashion, specifying a model for technological change which then implies operating cost functions, replacement cost and residual values for each replacement cycle into the future (Elton and Gruber 1976).

Alternatively, one can model replacement over a limited time scale, either by fixing the time horizon, or by fixing the number of replacement cycles. Christer (1984) did the latter and described a two-cycle model which models the immediate replacement decision problem by considering existing plant as having age τ and age-related operating cost m_{0i}, and new plant as having operating cost m_{1i}. In its discrete form, the annuity for this model is

$$c_{rent}^2(K,L) = \frac{\sum_{i=1}^{K} m_0(i+t)v^i + v^K\left\{R_1 - S_0(K+\tau) + \sum_{i=1}^{L} m_{li}v^i + v^L\left[R_l - S_l(L)\right]\right\}}{\sum_{i=1}^{K+L} v^i} \qquad \ldots(4.6)$$

Here K and L are decision variables, with K modelling the time (from now) to replacement of the existing asset; K + L is the time to second replacement.

The advantage of this model is that one only need estimate the operating cost of the existing and new assets (as functions of age), the capital cost for the new asset, R_1 , and the age-related resale or residual value of new and existing assets, S_0, S_1.

A Fixed Planning Horizon Model

In the financial appraisal of projects, a standard approach fixes the time horizon and determines the NPV of future costs over this horizon (*e.g.*, Northcott 1985). This fixed horizon model has been studied by Scarf and Hashem (2003) and its simplicity lends itself to application in complex contexts (*e.g.*, Scarf and Martin 2001). The annuity for this model can be derived from Equation 4.6 *above simply by setting* X = K and K + L = h, the length of the planning horizon, and then considering h as fixed. Whence, there is only one decision variable, X, the time to replacement. Given the possibility that X = h, that is, no replacement over the planning horizon whence we retain the current asset, the annuity function has a discontinuity at X = h , and X = h^* implies that it is not optimal to undertake the 292 P. Scarf and J. Hartman (replacement) project. Furthermore, since the replacement at the end of the horizon has a fixed cost (with respect to the decision variable X) its inclusion or exclusion has no effect on the optimal time to replacement. It is natural not to include the replacement cost at the horizon-end since a standard financial appraisal approach would only account for revenue costs up to *project execution, capital costs at project execution,* subsequent revenue costs up to the horizon-end, and residual values. Including the replacement at h on the other hand allows cost comparisons with the two-cycle model and the associated rent, Equation 4.2. We take the former approach here however and the annuity is

$$c_{rent}^{h}(X) = \begin{cases} \{\sum_{i=1}^{X} m_{0(i+\tau)}\mathrm{v}^{i} + \mathrm{v}^{X}[R_1 - S_0(X+\tau)] + \sum_{i=X+l}^{h} m_{l(i-X)}\mathrm{v}^{i} & \\ \qquad - \mathrm{v}^{h}S_1(h-X)\} / \sum_{i=1}^{h}\mathrm{v}^{i}, & X < h, \\ \{\sum_{i=1}^{h} m_{0(i+\tau)}\mathrm{v}^{i} - \mathrm{v}^{h}S_0(h+\tau)\} / \sum_{t=1}^{h}\mathrm{v}^{i}, & X = h. \end{cases} \qquad ...(4.7)$$

A Modified Two-cycle Model

It is interesting to consider the behaviour of these models at Equations 4.2 and 4.3 when the *operating costs are constant* (or increasing only slowly), since it is not unusual for plant to age only slowly. Of course, replacement of an existing asset in these circumstances would only be contemplated if the operating cost (or functionality) of the new asset is significantly lower (or functionality higher), *e.g.,* electricity supply network components; see Brint et al. (1998). The behaviour is simplest to follow for the continuous time formulation when the discount factor is unity (no discounting) and

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residual values are zero. Under these circumstances, the costs per unit time (annuity) for the two-cycle model and the fixed horizon model become

$$c^2_{rent}(K, L) = (Km_0 + R + Lm_1 + R)/(K + L) \quad ...(4.8)$$

And

$$c^h_{rent}(X) = \begin{cases} [Xm_0 + R + (h - x)m_1]/h, & X < h, \\ m_0 & X = h. \end{cases} \quad ...(4.9)$$

4.6 PLANNING AND SCHEDULING PLANT AND OVERHAULING SHUTDOWNS

Planning is the heart of good inspection and preventive maintenance. As described earlier, the first thing to establish is what items must be maintained and what the best procedure is for performing that task. Establishing good procedures requires a good deal of time and talent. This can be a good activity for a new graduate engineer, perhaps as part of a training process that rotates him or her through various disciplines in a plant or field organization. This experience can be excellent training for a future design engineer.

Writing ability is an important qualification, along with pragmatic experience in maintenance practices. The language used should be clear and concise, with short sentences. Who, what, when, where, why, and how should be clearly described.

4.7 PLANNING

Most parts and materials that are used for preventive maintenance are well known and can be identified in advance. The quantity of each item planned should be multiplied by the cost of the item in inventory. The sum of those extended costs will be the material cost estimate. Consumables such as transmission oil should be enumerated as direct costs, but grease and other supplies used from bulk should be included in overhead costs.

Feedback From Actual

The time and cost required for every work order should be reported and analyzed to provide guidance for more accurate planning in future. It is important to determine what causes the task and times to change. Blindly assuming that the future will be like the past, or even that the past was done perfectly, may be an error. Comparisons should certainly be made between different individuals doing the same tasks to evaluate results in the amount of time required, what was accomplished during that time, quality of workmanship, and equipment performance as a result of their efforts.

Some people will argue that setting time standards for preventive maintenance is counterproductive. They feel that the mechanic should be given as much time as he desires to ensure high-quality work. This is generally not true. In fact, the required tasks will generally expand or contract to fit the available time. Preventive maintenance inspection and lubrication can in fact be treated as a production operation with incentives for both time performance and equipment uptime capability. The standard maintenance estimating and scheduling techniques of time slotting, use of ranges, and calculations based on the log-normal distribution may be followed as reliable data and analytical competence are established. Since preventive maintenance time and costs will typically comprise 30–60% of the maintenance budget, accurate planning, estimating, and scheduling are crucial to holding costs and improving profits.

4.8 SCHEDULING

Scheduling is, of course, one of the advantages to doing preventive maintenance over waiting until equipment fails and then doing emergency repairs. Like many other activities, the watchword should be "PADA," which stands for "Plan-a- Day-Ahead." In fact, the planning for inspections and preventive activities can be done days, weeks, and even months in advance to assure that the most convenient time for production is chosen, that maintenance parts and materials are available, and that the maintenance workload is relatively uniform.

Scheduling is primarily concerned with balancing demand and supply. Demand comes from the equipment's need for preventive maintenance. Supply is the availability of the equipment, craftspeople, and materials that are necessary to do the work. Establishing the demand has been partially covered in the units on on-condition, condition monitoring, and fixed interval preventive maintenance tasks. Those techniques identify individual equipment as candidates for preventive maintenance.

Prioritizing

When the individual pieces of equipment have been identified for preventive maintenance, there must be a procedure for identifying the order in which they are to be done. Not everything can be done first. First In–First Out (FIFO) is one way of scheduling demand. Using FIFO means that the next preventive task picked off the work request list, or the next card pulled from the file, is the next preventive maintenance work order. The problem with

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this "first come, first served" method is that the more desirable work in friendly locations tends to get done while other equipment somehow never gets its preventive maintenance. The improved method is Priority = Need Urgency × Customer Rank × Equipment Criticality. The acronym NUCREC will help in remembering the crucial factors.

NUCREC improves on the Ranking Index for Maintenance Expenditures (RIME) in several ways:

1. The customer rank is added.
2. The most important item is given the number-one rating.
3. The number of ratings in the scale may be varied according to the needs of the particular organization.
4. Part essentiality may be considered.

A rating system of numbers 1 through 4 is recommended. Since most humans think of number 1 as the first priority to get done, the NUCREC system does number 1 first.

Need urgency ratings include

1. Emergency; safety hazard with potential further damage if not corrected immediately; call back for unsatisfactory prior work
2. Downtime; facility or equipment is not producing revenue
3. Routine and preventive maintenance
4. As convenient, cosmetic.

The customer ranks are usually as follows:

1. Top management
2. Production line with direct revenue implications
3. Middle management, research and development facilities, frequent customers
4. All others.

The equipment criticality ratings are as follows:

1. Utilities and safety systems with large area effect
2. Key equipment or facility with no backup
3. Most impact on morale and productivity
4. Low, little use or effect on output.

The product of the ratings gives the total priority. That number will range from 1 (which is 1 × 1 × 1) to 64 (4 × 4 × 4). The lowest number work will be first priority. A "1" priority is a first-class emergency. When several work requests have the same priority, labor and materials availability, locations, and scheduling fit may guide which is to be done first. The priorities should be set in a formal meeting of production and maintenance management at which the equipment criticality number is assigned to every piece of equipment. Similarly, a rank number should be applied to every customer and the need urgency should be agreed on. With these predetermined evaluations, it is easy to establish the priority for a work order either manually by taking the numbers from the equipment card and the customer list and multiplying them by the urgency or by having the computer do so automatically. Naturally, there may be a few situations in which the planner's judgment should override and establish a different number, usually a lower number so that the work gets done faster.

Ratings may rise with time. A good way to ensure that preventive maintenance gets done is to increase the need urgency every week. In a computer system that starts with preventive maintenance at 3, a preventive task that is to be done every month or less frequently can be elevated after one week to a 2, and finally to a 1 rating. Those increases should ensure that the preventive task is done within a reasonable amount of time. If preventive maintenance is required more often, the incrementing could be done more rapidly.

Dispatch of the preventive maintenance work orders should be based on the demand ordered by priority, consistent with availability of labor and materials. As discussed earlier, predictive maintenance provides a good buffer activity in service work, since time within a few days is not normally critical. The NUCREC priority system helps ensure that the most important items are done first. Some pressure will be encountered from production people who want a particular work request filled right away instead of at the proper time in the priority sequence. It can be helpful to limit the "criticality 1" equipment and "rank 1" customers to 10%, since, according to Pareto's Principle of the Critical Few, they will probably account for the majority of activity. If rank 2 is the next 20%, rank 3 is 30%, and the balance is 40% for rank 4, the workload should be reasonably balanced. If temporary work needs exist for selected equipment or a customer needs to be given a higher priority, then equipment should be moved to a lower criticality for each equipment that is moved higher. After all, one objective of prioritization is to ensure that work gets done in proper sequence.

A preventive maintenance action that is done on time should ensure that equipment keeps operating and that emergency work is not necessary. Coordination with production equipment is not always available for preventive maintenance just when the maintenance schedulers would like it to be. An overriding influence on coordination should be a cooperative attitude between production and maintenance. This is best achieved by a meeting between the maintenance manager and production management, including the foreman level, so that what will be done to prevent failures, how this will be accomplished, and what production should expect to gain in uptime may all be explained.

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The cooperation of the individual machine operators is of prime importance. They are on the spot and most able to detect unusual events that may indicate equipment malfunctions. Once an attitude of general cooperation is established, coordination should be refined to monthly, weekly, daily, and possibly even hourly schedules. Major shutdowns and holidays should be carefully planned so any work that requires "cold" shutdown can be done during those periods. Maintenance will often find that they must do this kind of work on weekends and holidays, when other persons are on vacation. Normal maintenance should be coordinated according to the following considerations:

1. Maintenance should publish a list of all equipment that is needed for inspections, preventive maintenance, and modifications and the amount of cycle time that such equipment will be required from production.
2. A maintenance planner should negotiate the schedule with production planning so that a balanced workload is available each week.
3. By Wednesday of each week, the schedule for the following week should be negotiated and posted where it is available to all concerned; it should be broken down by days.
4. By the end of the day before the preventive activity is scheduled, the maintenance person who will do the preventive maintenance should have seen the first-line production supervisor in charge of the equipment to establish a specific time for the preventive task.
5. The craftsperson should make every effort to do the job according to schedule.
6. As soon as the work is complete, the maintenance person should notify the production supervisor so that the equipment may be put back into use.

Overdue work should be tracked and brought up to date. Preventive maintenance scheduling should make sure that the interval is maintained between preventive actions. For example, if a preventive task for May is done on the 30th of the month, the next monthly task should be done during the last week of June. It is foolish to do a preventive maintenance task on May 30 and another June 1, just to be able to say one was done each month. In the case of preventive maintenance, the important thing is not the score but how the game was played.

4.9 PLANNING AND SCHEDULING OF PLANT SHUTDOWNS

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Usually periodic overhauls of plant and equipment constitute major plant shutdowns, and these jobs pose planning problems, which are quite different from those for the normal workload of the maintenance department. Plant shutdowns are essentially projects, since they are (*i*) non-routine, large and take significant amount of time, and (*ii*) complex consisting of a multiplicity of interrelated activities which must be executed in a defined order for completing the entire task. All these activities have to be carried out in a coordinated manner. Therefore, plant shutdowns must be recognized and managed as separate undertakings calling for different methods of planning, scheduling and monitoring of progress.

Accordingly, project planning, methods are generally used for planning of maintenance shutdowns. A wall-mounted bar chart may be quite adequate for planning a plant shutdown with upto 50 activities. However, major plant shutdowns may involve upwards of few hundred activities, and many tens of these activities may be simultaneous. Network planning method is used for planning these shutdowns. Moreover, for smaller shutdowns, such network analysis may be manual with extraction onto a bar chart to facilitate control. However, for large projects, network planning and associated scheduling and control must be computerized.

Basics of Project Planning

A project is a collection of interrelated activities, which must be executed/ performed in a defined order, with well-defined start and finish times, for completing the entire task to accomplish a specified objective that fulfills the needs of the organization. A project is characterized by the existence of precedence relationships. Some activities cannot be performed until some preceding activities have been completed. (The activity that has to be performed just before a particular activity is its predecessor activity and the one that immediately follows it is its successor activity). This requirement establishes a technical precedence relationship. Other activities may be performed independently. Thus together with precedence relationships, in a project certain activities can be done simultaneously, if the resources permit. Task independence (exemplified by parallel/simultaneous activities) and precedence relationships need to be indicated on the project network and incorporated into the job plan.

Kelly and Walker developed the critical path method (CPM) for project planning and scheduling in 1959. In CPM, the following assumptions are made:

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1. All time estimates are deterministically known for every activity of the project.
2. The precedence relationship is known for all the activities.
3. The project can be represented as a directed graph in which the time (or cost) estimates are deterministic, and the longest path of the network is the indicator of the project duration (also called its critical path).

A path is a chain of sequential activities beginning at the project's start and ending at its completion. In a project network, several, or many, paths may exist, and all the activities, and hence all the paths, must be completed before the project is finished.

The path, which has the longest expected elapsed time, will determine the completion date of the project. This path is called the critical path of the project. The assumption of deterministic activity times can be relaxed with the use of the program evaluation and review technique (PERT), which was developed by the U.S. Navy in 1964. PERT deals with probabilistic activity duration, and uses three time estimates for each activity, namely, its optimistic, most likely, and pessimistic times. The mean time of the activity is then derived from these three time estimates, using the Beta distribution approximation. The analysis of a CPM, or PERT, network is done by the use of critical path analysis (CPA).

The general methodology of CPA is as follows:

Step 1: Break up (Conceive) the project in terms of specific activities and/ or events. Determine the time of each activity. Note: in CPM, it is a deterministic estimate, and in PERT, it is probabilistic with three estimates, as noted above.

Step 2: Establish the interdependence and sequence of specific activities (also called precedence relationship, as noted above).

Step 3: Prepare the network of activities and/of events.

Step 4: Assign time — estimates and/or cost-estimates to all the activities of the network. Note: In PERT, these are the mean activity times derived from the optimistic, most likely and pessimistic estimates.

Step 5: Identify the longest path (time-wise) on the network. This is the critical path of the network, and project completion time equals the critical path time (sum of times of activities on the critical path).

Step 6: Determine slack (or float) for each activity, not contained on the critical path. Note: The activities on the critical path do not have any slack time.

Step 7: Use regular monitoring, evaluation and control of the progress of the project by preplanning, rescheduling and relocation of resources, such as manpower, funds etc., as needed.

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From Step 5, we find that the critical path determines the project completion time and activities on the critical path do not have any slack. This stresses the following points:

1. If any activity on the critical path gets delayed by tij time units, the total project will be delayed by tij time units. Strict monitoring is essential for these activities.
2. Since activities which are not on the critical path have some slack time associated with them, from time to time, some resources from these activities can be diverted to the activities on the critical path.
3. If the total project time needs to be compressed (shortened), then quite obviously one has to focus on the activities on the critical path. The times of some of these activities can be compressed (reduced) by deployment of additional resources. This is called crashing; and the project duration can be effectively crashed by the use of additional resources selectively on the activities on the critical path.

The identification of the critical path, in step 5, necessitates the calculation of the earliest expected and latest expected times of all events, or nodes, of the network, given the duration of all activities of the network (all *tij's*). Forward pass is used for the calculation of the earliest times and backward pass, or backward calculation, is used for the latest times of the nodes. From these two, the earliest start time (EST), latest start time (LST), earliest finish time (EFT) and the latest finish time (LFT) of all the activities have to be determined. These, I turn, enable the determination of slacks (or floats) and the identification of the critical path. We will not discuss the method of calculation of these times in this unit.

Network Planning for a Maintenance Shutdown

Here in under, we will discuss two aspects of the use of network analysis for planning and monitoring of maintenance shutdowns. In the first paragraph, we will highlight certain points with regard to the use of the CPA methodology, and in the second, we will discuss two practical situations wherein network analysis can be most effectively used for planning and monitoring of plant shutdowns.

The first three steps of the CPA methodology are usually done together and *constitute the first stage of the use of network analysis.* The output of this stage is the activity network, or the logic diagram, of the maintenance shutdown (project network). State one starts with the preparation of the list of activities, which will constitute the shutdown. This requires careful enquiry and detailed discussion with the concerned personnel.

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The points to remember here are the following:

1. each activity must have a well-defined (and recognizable) start and finish, and
2. although an activity usually consumes both time and resources, there exist some activities which consume only time (a example is 'waiting for paint to dry').

Then the relationships between the activities are identified and noted clearly on the activity list. This list forms the basis on which the network, or logic diagram, is drawn. While drawing the network, please keep in min that an activity cannot start till all its predecessor activities have been completed, and the network start with the first node and ends with the last node. With the network drawn, in the second stage, the activity durations, or times, are obtained, noted on the list of activities and incorporated in the activity network. The estimates of the activity times can be obtained either through discussions with maintenance engineers, supervisors and mechanics, or through comparative estimation (estimating using benchmarks, which have earlier been developed through the use of predetermined time standards (PMTS) or time study). In cases where one deterministic time is difficult to estimate and quite a few things can go wrong (and this is often the case with maintenance jobs), three estimates—optimistic, most likely and pessimistic—can be obtained, as noted earlier, and the means activity time can be derived there from. In stage 3,the EST, LST, EFT, and LFT for all the activities are calculated with the help of the activity times/durations, and the critical path is identified. Thereafter, with the help of the plan from this network analysis, regular evaluation and monitoring of progress are initiated, and resource leveling and crashing, as needed, can also be taken up.

There are two important situations encountered in practice. In plant shutdowns of short durations, time is the largest constraint and generally the availability of necessary resources does not present much problem. So the first situation is one of unlimited resources and limited time. On the other hand, in case of large shutdowns, usually we have the case of limited resources and/or limited time (in many cases, both). In the first case of unlimited resources, the control of project duration is comparatively simpler and is attained through the control of activities on the critical path and use of float on the non-critical activities. The objective here is to ensure that the activities on the critical path are started and finished at the earliest, and the distribution of resources, say manpower, in order of criticality can also help in the attainment of this objective. The total shutdown time in short duration shutdowns can be reduced by applying extra resources on the activities on the critical path. The progress of work can be better displayed through the use of a bar chart, and accordingly, bar charts are used for short duration plant shutdowns. The necessary bar chart is extracted from the

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updated activity network. The use of network analysis is most effective in longer duration plant shutdowns. Bar charts cannot be used in these projects because of the exceedingly large number of activities. More importantly, network analysis enables an objective analysis of resource requirements for the constituent activities. Resource leveling can be done with the aim of ensuring that the shutdown duration does not extend beyond the planned project duration (namely, the critical path completion time). Selective crashing is also enabled and through such selective use of additional resources, wherever possible, the incidence of time overruns can be significantly reduced.

SUMMARY

- Reliability assessment in this context is considered during the *preliminary* or *schematic design* phase of the engineering design process, with an estimation of the probability that items of *equipment*will perform their intended function for specified intervals under stated conditions.
- Early economic life models such as Eilon et al. (1966) considered an idealized equipment replaced at age T, that is, replacement every T time units, in perpetuity.
- Planning is the heart of good inspection and preventive maintenance. As described earlier, the first thing to establish is what items must be maintained and what the best procedure is for performing that task.
- Scheduling is, of course, one of the advantages to doing preventive maintenance over waiting until equipment fails and then doing emergency repairs. Like many other activities, the watchword should be "PADA," which stands for "Plan-a- Day-Ahead".
- Plant shutdowns are essentially projects, since they are (*i*) non-routine, large and take significant amount of time, and (*ii*) complex consisting of a multiplicity of inter-related activities which must be executed in a defined order for completing the entire task.

REVIEW QUESTIONS

1. Explain designing for Reliability.
2. Explain designing for Availability.
3. Discuss in detail
   (*a*) Markov modeling
   (*b*) Binomial method
   (*c*) Equipment aging models

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(d) Failure modes and effects analysis/criticality analysis

(e) Fault-tree analysis

4. What are different types of FMEA and their associated benefits?
5. Discuss Fault-tree analysis steps.
6. Discuss weibull failure distribution.
7. Discuss the following economic life models
   - Model for individual plant
   - a Two-cycle model
   - A fixed planning horizon model.
8. What do you understand by capital replacement for a network system.
9. Explain the procedure for planning?
10. Discuss the scheduling of a process.
11. Discuss the planning and scheduling of plant shutdowns.

FURTHER READINGS

- **Comprehensive Maintenance Management: Policies, Strategies And Options:** Amit Telang and A.D. Telang, PHI Learning.

NOTES

UNIT V TRENDS IN MAINTENANCE MANAGEMENT

★ STRUCTURE ★

5.1 *Condition Based Maintenance (CBM)*
5.2 Implementing Condition based Maintenance
5.3 *Condition Monitoring* Techniques
5.4 Benefits of Condition based Maintenance
5.5 Reliability Centered Maintenance (RCM)
5.6 Concept of RCM
5.7 RCM Methodology
5.8 Benefits of Implementing RCM
5.9 Total Productive Maintenance (TPM)
5.10 Motivations and Identifying Characteristic of TPM
5.11 TPM Promotion
5.12 Maintenance Audit
5.13 Types of Audit
5.14 Importance of Maintenance Audit
5.15 Methodology of Maintenance Audit
5.16 Study of Key Result Areas
- *Summary*
- *Review Questions*
- *Further Readings*

5.0 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain condition based maintenance (CBM).

- describe reliability centered maintenance (RCM).
- define total productive maintenance (TPM).
- explain maintenance audit.

NOTES

5.1 CONDITION BASED MAINTENANCE (CBM)

It has been observed that one-third of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. Maintenance of plant equipment based on its perceived condition is a more cost effective strategy than either maintenance based on time or usage hours. Maintenance after the breakdown incurs interruption to production or service, more maintenance activity and extra spares usage. Planned preventive maintenance can result in unnecessary maintenance activity and downtime and in excessive spares usage, whilst being ineffective in preventing breakdown.

In condition based maintenance (CBM) the equipment is maintained when measurements indicate an incipient failure. The condition of the machine may be determined continuously or at regular intervals by monitoring vibration, wear debris, temperature and performance parameters. Any change in any of these parameters would mean a change in the condition or health of the machine. Following conditions should be satisfied before implementing a condition based maintenance programme:

- The existence of failures, which do not occur at regular intervals.
- These failures are either a safety hazard or incur significant costs in lost production, breakdown maintenance labor and materials.
- A monitoring method exists that can give sufficient advance warning of the impending failure for the maintenance/production system to act to avoid failure.
- The monitoring and corrective maintenance costs less than the lost production and breakdown maintenance including associated overheads.
- The monitoring method is compatible with the existing company procedures and workforce attitudes and expertise.

Condition based maintenance should not be looked at as a substitute for more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, total plant maintenance management programme.

5.2 IMPLEMENTING CONDITION BASED MAINTENANCE

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Implementing condition based maintenance involves measurement or monitoring of appropriate physical variables or signatures of the machine using instrumentation and interpreting the signatures to indicate if maintenance of the machine is called for or not. Flow diagram of the condition monitoring procedure is shown in Figure 5.1.

Key steps involved in implementing the procedure are as follows:

Listing and Identification of Plant Machines

Listing and numbering of all machines in the plant should be carried out. This is necessary in order to locate all machines within the plant, identify them in the maintenance program and retrieve data.

Selection of Critical Machines

Critical machines are those whose failure may cause loss of production, unacceptable quality, or cause safety hazard to personnel. The criticality level will influence the monitoring frequency. Equipment history records and downtime losses help in identifying critical machines for condition monitoring purpose. Wherever history records are not available the knowledge and experience of maintenance and operation personnel will be of great help in identifying the critical machines. Following guidelines are found useful in identifying the critical machines in a plant:

- Parts of a continuous process
- Parts of a single production line
- Equipment without standby
- Parts of a production line without (or with inadequate) intermediate storage capacity
- Parts of a line transferring dangerous fluids
- Machines operating at high temperature, pressure or voltage
- Machines containing high inertia high speed components
- Machines arranged in very compact layouts with high maintenance cost.

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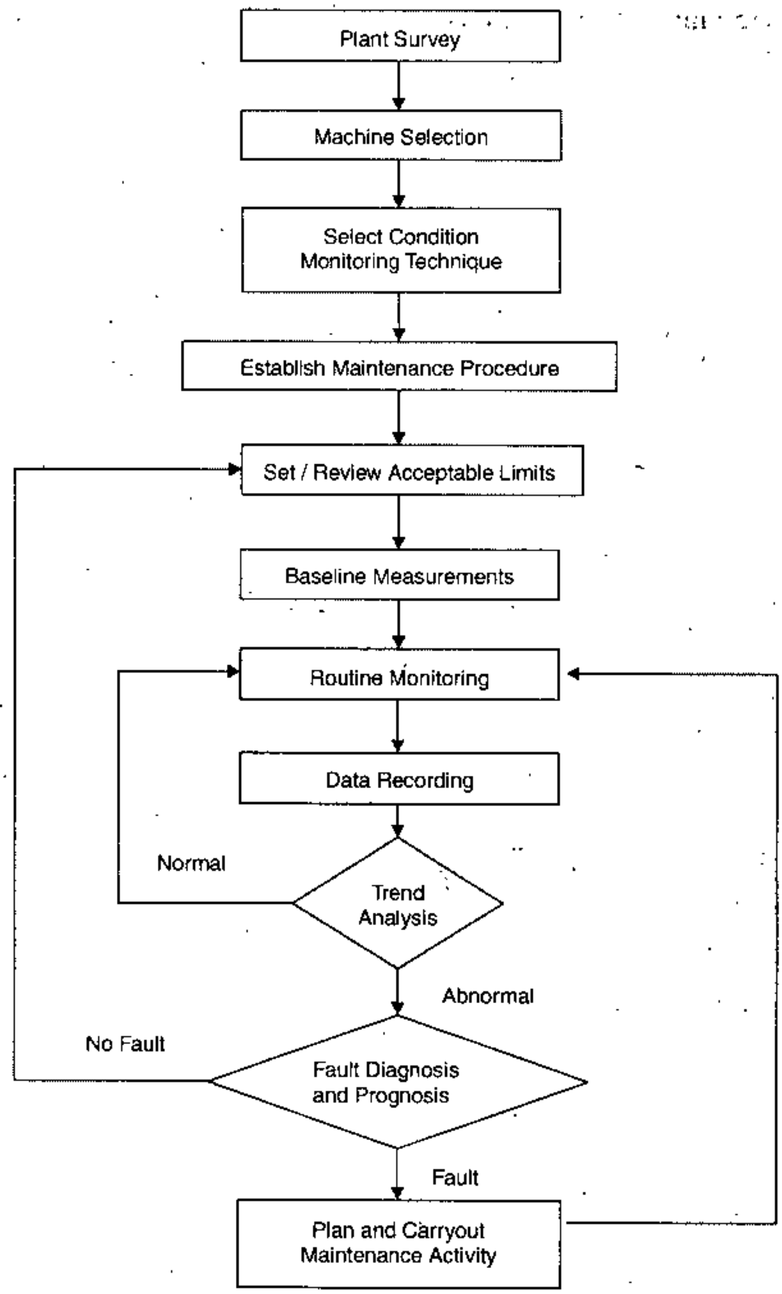

Fig. 5.1. *Flow diagram of a condition monitoring procedure.*

Selection of Condition Monitoring Technique

Once critical machines have been identified, the nature of maintenance action is to be based on anticipated failure consequences and failure frequency. The consequences are generally evaluated with respect to safety and economics. Condition monitoring is applied to components having considerable failure consequences and a non-negligible failure frequency. Such components are known as significant components and are determined by carrying out failure modes, effects and criticality analysis (FMECA). A component is considered significant if its risk priority number (RPN), exceeds a predetermined value in a particular scale. Risk priority number is given as:

$$RPN = FI \times FC \times FDP$$

Where, FI is failure intensity, FC is failure criticality and FDP is fault detection probability. Values of FI, FC and FDP could be fixed on a scale of 10. In order to monitor the condition of these significant components, monitoring parameters could be identified enabling us to follow the failure developments. Selection of suitable monitoring parameters is based on the study of failure progression and engineering knowledge concerning measuring equipments. Figure 5.2 explains the method for selection of a condition monitoring technique. Table 5.1 gives the monitoring techniques commonly used for condition monitoring.

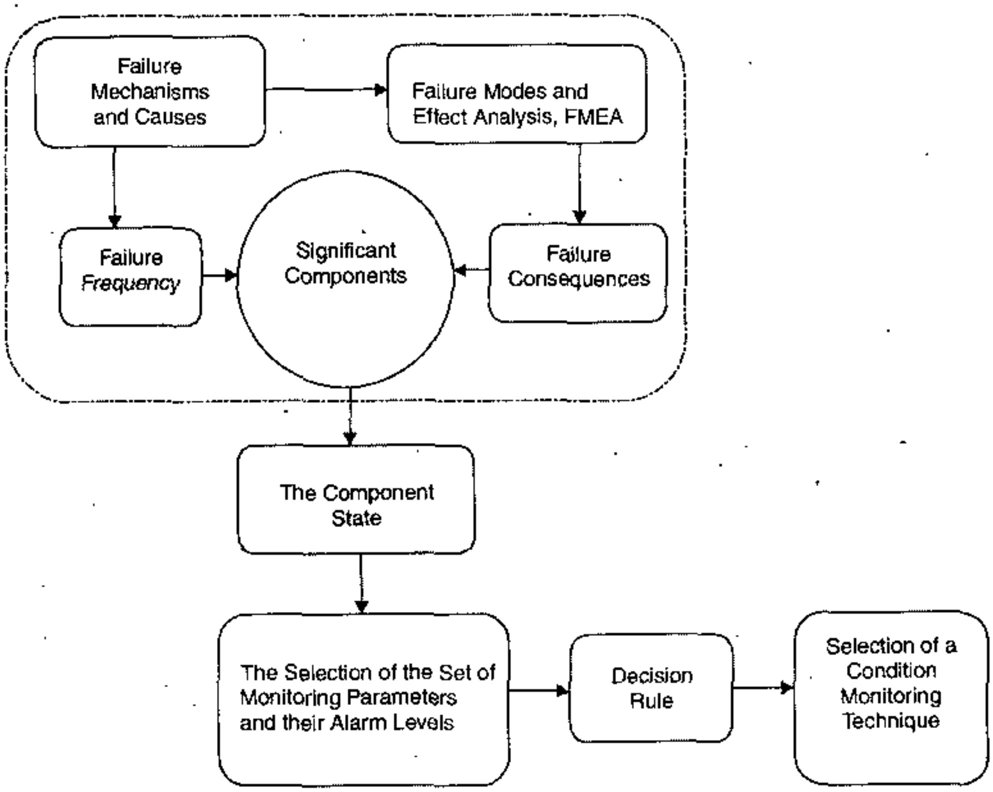

Fig. 5.2. *A sequential method for the selection of a condition monitoring technique.*

An ideal condition monitoring technique should have the following attributes:

1. Simplicity in use with pass-fail indication on a simple scale, where the technique involves the use of an instrument, simplicity implies no range control and automatic calibration.
2. Insensitivity to sensor location so that repeatability is not lost by careless technicians.

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3. Insensitivity to the load condition of the machine so that measurements are not **Maintenance Audit** omitted because of inconvenience. This precludes off-load monitoring techniques unless regular off-load periods are programmed.
4. Robust equipment to withstand the type of maltreatment common in industrial situations. For example, instruments should withstand dropping and cables withstand water, oil and heavy boots.
5. Intrinsically safe techniques in both the technical sense and manner of use. Safety procedures can bog down a monitoring programme in red tape.

Unfortunately very few techniques meet all of the above attributes. This does not mean that other techniques are unusable, merely that problems associated with the technique may reduce the advantages of condition based maintenance.

5.3 CONDITION MONITORING TECHNIQUES

Visual Monitoring

Optical techniques are used to enhance the powers of the naked eye. The three main ways in which this is done are: magnification, providing access, and freezing or slowing movement. Magnification can be provided by a magnifying glass, telescope or microscope.

- Binoculars are widely used to inspect remote equipment such as smoke or fume stacks, walls, roofs, steam traps, switchgear and other electrical equipment.
- Hand held microscopes are valuable for onsite inspection of wear surfaces or debris access can be provided to the insides of plant machines or vessels by light probes, boroscopes and videoimagescopes.
- The simplest light probe is a torch which can be used in conjunction with mirrors on sticks to illuminate and observe dark internal parts of units.
- Boroscopes are purpose built devices of small diameter (0.2–0.6") designed to illuminate and view the inaccessible component. There are both rigid and flexible versions with heads capable of illuminating and viewing any different magnifications and angles to the bore.
- Motion analyzes allow the high and low speed analysis of visual events. A tiny video camera mounted at the head captures the image, transmitting it electronically to video monitor and motion analysis system.

Comparison can be made between these techniques as follows:

Table 5.1

	Rigid Boroscopes	Flexible Boroscopes	Motion analyzes
Resolution	Excellent	Fair	Fair
Access - through hole	Excellent	Excellent	Fair
- straight tube	OK	Excellent	Fair
- bent tube	No	OK	OK
- tortuous path	No	Fair	OK
Light intensity	High	Fair	Fair
Viewing sensitivity	Good	Fair	High

Timed viewing becomes necessary with moving components to freeze or slow the motion. The three types of instrument used are stroboscope, photographic camera and video camera.

- The stroboscope illuminate the component with a short duration pulsed light at a selectable frequency, which can be triggered by the movement of the component. This appears to freeze the motion so that the component can be observed by eye or by any of the instruments described. Off-tuning the strobe frequency causes the component to appear to move slowly. This technique enables an off-load inspection to be carried out on-load, *e.g.*, the condition of belt drives may be examined this way.
- The camera systems are used to slow and record components in motion. Photographic systems can operate up to 1000 frames/sec giving a slowing by a factor of 50. The video systems operate normally to the same frame frequency and exceptionally to12000 frames/s, but there is more flexibility in replay since single frames can be played back.

Storing the information obtained by any of the optical techniques can readily be carried out using video recorders, which then permit computer analysis. Visual monitoring techniques can be used on or off load, providing visibility to remote, small or moving components.

Temperature Monitoring

Temperatures of the mechanical or structural components of a unit are monitored to ensure that they remain within permitted limits, or that deterioration is detected. Location of the measurement is critical to both the application and the choice of technique. Measurements made at a surface are more difficult than that those made within a fluid or a solid, because the sharp discontinuity in the temperature profile that occurs in the convective

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boundary layer is sensitive to the presence of the temperature sensor. Sensors for surface measurement are therefore restricted to thin devices such as thermal label indicators which alter the profile only slightly whilst maintaining good thermal contact.

For immersed and in-body temperature measurement use:

- Liquid expansion sensors such as mercury or alcohol in glass or metal.
- Bimetallic expansion sensors.
- Thermorcouple, thermistor or platinum resistance sensors.

For surface temperature measurement:

- Self-adhesive thermal labels, which respond to temperature rise by changing colors are cheap and ideal. They contain up to 8 bands each changing at a different temperature. Reversible and non-reversible versions exist. The nonreversible are ideal for routine monitoring.
- Temperature paints and crayons work the same way but are not so convenient to use.
- Thermocouple sensors designed for surface contact are most convenient and come with a variety of hand-size indicators, but suffer from systematic error due to interference with the heat flow and non-repeatability caused by poor conductive contact.
- Non-contact infrared temperature measurement devices sense the infra-red radiations from the surface and deduce from this the surface temperature. Metal surfaces should be painted or otherwise covered with a non-metallic surface. Hand-held, non-contact temperature meters are very convenient and reasonably priced.

Scanning thermographic cameras are now widely available to present a temperature pattern on a two dimensional display. These are appropriate when the monitoring is used to detect a localized hot or cold spot, *e.g.*, a breakdown in lagging or a failed electronic component. Instruments range from simple monochrome systems having the size of a dictionary to shoulder mounted systems with video output and disc data storage.

Typical temperature rises in a working system involving electrical installations as given by Agema are:

- Minor problem, 1°C–10°C
- Problem, 10°C–35°C
- Serious problem, 35°C–75°C
- Critical problem > 75°C

Display of absolute temperature (and hence colors portrayed) depends on the emissivity, ambient temperature and object distance. All of these can be compensated for in advanced systems. Following are the examples of different changes in colors with decreasing temperature:

A			B
Red	Strong thermal radiation	Higher temperature	White
Orange			Yellow
Yellow	Average thermal radiation	Average temperature	Orange
Green			Red
Blue	Low thermal radiation	Lower temperature	Purple
Indigo			Blue
Violet			Indigo

Malfunctions that can be monitored using temperature monitoring are:

• Faults in Electrical Components	- switch gear contact resistance - solid state controller failure - cabling faults - insulation faults leakage, arcing - motor stator shorts
• Coolant Failure	- in bearings - spot welding - transformer cooling circuit blockages
• Incorrect Heat Generation	- furnace burners - belt drives
• Incorrect Heat Transmission	- lagging - refractory - dust blockages
• Rolling Element Bearings	- temperature relates to load/speed/lubricant
• Hydrodynamic Beaings	- temperature relates to lubricant coolant

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Lube Oil Monitoring

A used sample of oil consists of:

- The base oil and its additives which provide the lubricating and cooling properties of the lubricant.
- The contaminants in the form of solids, liquids and gases, which get carried away by the lubricant as it circulates through the system. Mechanical deterioration is primarily indicated by the presence and type of wear debris. Table 5.2 shows relationship between wear characteristics and particle features.

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Table 5.2: Relationships between wear characteristics and particle features

Wear Characteristics	Wear particle feature
Severity	Quantity (concentration) Size Morphology
Rate	Quantity Size Morphology
Type	Size Morphology
Source	Composition Morphology

Table 5.3: Oil properties, which can be monitored

Property	Units	Description	Comments
Viscosity (Kinematic)	mm^2s^{-1}	A measure of the oil's resistance of flow.	Oil viscosity drops substantially with rise in temperature.
Viscosity index (VI)		A measure of the oil's resistance to droping in viscosity.	From 0 to 300, the higher the value the less change of viscosity with temperature.
Density ($\hat{x}$)	Kgm^{-3}	A measure of the oil's mass per volume.	Typical oil would be from 880 kgm^{-3} (20°C) to 830 kgm^{-3} (100°C), varrying with pressure.
Total acid number (TAN)	mg $KOHg^{-1}$	Amount of potassium hydroxide neutralizing 1 g acid sample.	Increase with oxidation and in the presence of high sulphur diesel fuels.
Total base number (TBN)	mg $KOHg^{-1}$	Acid equivalent to KOH needed to neutralize 1 g base.	Included to restrict acids in their corrosive effect.
Water content	ppm	Dissolved, but at higher levels may form a fine dispersion of droplets.	Unhelpful both for the power fluid and for the lubricant (Even at 100 ppm).
Pour point	°C	Lowest temperature at which the oil will just pour from a container.	Oils are normally used at least 10°C above the pour point.
Flash point	°C	Temperature at which vapours given off ignite in presence of a flam.	Typical between 150°C and 250°C for a mineral oil.

Lubricant Condition

Lubricant is monitored to determine its effectiveness and hence allow change on condition. Table 5.3 explains the oil properties, which can be monitored. Table 5.4 gives pollutants and their effect on lubricating oil. The major modes of failure and their associated monitoring techniques are shown in Table 5.5.

Table 5.4: Pollutants and their effect on lubricating oil

Lubricant property	Pollutants influencing changes in properties
Acidity	Oxidation products, sulphurous products
Alkalinity	Possible additives
Ash	Base mineral constituents
Flash point	Fuel dilution
Insolubles	Carbonaceous products; dust wear products; corrosion products; additive degeneration products
Specific gravity	All
Viscosity	Fuel dilution, water oxidation products
Viscosity index	Different oil mixes

Table 5.5: Failure modes and techniques

Failure mode	Techniques
Viscosity	Viscosity comparator, *e.g.*, inclined plate
Oxidation	Viscosity comparator
Corrosives	Corrosion tests
Solids	Millipore filters, particle counters
Water	Crackle test (oil drop on hot plate)
Microbes	Culture slides
Additives depletion	Spectrometric analysis for additive elements Blotter spot test for alkalinity. Total base number

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Table 5.6: Major wear debris monitoring techniques used

Technique	Off/on-line	Particle	Quantify	Size/ Morphology
Spectrometric oil analysis	Off	<10μm	Sample sent to laboratory to obtain ppm of elements	No
Magnetic plugs	On	>100μm	Debris meter	Yes
Filter	Off/On	>5μm	Debris tester	Yes
Ferrography	Off/On	1μm <<200μm	Direct reader Ferrograph	Analytical Ferrograph

Wear debris

Wear debris monitoring is concerned with the condition of the primary wearing components of machinery, and is achieved by monitoring and analyzing the wear particles that are washed away by the fluid. The quantity and size of wear debris generated indicates an increasing trend in abnormal conditions. The major wear debris monitoring techniques are shown in Table16.6. All these techniques can be operated off-line with the sample being collected on or off load condition.

Some of the oil sampling methods used are:

- Through sampling value
- By suction sampling
- Through drain stream
- Through magnetic chip detector housing

The sampling frequency depends on:

- Function – *i.e.,* importance of the machinery
- Age– time since overhaul
- Operating schedule, loading characteristics of the machine
- Safety considerations
- Rapidity of failure from defect initiation
- New equipment with possible infant mortality requires frequent sampling

During sampling following precautions are recommended:

- The sampling container must be absolutely clean, showing no visible trace of dirt, water, or other matter; it should be discarded after use
- Extreme care is necessary during sample withdrawal to ensure that no foreign contaminants are introduced; if the sample is taken by gravity

flow, the first few milliliters should be discarded before filling the sample bottle

- Sampling must be done during operation or shortly after shut down of the machinery while the lubricant is at normal operating temperature, and before particulate settling can occur
  - o A complete identification with following information must accompany the sample
  - o Machine or system identification
  - o Date of sampling
  - o Total operating hours
  - o Hours since last lubricant or fluid change
  - o Hours since last filter change
  - o Lubricant or fluid type, and addition since last sample
  - o Person to be informed of the results of the analysis.

Spectrometric oil analysis determines parts per million (ppm) of the pertinent elements. Reporting delays are typically one day plus post time with facilities to fax or electronically transfer data. The limit on the size of particle that spectrometric oil analysis will detect means that the technique will miss some large debris resulting from tooth breakage or the early stage of bearing damage. The filter method is cheap to set up needing only an oven, a filter set, a debris tester and if analysis is required a binocular microscope. Sensitivity down to 5 μm covers reasonable wear but the debris tester mainly detects ferrous material, being only slightly sensitive to non-ferrous materials and nonmetals. This method has proved to be widely effective.

The use of magnetic plug limits the size range and has no advantage over filtering except for on-line monitoring.

The ferrography system is most effective with ferrous debris but the tests are more expensive so the technique is not as widely applied as Spectrometric Oil Analysis or filtering. There are a number of on-line systems, which appear to prove successful for use where the process is sufficiently critical to warrant the cost.

Transformer oil

The common modes of failure on transformers can be detected early on by monitoring the gases dissolved in the oil. The ratios of specific hydrocarbons created by overheating and arcing lead to diagnosis. Common modes of failure are inter-turn shorts, overheating of the insulation, integral switchgear high resistance or arcing.

Table 5.7 gives guidelines for possible diagnosis in case of diesel engine, gearbox and hydraulic system based on common contaminants present. Some of the equipment manufacturers provide guidelines of the contaminants limits allowed for their equipment.

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Vibration Monitoring

Vibration monitoring is based on the concept that provided the operating conditions have not been changed; an increase in vibration is an indication of an impending failure. The greater the increase in vibration level the greater is the deterioration. A machine vibrates when the frame, having mass and elasticity, is subjected to periodical forces. The forces may be produced by components attached directly to the frame; they may be developed by reaction forces or transmitted to the frame from rotor via the bearings. Forces transmitted the rotor may be centrifugal due to unbalance or they may be impulsive such as are caused by teeth meshing in a gear train or by fluid striking an impeller blade. Knowing the machine details (such as shaft speed, number of gear teeth, number of impeller blade, etc.), it is possible to calculate the frequency at which vibration will be produced by a particular component. By comparing a list of such frequencies with the frequencies at which an increased vibration is detected it is possible to identify the source of the increase.

Table 5.7: Common contaminants and possible diagnosis

Symptom	Diagnosis
Diesel Engine	
Silicon, iron, chromium, aluminium	Damage to the air filter, cracks or absence of clips on the air manifold system allowing the ingress of abrasive silicon dust and subsequent damage to the cylinder liner/piston/piston ring
Sodium, copper, lead	Coolant leak with damage to the main bearings or the ingress of salt through the air manifold
Chromium	Bore polishing and damage to the piston rings
Copper	Material leeching from the oil cooler
Copper and lead	Main bearing damage
High viscosity	Degradation of the lubricant through oxidation and nitration, or high soot loading, or incorrect lubricant top up
Low viscosity	Fuel dilution (low flash point) or incorrect lubricant
Low total base number	Lubricant degradation
Low total acid number	Lubricant degradation

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High oxidation (infrared)	Lubricant degradation
High nitration (infrared)	Lubricant degradation
Gearbox	
Silicon, iron	Abrasive wear resulting from ingress of dust
Iron, chromium, nickel	Wear of bearing material (rolling element)
Low viscosity	Wrong lubricant
High viscosity	Lubricant degradation or wrong lubricant
Hydraulic system	
Silicon, iron	Abrasive wear resulting from ingress of dust
Increasing total acid number	Lubricant degradation
Low or high viscosity	Wrong lubricant

Thus a vibration monitoring system should provide:

1. A measure of the increase in vibration level to indicate the urgency of the need for attention.
2. A measure of the frequency at which the increase occurs to permit a diagnosis of the problem and
3. Phase shift in vibration is also a useful parameter in diagnosing machine problems.

Table 5.8: Identification of causes of vibration

Cause	Identification
Unbalance	Major component of the vibration is at shaft RPM Major component at 1 × RPM usual 2&3 × RPM sometimes
Damaged rolling element bearing	Major components at ball/roller speeds
Oil Whirl	Major component at approximately half the shaft speed
Damaged or worn gears	Tooth meshing frequency predominates
Reciprocating forces	1st, 2nd and higher orders of shaft speed
Mechanical looseness	Major component at 2 × shaft speed
Bad belt drivers	1, 2, 3 and 4 × RPM of belts

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Thus, vibration is a useful tool to detect the presence of mechanical trouble in its early stages of development. Different problems cause vibration in uniquely different ways. This is clearly shown in vibration identification Chart in Table 5.8. Close inspection of this chart reveals that the key to identifying each trouble is primarily the frequency at which the vibration occurs.

As vibrations are movements of the machine around a rest point, they may be quantified in terms of displacement, velocity or acceleration.

- Displacement is more sensitive to low frequency vibrations, and is best suited for measurements where clearance between parts is critical.
- Velocity gives the same relative size to low and high frequency and is more pronounced in intermediate ranges and is well suited for general condition monitoring measurements.
- Acceleration is more sensitive to high frequency vibrations and will thus be used for monitoring of vibrations where the frequency range of interest covers high frequencies.

The most accepted way to quantity the levels is to measure a time average of the square of the vibration as it varies (RMS value). Vibration levels are quantified in

Displacement	micron (μm)
Velocity	mm/s
Acceleration	m/s^2 or 'g'

For measuring velocity and acceleration values, a logarithmic scale is often used. In this scale vibration is given in "decibels" (dB).

$$\text{Velocity (v dB)} = 20 \log_{10} (v_1/v_2)$$

Where, v_1 = measured velocity in linear units (mm/s)

v_2 = reference velocity (usually 10^{-5} mm/s)

$$\text{Acceleration (a dB)} = 20 \log_{10} (a_1/a_2)$$

Where a_1 = measured acceleration in linear units (m/s^2)

a_2 = reference acceleration (usually 10^{-2} m/s^2)

Functional elements of a vibration measuring instrument are as shown in Figure 5.3. The transducer element converts the vibratory signal to an electrical signal. There are several type of such transducers, which can be used, the choice of which depends on several factors. Piezoelectric type seismic vibration transducer is of self generating type and is most widely used. The output of this transducer is proportional to the acceleration of the vibrating object, to which the transducer is attached. Eddy current proximity type of vibration transducers are used for measuring shaft vibrations. The output of such transducers is proportional to displacement. The signal conditioning include amplifier or filters or differentiators, integrators etc., and convert the signal so that it is recorded or displayed, according to the requirements.

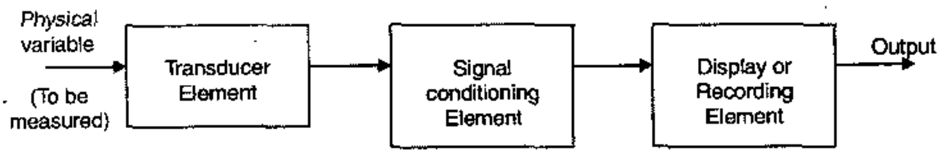

Fig. 5.3. *Functional elements of a vibration measuring instrument.*

Piezoelectric accelerometers are rigidly attached to the vibrating surface by using a stud or by a magnet provided for that purpose. Vibration measurements are normally carried out in three directions *i.e.,* vertical, horizontal and axial, and the transducers are normally mounted on the bearing housing. Proximity probes used for shaft vibration are fixed in bearing housing. Two proximity probes are mounted at right angle to each other to display the shaft orbit.

To check if there is a problem with the machine, the measured vibration levels are regularly compared with a reference level. National and international standards are available, which could be used as guidelines to start with (VDI 2056, BS 4675 and ISO 2372). Several standards exist for shaft displacement measurement. Some of such standards are VDI 2059, API specifications, Erskine's criterion etc. But it is always desirable that one develops his own guideline for reference level.

Vibration monitoring systems

Any of the following three types of the monitoring system can be used:

- Periodic manual monitoring
- Automatic surveillance and
- Continuous monitoring systems.

The selection of appropriate monitoring system depends upon the cost of downtime and the criticality of the machine. When selecting a monitoring system it is essential to take into consideration the details of each individual machine to be monitored. The important factors influencing the selection are:

- Application of machine
- Continuous or intermittent operation
- Machine type
- Speed (driver and driven units)
- Type of drive

- Type of transmission
- Bearings and
- Machine operating environment

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Periodic manual monitoring

This is the routine on-site manual measurement of machinery vibration levels, taken at set intervals. Its principal purpose is to detect and plot changes in those levels, which may indicate the onset of a problem. To ascertain the cause of an increase in the vibration level a vibration analyzer, measuring amplitude, frequency and phase, is used for diagnostic purpose. Figure 5.4 shows a manual monitoring system.

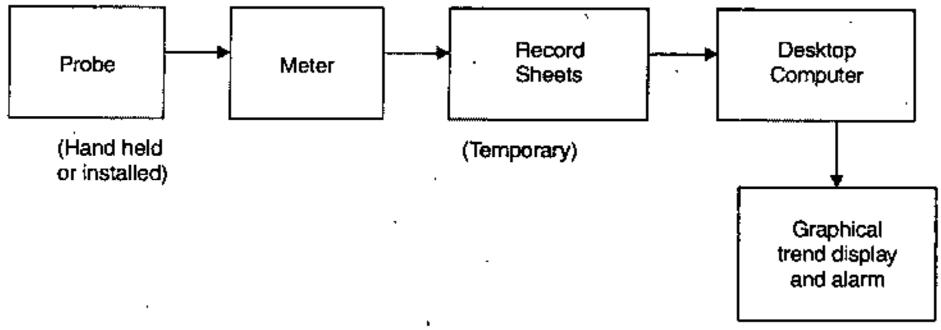

Fig. 5.4. *Manual measurement recording and computer storage and analysis type off-line system.*

Periodic manual monitoring has now been automated through the development of the microprocessor based data collector. It is used in conjunction with a personal computer, suitable software and printer to generate hard copy reports.

The automatic data collector is portable, hand-held and battery operated. It is microprocessor controlled and programmed from the host computer. LCD display guides the operator through a measurement route indicating all the required information such as machine type, test point, measurement direction, units of measurement, alarm level and machine speed.

The majority of measurements taken would be overall vibration levels. However, certain critical machines with complex vibration signature can benefit from amplitude Vs frequency spectra checks. To capture such vibration spectra the data collector requires an on-board FFT analysis capability.

Upon completion of a measurement route, the data collector is off-loaded to the computer, which with user-friendly software enables the maintenance manager to generate a wide range of text and graphic reports. The advantages of such a system are:

- Periodic readings are taken in a controlled and disciplined manner
- Operator error is reduced to a minimum as there is no requirement for selecting the range and unit of measurement

- Manual transcription errors are eliminated
- Frequency band trending offers considerable advantages compared to just trending overall vibration levels.
- *Automatic generation of alarm reports, trend graphs and machinery* vibration signatures.

Figure 5.5 shows a manual measurement automatic recording, storage and analysis type off-line computerized system.

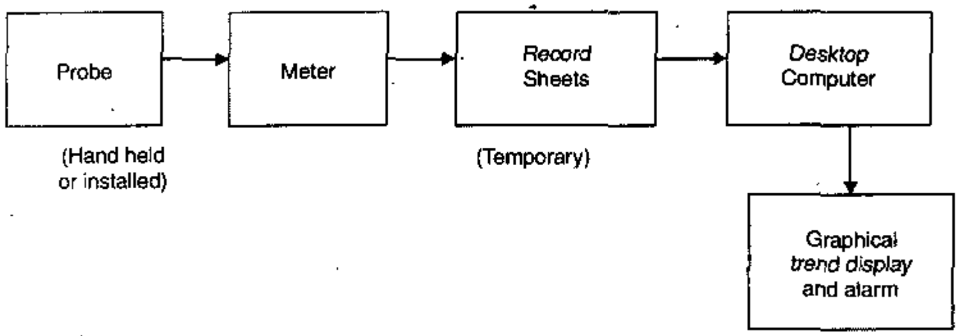

Fig. 16.5. *Manual measurement automatic recording storage and analysis type off-line computerised system.*

Automatic surveillance

A typical system consists of an array of transducers permanently mounted on machinery wired to multiplexers and controlled by commercially available personal computers, which are programmed to automatically scan and collect both vibration and process data. The sensors are interrogated at pre-progammed intervals, simultaneously measuring displacement, velocity, acceleration, and spike energy from any one transducer.

When a problem area is identified, the system automatically increases its sampling rate until such time as the offending machine is corrected. In addition, spectra capture via FFT analysis can be automatically performed for detailed assessment of machinery faults. It being an on-line, system operating personnel can see all dynamic data at a glance.

Unlike continuous monitoring system, where a signal conditioning card is required for each channel of measurement, in this system only one signal conditioning card per measured vibration parameter is needed, which can be applied to as many as sixty channels. It is very cost effective option for protecting a large number of strategic rotating machines. Figure 5.6 shows an on-line computer based condition monitoring system.

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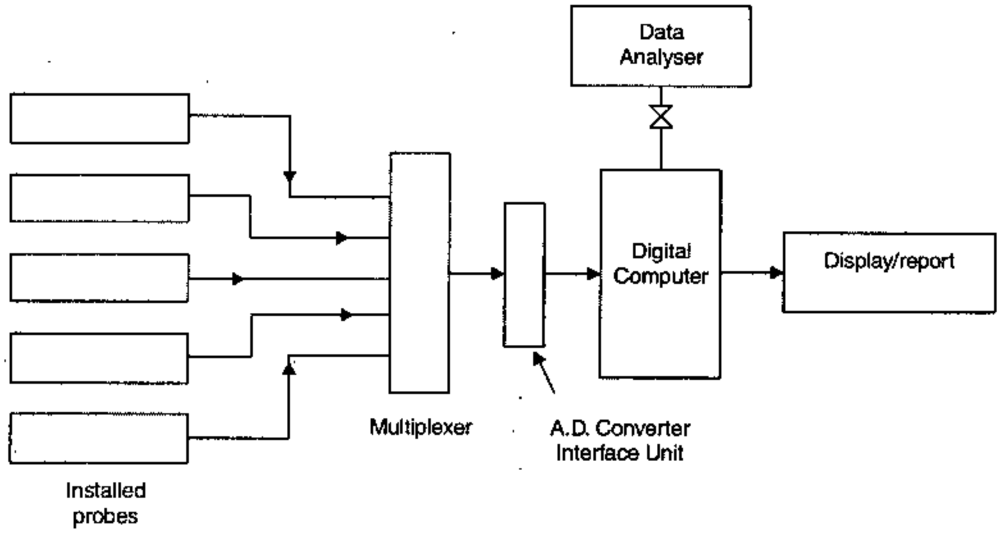

Fig. 5.6. *On-line computer based condition monitoring system.*

Continuous monitoring

Continuous monitoring is intended for the on-line continuous protection of critical machinery. It incorporates all the key features of periodic manual monitoring and automatic surveillance in one self-contained unit. Transducers are hard-wired to a microprocessor based plant information center, which is located in the process control room or near to a high concentration of machines in the plant.

It provides the operator with comprehensive machine and plant performance data and enables engineers to make objective maintenance decisions based on historical machinery trends. A plant information center continuously monitors vibration amplitude, axial position, temperature, thrust, speed, bearing /gear condition, together with inputs from virtually any other process parameter that requires monitoring. The visual display unit can simultaneously present upto 30 channels of information with a vertical bar showing as a percent of the alarm set point. In the event of an alarm an FFT spectrum analysis automatically captures the vibration spectrum so that it can be compared with stored baseline signatures to identify a particular machinery problem. Alarm events and operator acknowledgements are automatically stored for retrieval purposes at a later date. To assist in evaluating a machine's condition, various maintenance reports are possible. These include long-range trend reports based on 52 weekly averages, fourteen-day, 24 hours or even one minute trends. It gives the added protection of continuous monitoring with automatic warning and machine shutdown facilities. The details of a typical on-line computer based system is shown in Figure5.7.

Due to complexities of integrated process plants most situations will require a combination of periodic manual monitoring, automatic surveillance and continuous monitoring systems. These can be integrated to provide the maintenance manager with comprehensive machine and process information at a single data terminal.

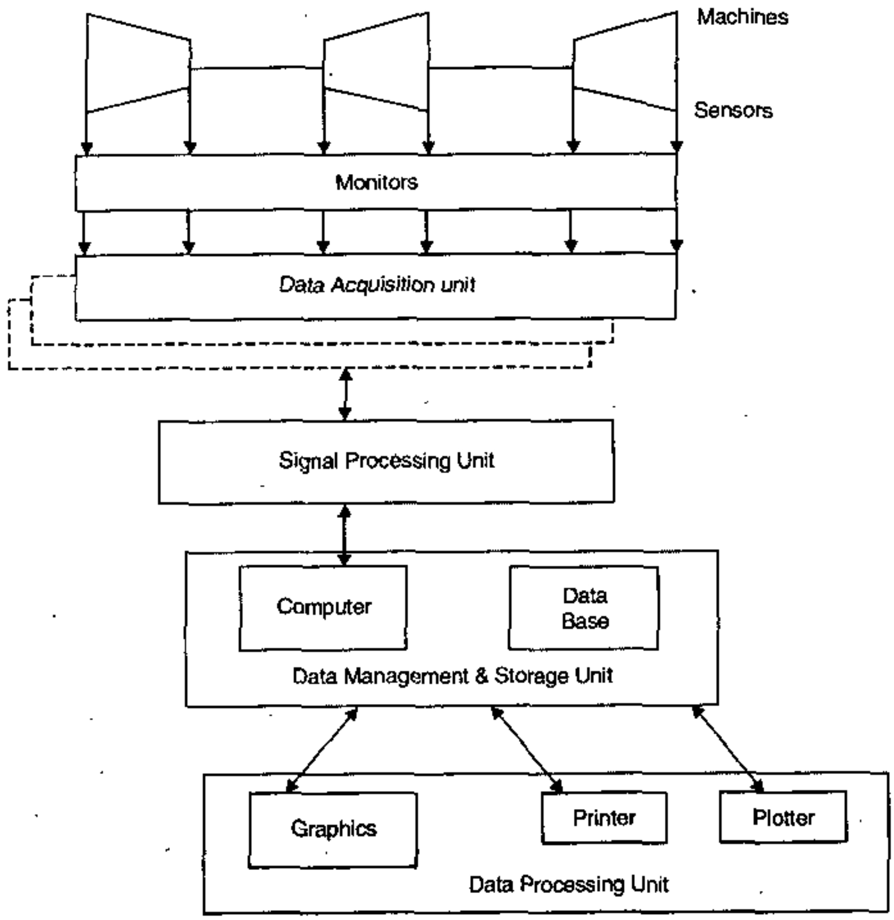

Fig. 5.7. *Computerised machinery monitoring system.*

Shock pulse measurement

Shock pulse measurement is a special method assigned to condition monitoring of roller bearings. The most common type of failure is fatigue break up in the races or rollers of the bearings. When the rollers are passing these spalled areas, high frequency vibration pulses are transmitted through the bearing. The shock pulse meter picks up these transients through a piezoelectric accelerometer detecting vibration at its own resonance frequency, 32 kHz. At this high frequency, the normal machinery vibrations will usually not affect the measurements. Therefore the method is rather sensitive to the bearing condition.

A further development of the shock pulse meter is an instrument called Bearing analyzer. In addition to the wear condition of the bearing this

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instrument also gives what they call a lubrication number. According to the handbook, this is directly correlated to the lubrication film thickness in the bearing. One disadvantage with the instrument is that it requires knowledge of the bearing design as well as parameters such as rpm and shaft diameter.

5.4 BENEFITS OF CONDITION BASED MAINTENANCE

Benefits of condition based maintenance program are as follows:

1. It reduces catastrophic machine failures. Damage caused because of catastrophic failures is usually much more intensive.
2. It minimizes the repair time and helps in reducing the costly downtime. Regular monitoring and analysis of machine condition helps in identifying defective component(s) and plan for the maintenance work.
3. It helps in reducing the maintenance cost.
4. It reduces spare parts inventories. Many spare parts could be purchased just in time for the repairs to be made during scheduled machinery shutdowns.
5. Under this program machinery performance is optimized, as machinery always operates under specified conditions.
6. Its application saves energy requirements, as the machinery is always allowed to operate under optimal operating conditions.
7. Application of CBM reduces the need for standby equipment or additional floor space to cover excessive downtime. Thus capital investment on equipment or plant is less.
8. Prevention of catastrophic failures and early detection of incipient machine and systems problems increases the useful operating life of the plant machinery.
9. Maintaining optimal machine performance level helps in producing quality product.
10. It reduces overtime requirement to makeup for lost production due to breakdowns or poorly performing machines.
11. It helps in reducing penalties that may result because of late deliveries caused because of breakdowns or poorly performing machines.
12. It helps in reducing warranty claims caused due to poor product quality caused because of poorly performing machines.
13. Predictive maintenance techniques help in verification of new equipment condition before acceptance. Vendor could be asked to correct the deficiencies before the final payment is released.

14. Regular monitoring of machinery helps in reducing destructive failures, which could cause personal injury or death. Increased safety helps in reduction in penalties levied against a company for unsafe machinery.
15. Increased safety helps in reduction in insurance premiums for the plants.
16. Predictive maintenance techniques help in determining whether or not repairs on existing plant machinery have corrected the identified problems. This eliminates the need for second outage that many times is required to correct improper or incomplete repairs.
17. The understanding of the operation and condition of the plant is improved, resulting in more respect for maintenance work force from the rest of the plant workers. Thus helps in improving maintenance workforce self esteem and motivation.
18. It helps in achieving reduced life cycle costs.

5.5 RELIABILITY CENTERED MAINTENANCE (RCM)

Controlling maintenance costs, together with improving plant reliability and capacity has become an area of escalating attention in the ever increasing need to increase manufacturing competitiveness. A number of new maintenance philosophies have evolved and proven themselves in assisting maintenance managers in providing better plant utilization at lower cost. Amongst these are preventive maintenance, predictive maintenance, proactive maintenance, condition based maintenance and more recently reliability centered maintenance (RCM). A RCM strategy employs preventive, predictive and proactive maintenance technologies in an integrated manner to increase confidence that a machine will operate dependably over an extended life cycle. The integrated approach of various techniques is required, as no single technique is sufficient to accurately understand the problems of complex equipment.

However, in combination, the various technologies provide a powerful set of capabilities of deriving a holistic picture of machine health. The ability to use the various techniques focussed around reliability affords an opportunity to move beyond fault detection towards developing a meaningful and valuable tool for a maintenance improvement program. The focus shifts on the elimination of machine failure, rather than the prediction of failures. Alongwith the preventive, predicted and proactive approaches, the RCM philosophy include knowledge based diagnostics of samples to incorporate a learning component within the program. The element of knowledge is permanently embedded within the working practices so that the organization does not repeat bad practices and make continuous error.

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5.6 CONCEPT OF RCM

RCM is a methodology as well as a philosophy, and it is not possible to define it with the help of one definition. The following definitions will help in understanding the concept of RCM.

RCM is a systematic approach for quantitatively assessing the need to perform or review preventive maintenance tasks and plans. It provides a methodology targeted on system functions, the failures relating to that function, and in particular to the effects of dominant functional system failures. A decision tree is used within RCM to identify and classify critical system components together with an appropriate and applicable maintenance policy. The main concept underlying the development of RCM is an attempt to retain the design reliability of equipment, through the analysis of factors which affect its operating reliability, and with a view to optimize preventive maintenance programs via effective maintenance planning. RCM provides a structured and logical approach to determine the maintenance requirements of any physical asset in its operating context. The methodology helps in identifying what causes the functional failures of equipment and what are the consequences of any failure? RCM concept then recognizes that in true sense any maintenance is carried out, not so much to prevent the failures but to reduce the consequences of failures.

RCM approach takes in consideration that all equipment or components do not follow an age dominated failure mode and, therefore the maintenance requirements of all components cannot be evaluated in a similar manner. Thus RCM is a process used to determine the maintenance requirements of any physical asset in its operating context. A great strength of RCM is the way it provides simple precise and easily understood criteria for deciding which (if any) of the preventive tasks is technically feasible in any context, and if so for deciding how often they should be done and who should do them.

To summarize

- RCM is a process used to determine the maintenance requirements of any physical asset in its operating context.
- RCM is a process used to determine what must be done to ensure that any physical asset continues to fulfil its intended functions in its present operating context.
- RCM is a method for developing and selecting maintenance design alternatives based on safety, operational and economic criteria. It employs a system perspective in its analysis of system functions, failure of functions and prevention of these failures.

- RCM is a system consideration of system functions, the way function can fail and a priority based consideration of safety and economics that identifies applicable and effective PM tasks.

Thus RCM has four unique features:

1. Preserve functions
2. Identify failure modes that can affect functions
3. Prioritize function needs via failure modes
4. Select only applicable and effective tasks.

5.7 RCM METHODOLOGY

The concept of RCM was developed in the early 1970s by the maintenance steering group of commercial airline industry in order to reduce maintenance downtime, maintenance cost and improve flight safety. It has also been successfully employed in grain terminals, coal mining, oil refinery, gas plants and paper industry. The methodology of the RCM is presented in the flow chart as shown in Figure 5.8.

System Selection and Information Collection

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System Boundary Definition

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System Description and Functional Block Diagram

↓

System Functions and Functional Failures

↓

Failures Mode and Effect Analysis

↓

Fault Tree Analysis

↓

Tasks Selection

Fig. 5.8. *Flow diagram of RCM methodology.*

The various steps of the methodology are briefly discussed here.

1. **System Selection and Information Collection:** Various factors like large PM cost and actions, large corrective actions and cost, safety and environmental issues are considered for selection of system. Documents such as system schematics, equipment history files, vendor manuals, system operation manuals are need to be referred for collection of information.
2. **System Boundary Definition:** Major equipment included in the system are identified with primary physical boundaries. Defining of boundaries is required to make sure that the potentially important functions are not neglected and to establish the IN interfaces, factors coming into the system

like power signals, flow heat etc. and OUT interfaces, factors that leave the system.

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3. **System Description and Functional Block Diagram:** The various type of information developed in this phase are the following:
   (*a*) Description of functions, redundancy and protection features
   (*b*) Hierarchy of functions
   (*c*) IN/OUT interfaces
   (*d*) Equipment list for each functional subsystem
   (*e*) Equipment failure history of past 2-3 years.
4. **System Function and Function Failure:** Function statements are developed for each functional subsystem by capturing every output interface. Functional failure statements focus on loss of function and not on equipment.
5. **Failure Mode and Effect Analysis:** In this step, the specific component failure modes — how the component must fail in order to produce functional failure — and the root cause for each failure mode are defined. Then the consequences of the failure mode are listed at three levels, locally at the level of component, at the system level and at the plant level. The primary reasons for conducting FMEA are to assure that the failure mode in question does in fact have a potential relationship to the functional failure being studied and to introduce initial screening of failure modes that are not detrimental.

FMEA technique was developed by the American defence industry in the 1960s to address the problems experienced with complex electronic weapon control systems. Subsequently it was extended for use with other electronic, electrical and mechanical equipment. FMEA can be performed in a variety of different ways depending on the objective of the assessment, the stage of equipment development and the information available on its components at the time of analysis. The FMEA focus may dictate a different worksheet format in each case; nevertheless, there are two basic approaches:

(*a*) The Functional FMEA, which recognizes that each item is designed to perform a number of functions which can be classified as outputs. These outputs are identified and loss of essential inputs to the item or internal failures are then evaluated with respect to their effects on system operations.

(*b*) The Hardware FMEA, which sequentially lists individual equipment items and analyses the effect of each item failure mode on the operation of the system. In many cases a combination of these two approaches is employed.

The FMEA worksheet is tabular in format to foster a systematic approach to analysis. The various columns of the table are:

- **Item identity/description:** A unique identification code and description of each item.
- **Function:** A brief description of the function performed by the item.
- **Failure mode:** Each item failure mode is listed separately — there may be several for an item.
- **Possible causes:** The likely causes of each failure mode.
- **Failure detection method:** Features of the design through which the failure is recognized.
- **Failure effect:** The effect of the failure at the local level, system level and plant level.
- **Compensating provisions:** Any internal compensating provisions which could mitigate the effect of the failure.
- **Remarks:** Comments on failure mode and effects, any recommendation etc.

Further columns can be added to the table to incorporate severity and frequency of failure, probability of failure effect, data source etc.

6. **Fault Tree Analysis/Logic Tree Analysis:** There are two approaches that can be used to analyze the causal relationships between component failures and system failure. These are inductive or forward analysis and deductive or backward analysis. FMEA is an example of inductive analysis, it starts with a set of component failure conditions and proceeds forward, identifying the possible consequences. This is a 'what happen if' approach. Fault tree analysis is a deductive 'what can cause this' approach and is used to identify the causal relationship leading to a specific system failure mode—the top level. The fault tree is developed from this top, unwanted event, in branches showing the different event paths. Component failure events represented in the tree are progressively redefined in terms of lower resolution event until the basic events on which a good quality failure data are available are encountered. The events are combined logically by use of gate symbols, which shows the structure of a fault tree. Using the fault tree analysis, the probability of the top event or the top event frequency can be calculated by providing the information on the basic event probabilities.
7. **Task Selection:** The RCM process require that each task selected must satisfy the applicable and effective test, which are defined as follows:
   - **Applicable:** The task will prevent or mitigate failure, detect onset of a failure or discover a hidden failure.
   - **Effective:** The task is most cost effective option.

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In RCM tasks are designed to prevent three types of failures:

1. Dangerous failures injurious to the public, employees or to the environment, such as boiler safety valve, or the rupture of a tank of volatile chemicals. Example of Bhopal gas leak is an example of this type of failure.
2. Expensive failures where the consequences are operational downtime and large breakdowns such as loss of cooling water to a data center or breakage of the chain in an auto assembly line. The breakdown of power transmission is an example of this type of failure.
3. Frequent failures that happen continually and are disruptive to the work environment resulting in high repair cost. Frequent breakdown of buses of a transport company is an example of this type.

Under RCM, the problem is not failure at all, it is the consequences of failure.

Identification of Critical Parts and Tasks

The identification of critical parts of equipment and preparing the task list is the heart of the RCM system. This list represents the accumulated knowledge of the manufacturer, skilled mechanics, engineers, contractors, insurance companies, trade associations, equipment distributors and consultants. The list reminds the management what task to do, who has to do it, what parameters to look into, how to do it and when to do it. The task list can be divided into two categories:

Category 1: The list of tasks that help to extend the life of an equipment or increase the mean time between failure. The examples of this category are clean the machine, lubricate, tighten the screws, secure any loose guards, replace a worn out component etc.

Category 2: This list of tasks detects when the equipment has begun its descent into breakdown. The examples are routine inspection, measurement of parameters, taking samples for analysis, review of the history of machine, interview of the operator and others tools of condition monitoring.

The following issues should be considered while preparing the task list.

1. **Complete description of the task:** The task should be completely, unambiguously described, preferably with the help of drawings. Any precaution to be taken while doing the task or the risk of release of gases, possible spillage etc., should be outlined.
2. **Planning aspects of the task:** Performance characteristics and specification about the task should be recommended. Skill level needed, any special license required, special tool required, parts needed, value of

the parts, total cost of the task, tasks to be subcontracted should be specified.

3. **Operational aspects of the task:** The planned frequency (clock days, utilization, condition), time required to perform the task, involvement of other departments, impact on other departments and any notification required is to be specified in the task list.

Types of Task List: The listing of tasks can be done on the basis of unit, string, future benefits or condition based. Each method has its own merit and demerit. The selection of a method is situation specific and at many instances a combination of two or more methods are used.

Unit base task list: This is the most popular type of task list, where one machine or equipment is taken as a unit and all the tasks are completed on one unit before going on to the next unit. Short repairs also carried out by the mechanic with the tools and material carried by him. For large size systems like utilities, sometime several people from different sections converge at the same point to perform their task list. This type is called gang based. The advantages of unit based task list is that it is more effective, the mechanic gets to see the big picture. Person learns the machine well and has ownership. The disadvantage is a skilled mechanic with high training is required.

String based task list: This list has few items on many units in a string. Lubrication route is an example of string based system. This is an efficient method since a worker would be focused on only one activity. The advantages are: task can be performed by less skilled worker, requires lower training and have high productivity. The disadvantages of the method are loss of big picture about *a machine, monotony of job, no ownership and difficult to* supervise.

Future benefits: This type of task list is generally considered in the chemical plants, petroleum and other process industries where the processes are closely coupled. A breakdown or changeover at one place makes the whole system idle. In this the task list of the whole train is carried out whenever a breakdown or changeover took place. The advantages are little or no extra down time, easier to manage, and can be exciting. The only disadvantage is a large size team is required.

Condition based task list: This list is prepared based on some readings or measurements going beyond a predetermined limit. The method has high probability that some intervention is needed, involves the operator, brings maintenance close to production, supports quality programs. The disadvantage is that it requires a skilled manpower and sometime may be too late to avoid breakdown.

5.8 BENEFITS OF IMPLEMENTING RCM

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RCM focus is on system function approach. Complex redundant systems have reliability directly engineered into their design. The reliability of a system is reduced if maintenance tasks and frequencies are not its integral component. Over maintenance reduces the system reliability on account of maintenance induced failures. For highly reliable system, reliability very often is reduced due to human intervention under the pretext of PM. Therefore, RCM methodology has been successful in building up highly reliable systems. RCM methodology helps in achieving the following:

- High quality, cost effective maintenance plans in less time.
- Assurance that all maintenance important parts and their failure mode are critically considered in the development of maintenance programs.
- Increased probability that the level and content of the maintenance requirement is optimally specified.
- Provides the basis for routine, on-line information sharing among engineering, operations and maintenance staff.
- Longer useful life of expensive assets.
- Improved safety of equipment and plant personnel.
- Better environment protection.
- Improved operating performance in terms of output, quality and customer service.

5.9 TOTAL PRODUCTIVE MAINTENANCE (TPM)

The origin of TPM can be traced back to 1951 when preventive maintenance was first introduced in Japan. The Japanese took the concepts and techniques of preventive maintenance from the U.S.A. The induction of preventive maintenance from the U.S.A. heralded the modernization of plant maintenance in Japan.

Nippondenso Company Limited first introduced plant-wide preventive maintenance in 1960. This was the usual form of preventive maintenance, wherein operators devoted themselves only to production jobs and the maintenance personnel were responsible for the maintenance of plant and equipment. In the mid 1960's, Nippondenso undertook the automation of its production with the result that the manufacturing and assembly operations became largely automated. This brought in a new problem—one of maintenance of automated equipment. It was found that the maintenance crew, only by itself, could not effectively maintain the greatly increased number of automated equipment. Accordingly, the management of the company decided to change the allotment of duties of the operators of automated equipment in as much as each operator was made responsible for routine maintenance of his equipment. This was the origin of one of the important features of TPM, which is autonomous maintenance by production operators.

Thus, Nippondenso had already recognized the importance of preventive maintenance in improving equipment availability and had also by then introduced autonomous maintenance by production operators, as noted above, thereby freeing the maintenance personnel from the routine maintenance tasks and making it possible for the maintenance department to take up the essential tasks of maintenance planning based on equipment performance, plant and equipment modification for improved reliability and maintainability, development of reliability and maintainability specifications for new equipment and designing-out-of-maintenance. These tasks are aimed at maintenance prevention (MP). Thus preventive maintenance together with MP and maintainability improvement (MI) activities gave birth to productive maintenance (PM). The aim of productive maintenance is, therefore, the maximization of plant and equipment effectiveness in the pursuit of economic effectiveness and achievement of optimum life cycle cost of production equipment.

This was the origin of the second important feature of TPM, which involves activities to maximize equipment effectiveness. Moreover, Nippondenso, by then, had already developed quality circle activity with all the employees participating in it. It recognized the use of small group voluntary activity for promoting the adsorption of PM and getting the total involvement of plant personnel in productive maintenance of plant and equipment. Based on this, Nippondenso decided to evolve PM with all employees participating in it; use of total participation through small group voluntary activity for TPM promotion. This essentially was the origin of the third important feature of TPM, which is the use of company-led small group activity.

Based on the above development, Nippondenso evolved TPM between 1969 and 1971, and it was awarded the 1971 Distinguished Plant Prize (PM Prize) for the development and effective implementation of TPM by the Japanese Institute of Plant Engineers (JIPE). Thereafter, the formal definition of TPM was enunciated by JIPE in 1971.

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5.10 MOTIVATIONS AND IDENTIFYING CHARACTERISTIC OF TPM

Having discussed in chronological sequence the origins of the three important features of TPM, we can now take up in sequence the basic motivations, and identifying characteristics of TPM. Takahashi has identified three specific motives for the advocation and subsequent adoption of TPM in Japan [9]. These three motives are as follows:

1. Adoption of the life cycle approach for improving the overall performance of production equipment.
2. Improving productivity through a highly motivated workforce, which can be achieved through job enlargement in which all workers are given a range of challenging jobs in order to develop their skills at different crafts.
3. The use of voluntary small group activity for identifying the likely cause and frequency of failure of critical equipment, possible plant and equipment modifications, which will result in significant savings, and efforts to fully utilize existing equipment through improved availability.

The formal definition of TPM was also enunciated along the same lines. Two specific parts of the first motive are as follows:

1. Pursuit of economic life cycle cost of physical assets, which must include building in of reliability and maintainability features and the extension of the useful life of the assets, and since TPM deals primarily with production equipment and is used in manufacturing industries, such assets are plant and machinery, and
2. Improving the overall performance of plant and machinery, which should also take into account the effective use of such production equipment through the minimization of losses not only due to breakdowns, but also due to poor quality and losses due to set-up, adjustment, idling and minor *stoppages of the equipment and equipment operating at reduced speeds.*

Although the contribution of the last four causes, namely set-up, adjustments, idling and minor stoppages, and operation at reduced speeds, may seem small as compared to breakdowns and defective products, in actual practice, these four losses add up to a significant amount. This recognition differentiates *productive* maintenance (PM) from preventive maintenance. Whereas the practical application of preventive maintenance now-a-days covers much more than just 'routine', or periodic preventive maintenance, and includes condition-based maintenance, or *predictive preventive maintenance, plant modifications* and designing-out-of-maintenance, activities aimed at the minimization of quality losses and set-up, adjustment, idling and minor stoppages, and speed losses do not come under the purview of preventive maintenance.

To be able to stay in business, the manufacturing organizations have to ensure much higher levels of equipment availability. Such high levels of equipment availability cannot be achieved with the 'I operate - you fix' altitude wherein the production operators only run the machines and the maintenance department attends to all maintenance activities, including routine activities which are carried out to keep the machines in good running order, such as cleaning of the machines, periodic lubrication, periodic checks and inspections and minor adjustments and repair. The maintenance departments are finding it difficult to attend to such routine tasks.

Moreover, attending to such routine tasks is resulting in a situation wherein the necessary preventive maintenance activities, such as preventive replacement of critical components, equipment overhauls and necessary plant modifications, are getting backlogged for lack of available manpower, and this, in turn, is resulting in greater incidence of failures and loss of equipment availability. As against this backdrop, let us consider a situation wherein the production operators perform basic maintenance activities on their own machines. They not only maintain their own machines in good running order but also are capable of detecting potential problems before a major breakdown occurs (at which time, the maintenance department is called in to take the necessary preventive action to avoid a long shutdown). This will not only leave the maintenance department free to attend to more pressing tasks which require higher levels of skills, but also bring back in the production operators the pride of craftsmanship. The production operators will then cherish their machines and tools, preserve them and use them with care, and this, in turn, will inculcate in them a sense of belonging to the organization. Thus, the integration of simpler and routine maintenance tasks with the production work not only enlarges the production job and makes it more interesting but also fosters in the production operators a commitment to the plant. Moreover, with this the maintenance tradesmen are also able to carry out their tasks properly and under a more congenial atmosphere and this brings with it a feeling of job satisfaction in them.

This, as we had noted earlier, is what is meant by autonomous maintenance and a key ingredient of TPM is that the production operators perform basic maintenance tasks on their own equipment.

The objectives of maximization of equipment availability, minimization of quality loss, and minimization of set-up, adjustment, idling and minor stoppages and speed losses are major challenges to any manufacturing organization and these challenges call for reforms and improvements in standards, processes, methods and procedures. Such reforms and/or improvements cannot be carried out by a few technical people working in production and maintenance departments; these challenges require the active participation and involvement of all employees in the organization.

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In the preceding paragraphs we have discussed the need for having a highly motivated workforce, that is, the need for a high level of motivation in the persons who carry out the essential tasks, or activities, whether they are production operators, maintenance tradesmen, or quality control inspectors. After all, in the final analysis, these persons perform the important tasks, which directly affect equipment availability, product quality and productivity. These persons must not only do their allotted task to the best of their capability, but they should also forever attempt to reach higher levels of performance. Higher levels of performance require commitment to the job, motivation and a sense of belonging to the organization. This sense of belonging to the organization also inculcates in the employee a sense of belonging to the larger group, wherein the maintenance fitter not only identifies with the plant/equipment, he also identifies with the production operators and the quality control inspectors, who are also a part of the same group. Thus innovative ideas and suggestions for reforms and improvements must be preceded by an attitudinal change in the workmen leading to involvement, which, in turn, comes from a conscious effort through a synchronization of hand, head and heart and from creative work which is beneficial to the larger group. One of the practical and time-tested ways of inducing involvement and a sense of belonging in the workman is through active participation, wherein he voluntarily joins a group of people who meet to discuss their problems and suggest better ways of doing what they are doing; a voluntary small group of people who meet to discuss problems with housekeeping, quality, equipment availability and productivity, and to suggest reforms and improvements. This is active participation and quality circles and ZD groups are its different forms. In the context of TPM, we call these PM circles (and PM sub-circles).

Involvement of the workmen on the shop floor is not enough since, as discussed earlier, the objectives of maximization of equipment availability, minimization of quality loss and the minimization of four other types of losses cannot be achieved without the involvement and active participation of all employees in the organization. To be able to effectively deal with these challenges, the organization has to ensure the involvement of all functions in the organization, namely marketing/sales, design/ engineering, materials management/ purchasing, production, maintenance and quality control. Thus the promotion and adsorption of TPM requires the development of the TPM Promotion System which links the various PM sub-circles and PM circles to the Departmental PM Committees and the Departmental PM Committees, in turn, are linked upward to the Corporate PM Committee. The Corporate PM Committee establishes the company PM policies and objectives and overseas the activities of the various Divisional/Departmental PM Committees. Similarly, Divisional/Departmental PM Committees establish the PM policies and objectives for the division/department and oversee the activities of the PM circles, which come under them. There is an overlap and the shop manager/foreman who is a member of the Divisional/Departmental PM Committee is the PM circle leader. The PM sub-circles come under the overall direction and guidance of a PM circle and consist of volunteers who may be operators, maintenance tradesman etc., and is headed by a leader, who is typically also a volunteer.

5.11 TPM PROMOTION

We had noted that T in TPM stands essentially for total involvement, or involvement of all employees at all levels, and also that for this purpose, right at the beginning of its development at the Nippondenso Company, *taking a cue from quality circle (or QC circle) activities*, TPM was evolved as 'PM with all employees participating (in it) through small group activities'. We will discuss the basic characteristics of PM groups and circles before we discuss TPM promotion.

Characteristics of PM Groups and Circles

PM groups and circles are set up with the twin objectives of (*i*) tapping the knowledge and abilities/skill of the employees for solving work-related problems and for generating improvement ideas and suggestions, and (*ii*) developing a motivated workforce and improving communication between the employees and management through employee participation. PM groups are also small groups and similar in size as quality circles. But beyond this there are a few similarities. The two characteristic features of PM groups and circles are the two basic roles of small groups in TPM, which, in turn, are as follows:

1. Harmonizing group goals with the company, or corporate, goals,
2. Implementation of the five S's and autonomous maintenance.

Concept of TPM Promotion

In TPM, harmonizing the goals and themes of the small groups with the company, or corporate, goals is very important. The company, or corporate, goals are set by the top and senior management personnel. They set the organizational goals and they also determine the company wide PM policies. These goals and policies have then to be transmitted down the organizational structure, through departments and departmental managers, to the shops and sections, and these goals and policies form the basis for the determination of the departmental PM goals and policies. The departmental PM goals are, in turn, used for setting of goals for the PM groups and circles in the shops and sections and further down, the PM sub-circles, if necessary. This is the first ingredient of the concept of TPM promotion, namely 'top down' goal setting and direction of activities.

The goals of the PM groups and circles, so set, have, in turn, to be achieved by the respective PM groups and circles. For the achievement of the goals, the improvement ideas and suggestions have to be implemented. The implementation of improvement ideas and suggestions requires the involvement, active support and assistance of higher-level groups right through departmental PM committee, upto the company wide, or central, TPM promotion committee. Implementation of ideas and suggestions of the groups is essential for the sustenance and growth of motivation in the members. This brings us to the second ingredient of the concept of TPM promotion, namely, 'bottom up' (or bottom-to-top) small group activities and implementation of improvement ideas and suggestions of the groups.

These two ingredients of the concept of TPM promotion, namely 'top down' goal setting and 'bottom up' improvement activities, ensure that the activities of the PM groups and circles, at every level of the organizational structure, complement and enhance the organizational activities. This way they help in the achievement of the organization goals. For this, it is necessary that the PM groups should be integrated into the corporate, or company, organizational structure, and this, in turn, calls for a formal structure for TPM promotion.

TPM Promotional Structure

The effective administration of the scheme of small group autonomous activity, thus, requires a formal structure, that is, TPM promotion requires an organizational structure. TPM promotional structure of overlapping small groups is shown in Figure 5.8. This organizational structure ensures that the activities of the small groups in the various functions, like production, design and development, purchasing etc., and at the various levels in the organization are properly directed, coordinated and linked. TPM promotional structure enables cross-functional integration.

The TPM promotional structure is based on the following three important principles:

1. Use of overlapping small groups
2. Use of committee and subcommittees
3. Fanning out from the production/operations department to the entire company.

The small groups function at every level of the company, starting from the top and senior management levels to the production shops and production lines. The two ingredients of the concept of TPM promotion call for proper linking of the small groups at the different hierarchical levels, and this is done through the use of overlapping small groups. The leaders of the PM circles at the lowest, or the first, level are members of the small group at the next higher, or the second, level, and so on right upto the top. This ensures linking of different groups, and enhances vertical (both top to bottom and bottom to top) and horizontal (between shops, departments and functions) communication. . Notice that the promotional structure has a TPM promotion committee, four subcommittees (they can as well be called committees), and a TPM promotion office for overall administration of the scheme of small group autonomous activity. The TPM Promotion Committee is the apex body under the chairmanship of the Managing Director, or the Chief Executive Officer of the organization. It is responsible for directing the TPM activity of the entire company. It sets the TPM policy for the company and it also sets the TPM goals and activities for the company as a whole. It coordinates the TPM efforts of the various functions, or divisions and departments, to enable the achievement of the corporate goals. Under the TPM Promotion Committee, there a number of committees/subcommittees, with each committee/ subcommittee being responsible for a particular topic, such as education and training, implementation of five S's standards, and MI and MP. The number of committees/subcommittees will differ from one organization to another. Although TPM efforts are essentially directed at line activities, and the equipment operators, maintenance tradesmen, and the quality control inspectors and technicians are still the leading players, the TPM effort should spread to the other departments and functions of the company. Only when this happens, will the total involvement, as enunciated in the definition of TPM, be achieved. In this regard, one alternative is to take up the job of TPM promotion in two phases, with phase I concentrating on the production shops and departments, and in phase II, fanning out to the other departments such as design/engineering, sales and service, purchasing and general administration. In this context, Suzaki states that although, in most organizations, PM groups are still concentrated in the production shops/ departments, TPM has recently begun to spread out to other departments.

5.12 MAINTENANCE AUDIT

When you hear the term 'Audit', normally the figure of statutory auditors given special and fearful treatment at various company levels comes into your picture. Certain functions of a company are compulsorily audited by either mandatory provisions or as required by a certifying agency. For example, the finance statements like annual accounts etc., are to be

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compulsorily audited by a certified practicing auditor. Similarly, we have the recent energy conservation act passed by the parliament, which makes energy audit compulsory for high energy consuming industries. For obtaining certification in the ISO-9000, 14000 systems, once again auditing is prescribed by the standards. Factory Act specifies mandatory 'Safety Audit' for highly hazardous factories. All these audits are enacted by law to safeguard the rights of different types of stakeholders of an organization like shareholders, employees, customers, general public etc. It can be well recognized that without such regular audits, it would become difficult to identify problems in advance for corrective actions.

Apart from statutorily mandated audits, many enterprises are nowadays realizing the importance of auditing other important functions also. This is due to the high proportion of the effect such functions can have in their bottom lines. For example, maintenance and quality are two such important functions the cost of improper management of which has already been dealt with in other portions of this course.

Many organizations who have embarked on carrying out maintenance audits in a regular manner have found out to their surprise that there are many areas in the operation and maintenance function, which they once considered as their strongholds, had number of deficiencies to be rectified. Considering the status of maintenance function in the various installations of our country, we can safely conclude that in spite of spending huge sums of money, the maintenance performance factors like availability, reliability, maintainability and safety have not been up to desired level even compared to similar developing countries, not to speak of highly advanced nations. Many organizations concerned about the productivity of such non performing physical assets are now raising the issue of mandated maintenance audits also to be incorporated in the law. Hopefully, in the times to come there would be both a good demand as well as utilization of the 'Maintenance Audit' by Indian organizations. In this lesson, we would cover the various facets of maintenance audit and how the reader would be able to utilize the audit either as an auditor or auditee.

5.13 TYPES OF AUDIT

There are various types of audit that are possible to be carried out in an organization. It would be useful to understand these terminologies so that one is able to understand and appreciate their purpose and requirements for different situations. These are briefly described below:

1. **Statutory Audit:** It is the audit required by the law enacted by the parliament or legislatures of a country. Sometimes other statutory or

semi-statutory organizations like international labour organization, international standards organization etc., also make specific provisions for such statutory audits. On the other hand **Voluntary Audit** is the audit taken by an organization on its own interest.

2. **Internal Audit:** It is the audit taken by the internal department or *personnel of the company, normally* one department auditing the functions of the other department. **External Audit** is the audit conducted by an external agency (neutral third party) either due to the wish of the company management to identify problems for improvement or mandated by an enforcing agency like the Government.
3. **Preliminary Audit:** It is normally conducted for a brief period of time to identify major thrust problem areas in a function. The problems so identified may be subjected to detailed examination and problem solving at a later stage. On the other hand a **Detailed Audit** is carried out to study the complete features and requirements of a specific function. Normally a team of members conducts such audit for a considerable period.
4. **Management Audit:** It is the audit carried out to check and identify the suitableness of system and procedures of a management function. The audit carried out for ISO-9000 certification is an example of such an audit.
5. **Technical Audit:** It is the process of study of a technical component of a plant, with or without experimentation and instrument monitoring, to identify improvements in both the hardware and software aspects. For *example, environment audit of a factory involving measurement of* pollution parameters is a predominantly a technical audit. All these types of audits have some amount of overlapping in their purposes and applicability. For example, a statutory audit can also be a result of the voluntary requirement of the company. Or an external audit team may co-opt an internal member of the company to enhance the understanding of the process being audited.

All these types of audits have similar methodologies also. In this lesson, we would be discussing predominantly about the audit of 'Maintenance Management' function and the discussions are applicable to any type of audit mentioned above. The discussion about technical audit in maintenance function is out of scope of this lesson.

5.14 IMPORTANCE OF MAINTENENACE AUDIT

We are aware that maintenance function is a supporting activity to make the planned availability of plant and equipment possible. Since it is not a direct function connected to profits of the organization like production, finance or

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marketing, it is possible that the necessity of maintenance to be properly managed is overlooked by the top management. At the same time, maintenance management need to be at the optimum level as either over maintenance or under maintenance, both are likely to affect the costs incurred by the organization. We have already seen that though the actual maintenance costs may be only a small proportion like the tip of the iceberg, the consequential cost of improper maintenance could run to million of rupees, like the iceberg hidden below the water level. We have seen that the maintenance management requires many features to be complied by the different levels of personnel in the organization. In fact, maintenance management requires attention of management right from the chief executive level to the bottom most worker level. These requirements and functions need to be standardized, monitored, analyzed and corrective actions prescribed from time to time. Hence the importance of maintenance audit is very much emphasized.

Maintenance Audit when properly and regularly conducted will have the following benefits:

- Helps in confirming, the function is performing towards the objectives that are set forth for it.
- To compare the performance indices of the function with that of the targets as well as similar benchmarks for the industry sector or with the world class best benchmarks.
- To identify weak areas for performance improvement and implementation strategies thereof.
- To get certified towards proper system functioning from the auditing agency which may be requirement of a statutory and standards agency.
- To apply and obtain popular awards like the Total Productive Maintenance (TPM) award etc.

5.15 METHODOLOGY OF MAINTENANCE AUDIT

The steps in a maintenance audit are given below:

Initial Orientation: The auditing team has an initial meeting with the representatives of the company's senior management and the regulating agency, if any. In this meeting, the goals, scope and coverage, information requirement, schedule and the techniques of the audit to be employed are presented in a summarized form. The initial meeting enables both the auditing and auditee groups to understand each other's concern well and lays the foundation for a detailed interaction at later stages.

Preliminary Preparation: During this step, the auditors' team studies the management and technical information obtained in the initial orientation and prepares a plan for addressing the major concerns expressed by the company management or the regulator. Accordingly the most important areas of inquiry are identified and detailed audit visit plan and schedule are prepared. It covers the areas of audit, identification of management personnel to be interviewed, facilities and work areas to be visited, data requirements etc.

Preliminary Questionnaire Survey: The auditors prepare a detailed questionnaire on the various issues of concern in maintenance management and circulate in advance to the company management personnel. The questionnaire contains a systematic identification of elements and series of questions to collect information about the same. The questionnaire enables collection of documented information from a larger cross section of the target personnel. The answers to the questionnaire are compiled and conclusions are arrived at as to the selected areas and management personnel to be concentrated upon during the next steps.

Plant Visits: The auditing team undertakes a filed visit to the plant for collecting field information. During this visit, interviews are held with senior managers, supervisors, and technicians etc to obtain a first hand feeling of the management factors and concerns and feelings. During this visit, additional information required in terms of work processes, plant performance parameters, operation-maintenance interactions etc are also collected. In some special audits, plant visits are also taken up to a comparable third party organization to make comparative analysis of the system and technical parameters. At the end of the plant visits, the auditing team would have the data essential to understand the companies maintenance strategies, challenges and plans. It also enables to fully understand the present resource structure in terms of the organization, manpower, budgets etc and its deployment.

Data Analysis: During this step of the audit, the study team reviews, digests, summarizes, and analyses all data and information gathered. Profiles of maintenance management performance are developed and compared to the company's past performance and to the performance of the industry and to similar companies. Many of the criteria used to evaluate effectiveness and efficiency can be measured quantitatively in terms of cost and savings, man-hours, percent adherence to schedule or budget, energy consumption, reliability, availability and so forth. However, truly comparable benchmarks may not be readily available. Accordingly, the auditor must consider the company's performance within the context of its unique environment. Seasoned judgment, both in tempering quantitative evaluations and in measuring less tangible performance factors must be used.

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Development of Conclusions and Recommendations: Based on the above evaluation, the auditing team develops conclusions about the efficiency and effectiveness of the maintenance management system. The factors that were observed to be examples of good management practices are listed with supporting evidence and data and thus conclusions as to the strengths of the system are identified. Similarly, the possible sources of the problems are also identified, documented and possible consequences if these problems are not tackled are also listed. Alternative strategies to overcome the problems are identified and evaluated to indicate the most suitable option for problem solving.

Report Submission: The audit team prepares a comprehensive report indicating the scope of the audit, methodology adopted, information gathered, analysis performed and recommendations arrived at as a result of the audit. Normally, a draft report is submitted to ascertain the feedback of the company management and the final report is submitted incorporating the suggestions and the feedback. The report submission is often accompanied by a direct presentation to the management/regulator agency where the action plans for implementation of the suggestions and the requirement of the involvement of the auditors further can also be discussed.

5.16 STUDY OF KEY RESULT AREAS

Maintenance management audit has to focus on both the results achieved and processes used to have holistic idea of the system efficiency and effectiveness. Given below are the major maintenance benchmarks, which need to be studied in the audit.

Maintenance Costs: Some of the major cost factors/ratios that need to be analysed are Total Maintenance Costs, Maintenance Cost To Budgets, Maintenance Cost For Unit Output, Maintenance Cost/Sales, Maintenance Cost/Asset Value and Contractor Cost Ratio to the Total Maintenance costs.

Maintenance Materials Management Performance: The factors/ratios related to maintenance materials (Spare parts) management performance are material consumption value to total maintenance cost value, inventory turnover, number of stock outs, material inventory value to equipment replacement value and purchase value to issue value.

Performance of Plant and Equipment Maintenance: The ratios that represent the plant and equipment maintenance performance are downtime ratio, spare parts/ consumables consumption ratio, redundancy in equipment, design life to replacement life ratio etc.

Maintenance Organization Performance: The organizational performance of maintenance management is measured by ratio of maintenance manpower to asset value, planned maintenance work to unplanned maintenance work, backlog by craft, maintenance to non-maintenance work, line to staff support ratio, percent jobs waiting, ratio of work order hours to standard hours etc. The customer service function of the maintenance department is measured by percent service calls attended, service response time, meantime to repair, and breakdown analysis reporting.

Maintenance Management Processes: Though maintenance benchmarks or performance parameters give the audit team a comparable idea about the status, due to the requirement of standard definitions for these ratios, sometimes it becomes difficult to draw careful conclusions. Hence the auditing processes now a days are concentrating on the process parameters to make evaluations more meaningful. These process parameters of maintenance management are listed below:

- **Vision and Leadership:** In the modern strategy oriented management processes, it is needless to emphasize that policy and goals enunciated by a clear vision and leadership of the top management is very essential. The characteristics of the leadership that are looked for in an ideal situation are clear goals and targets, allocation of enough resources, commitment to continuous improvement programmes and leading by examples.
- **Maintenance Organizational Structure:** The nature and style of the organizational structure plays an important role in the efficiency and effectiveness of the systems. The characteristics that are seen of a proper organization structure are lesser number of hierarchies, clear roles and accountability, delegation, empowerment and multiskilling environment.
- **Spare Parts Management Process:** The importance of materials management for optimization of maintenance can be gauged from the fact that about 50 to 60% of the maintenance costs are consumed by maintenance materials. There should be proper systems and procedures for inventory control, spares classification and codification, vendor management and spares preservation and reclamation.

IT Systems Usage for Maintenance: The maintenance function has invariably taken the assistance of information technology (known as computerized maintenance management systems – CMMS). An audit will look for ideal features in the CMMS systems, the extent of use of the system and the utilization of its fullest capabilities.

Preventive Maintenance System: The use of preventive maintenance should be in a pro-active manner to identify and correct equipment deficiencies in advance rather than re-active problem solving. The PM system should be checked for optimum deployment of resources vis-à-vis achievement of targeted equipment availability.

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Predictive Maintenance System: Use of modern condition monitoring systems and techniques like vibration analysis, infrared thermal inspections, ultrasonic, lube oil analysis are to be encouraged to dovetail the efforts of preventive maintenance systems to improve availability. Modern plants increasingly depend upon outsourced expert support for sophisticated predictive maintenance practices.

Maintenance Planning and Scheduling through Work Order System: The work order system, whether through computerized means or otherwise, should be carefully planned and implemented so that the system enables smooth performance of the maintenance requirements while simultaneously capturing necessary information for management analysis.

Operation–Maintenance Interface: Modern philosophies and techniques like Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) have made the requirement of Operation–Maintenance cooperation and interface an extremely important requirement continuous improvement and sustainable development.

SUMMARY

- In condition based maintenance (CBM) the equipment is maintained when measurements indicate an incipient failure. The condition of the machine may be determined continuously or at regular intervals by monitoring vibration, wear debris, temperature and performance parameters.
- RCM is a methodology as well as a philosophy, and it is not possible to define it with the help of one definition.
- RCM is a systematic approach for quantitatively assessing the need to perform or review preventive maintenance tasks and plans. It provides a methodology targeted on system functions, the failures relating to that function, and in particular to the effects of dominant functional system failures.
- RCM methodology has been successful in building up highly reliable systems.
- The origin of TPM can be traced back to 1951 when preventive maintenance was first introduced in Japan.
- TPM deals primarily with production equipment and is used in manufacturing industries, such assets are plant and machinery.
- TPM stands essentially for total involvement, or involvement of all employees at all levels, and also that for this purpose, right at the beginning of its development at the Nippondenso Company.

- It would be useful to understand these terminologies so that one is able to understand and appreciate their purpose and requirements for different situations.
- Maintenance management audit has to focus on both the results achieved and processes used to have holistic idea of the system efficiency and effectiveness.

REVIEW QUESTIONS

1. What is condition based maintenance?
2. What conditions should be satisfied so that condition based maintenance programme could be implemented?
3. What are the key steps involved in implementing condition based maintenance in any plant?
4. Explain condition-monitoring procedure with the help of a flow diagram?
5. What guidelines would you suggest for selecting critical machines for condition monitoring purpose?
6. How will you select condition-monitoring technique once a critical machine has been identified?
7. What is significant component?
8. What are the attributes of an ideal condition monitoring technique?
9. How will you fix severity limits for a particular monitoring parameter?
10. What should be the basis for fixing the periodicity of monitoring?
11. What should be the requirements for an ideal diagnostic-instrument operator?
12. What type of skill development courses will be more helpful for maintenance personnel for successful implementation of condition monitoring in any plant?
13. Why it is necessary to have planned maintenance management system in any plant for successfully implementing condition based maintenance?
14. Explain the basis of identifying and analyzing a problem, while making use of visual monitoring technique? Name some of the instruments used in visual monitoring?
15. Explain the basis of identifying and analyzing a problem, while making use of temperature monitoring technique? Name some of instruments used for temperature monitoring?
16. Explain the basis of identifying and analyzing a problem, while making use of wear debris monitoring technique? Name some of the instruments used for wear debris monitoring?
17. Explain the basis of identifying and analyzing a problem, while making use of vibration monitoring technique? Name some of the instruments used for vibration monitoring?

18. Discuss as how RCM can be helpful to maintenance manager in improving his job functioning?

19. "A well knit preventive and proactive maintenance is a prerequisite for implementing RCM". Discuss.

20. "RCM methodology focuses on the maintenance of functions rather than the equipment per se". Comment.

21. "Under RCM methodology, the problem is not failure at all, it is the consequences of failure". Discuss.

22. What are the objectives of Total Productive Maintenance? How does it differ from Total Preventive Maintenance?

23. What is a bath-tub curve? How can it be used in practice?

24. Discuss preventive maintenance. In what ways is preventive maintenance *absolutely necessary in JIT/ Kanban /pull manufacturing as opposed to push* manufacturing.

25. Discuss the significance of Age-specific failure rate.

26. Every day the chief of maintenance needs concise information concerning the maintenance function. What information does he require?

27. When are the following policies useful?

(*i*) condition monitoring

(*ii*) preventive replacement

(*iii*) replacement on failure

28. Are the jobs in maintenance department popular with the young engineering graduates? What would you suggest to make the maintenance function more *attractive?*

29. What are the big six losses? What is the importance of these loses?

30. *Calculate the availability, performance* rate and quality rate from equipment performance data.

31. If the trend of computerization process continues to grow, what would be its impact on the maintenance function?

32. Why are audits important for management systems?

33. What is the main difference between audits for Safety and Maintenance?

34. State reasons for your opinion as to whether Maintenance Audit should be mandated by law or not.

35. State the different types of audits that are possible in an enterprise.

36. What are the major differences between a management audit and technical audit?

37. What types *are overlaps you foresee* between different types of audits? How these can be overcome?

38. Differentiate between a Preliminary and Detailed audit?

39. Why should the maintenance function be audited?

40. 'Maintenance Audit helps in analyzing performance factors and suggest improvements'— Explain this statement with some examples.
41. Explain the steps involved in a 'Maintenance Audit'?
42. What preliminary preparations are required before a maintenance audit can be commenced?
43. How can be questionnaire for 'Maintenance Audit' prepared?
44. What difference lies in the plant visits taken up at the auditee's plant and a comparable plant?
45. Describe the salient features to be covered in a maintenance audit report?

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FURTHER READINGS

- **Comprehensive Maintenance Management: Policies, Strategies And Options:** Amit Telang and A.D. Telang, PHI Learning.