Condition-Based Maintenance and Residual Life Prediction

Edited By
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Kanwal Jit Singh, and Harleen Kaur

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Maintenance

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Abstract
In order to stay competitive, it is necessary for companies to continuously increase the effectiveness and efficiency of their production processes. Production strategies such as Justin-Time and Lean Production demand high availability of production equipment in order to meet customer satisfaction. Maintenance is a critical aspect of managing assets and ensuring their optimal performance and longevity. It involves a range of activities aimed at preserving, repairing, and optimizing equipment, systems, and infrastructure to minimize downtime, increase reliability, and reduce costs. This chapter provides an overview of maintenance practices, including preventive, corrective, and predictive maintenance, as well as their benefits and challenges.

***Keywords*:** Preventive maintenance, corrective maintenance, routine maintenance, scheduled maintenance, predictive maintenance, breakdown maintenance

1.1 Introduction and Meaning

Past and current maintenance practices in both private and government sectors would imply that maintenance is the action associated with equipment repair after it is broken. The dictionary defines maintenance as "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

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with the operation of the device to keep it in proper working order. 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. 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 a predefined life expectancy or operational life associated with it.

1.2 Need for Maintenance

The need for maintenance is based on the actual or imminent failure. Ideally, maintenance is carried out to keep equipment and systems running efficiently during at least its usual life cycle (Lai *et al.*, 2019). As such, the practical functioning of equipment is based on time. If you want to graphically represent the failure rate of a piece of equipment in relation to time, it is probable that the graphic will take the shape of a bathtub, such as the one shown in Figure 1.1, where the Y-axis represents the failure rate and the X-axis represents time. This curve can be divided into three periods: premature death, lifecycle, and exhaustion period.

The first period, the premature death, of the curve is characterized by a high rate of failure, followed by a decreasing failure period. Most of the failures related at this time are linked to bad design, bad installation, or wrong use. The premature death period is followed by a period with a nearly constant failure rate known as the lifecycle. There are many theories

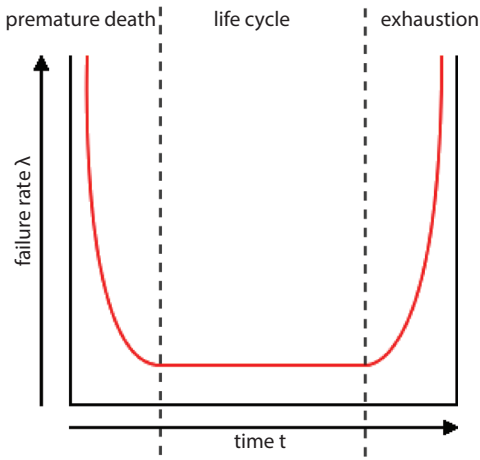

Figure 1.1 Product failure rate.

about why equipment fails in this time area. Most of them agree that poor preventive maintenance has often a key role. It is also generally agreed that exceptional practices related to predictive and preventive maintenance can extend this period. The exhaustion period is characterized by an increasing rate of failure. In most cases, this period includes a regular distribution of failures during the design life but in reverse (Jian *et al.*, 2021).

The lifecycle of most equipment needs periodic maintenance. If we use the example of a car, we could say that filters must be changed, front-end alignment must be maintained, oil change and proper lubrication are needed, and so on. In some cases, certain pieces need to be replaced, for example, the timing belt, to ensure the proper functioning of the main piece of the equipment, in this particular case, the car, once its design life has ended. Each time we do not carry out the maintenance activities planned by the designer, we shorten the operational lifecycle of the equipment.

1.3 Importance of Maintenance

• *Operator and Machine Safety*
By performing regular preventive maintenance, you will always be assured that your equipment will operate under safe conditions, both for the machine and the operators. Possible issues can be cut off before they cause any harm, without taking any chance.

• *Machine Efficiency*
With normal wear and tear, machines can cause lower efficiency. Proper preventive maintenance management will assure you of the optimal working conditions of the equipment and, moreover, conserve its life span.

• *Time Savings*
Planned preventive maintenance management will reduce the actual downtime caused by the breakdown and further enhance the products in less time, thereby saving a lot of time. Preventive maintenance will consume less time than emergency repairs and replacements.

1.4 Objectives of Maintenance

Equipment is an important resource that is constantly used for adding value to products. So, it must be kept in the best operating condition. Otherwise, there will be excessive downtime and also interruption of production if it is

used in a mass production line. Poor working conditions of equipment will lead to quality-related problems. Hence, it is an absolute necessity to maintain equipment in good operating conditions at an economical cost. Hence, we need an integrated approach to minimize the cost of maintenance. In certain cases, the equipment will be obsolete over a period of time. If a firm wants to be in the same business competitively, it has to decide on whether to replace the equipment or retain the old equipment by taking the cost of maintenance and operation into account (Stone *et al.*, 2020).

1.5 The Role of the Maintenance Department

Responsibilities of a Maintenance Department

1. Engineering and execution of planned maintenance: The responsibility for the continued economical use of the equipment lies with the operating supervisor. It is, however, the responsibility of the maintenance staff, in cooperation with the operating supervisors to organize preventive maintenance schedules and improve the equipment efficiency necessary to meet the production schedule requirements.
2. Generation and distribution of power and other utilities: The power engineer is responsible for the generation and distribution of utilities like steam and compressed air in suitable quantities, as well as the purchase and distribution of electrical power, water, etc., at minimum cost.
3. Stand-by power generation: Apart from purchasing electric power from electricity board (EB), if a stand-by diesel generator is available in the factory, the maintenance staff would be responsible for operating this generator and supplying sufficient power during power outages.
4. Administrative and staffing: To handle mechanical work involved in carrying out the functions of the maintenance department, an adequate skilled labor force, provided with suitable equipment and proper supervision, is necessary. The type and size of this group are determined based on a balance between the costs of establishing and maintaining the group versus the cost of contracting for the maintenance work to outside firms, considering the factor of emergency and round-the-clock service. It is the responsibility of the head of the maintenance department to plan and coordinate work

distribution among the crafts and to organize and carry out programs for the training of the supervisors and craftsmen.
5. Engineering and supervision of construction projects within the scope of the group: Maintenance engineering is a definite part of the preliminary and final design of construction projects. It is the responsibility of the maintenance group to be familiar with all the projects under consideration or execution that will eventually become a part of the plant.
6. Technical consultation: The maintenance engineer would act as a consultant to the production department in solving the mechanical problem of the equipment.
7. Plant safety activities and equipment: The provision and control of all safety equipment, their maintenance, and monitoring for the general observance of plant safety practices by all workforces in the plant, would be the responsibility of the maintenance department.
8. Plant insurance: Strategies for securing plant insurance and ensuring the preservation of all critical data and documents, as well as taking the necessary action in the event of accidents.
9. Service facilities: Engineering, administration, and maintenance of various service facilities delegated to the departments like yards, roadways, washing rooms, sewers and waste disposal sections, and employee welfare services within the budgets provided by the management.
10. Maintenance of plant and equipment records: Maintaining the property and all relevant records of all plant and equipment required for the annual accounts and audit.
11. Meticulous breakdown record-keeping for future maintenance planning: Keeping the breakdown record for each and every piece of machinery and equipment meticulously as required for future maintenance planning.
12. Efficient execution of all functions: Last but not least, performing all the above functions in a safe and efficient manner.

1.6 Responsibilities of a Maintenance Engineer

Reliabilityweb.com suggests the following functions for the maintenance engineer.

1. Ensures that the equipment is properly designed, selected, and installed based on the lifecycle philosophy.

2. Ensures that the equipment is performing effectively and efficiently.
3. Establishes and monitors programs for engine and compressor analysis, as well as vibration and other condition monitoring techniques.
4. Reviews deficiencies noted during corrective maintenance.
5. Provides technical guidance for the Computerized Maintenance Management System (CMMS).
6. Maintains and advises on the use and disposition of stock, surplus, and rental equipment.
7. Promotes equipment standardization, recommends spare part levels, and coordinates sharing of spare parts with other asset teams.
8. Becomes available for consultation with maintenance technicians.
9. Monitors new technology and keeps management and staff apprised of the new developments.
10. Champions quality assurance services including shop qualifications for outside services.
11. Develops standards and procedures for major maintenance jobs.
12. Periodically makes cost/benefit reviews of maintenance management programs for areas of responsibility and exchanges information across asset reams.
13. Providing technical guidance for preventive (PM) and predictive (PDM) maintenance programs.
14. Monitors competitors' activities in the field of maintenance management.
15. Becomes the focal point for monitoring performance indicators for maintenance management programs.
16. Optimizes maintenance strategies.
17. Becomes a focal point for analyzing equipment operating data, root cause analysis, and ultrasonic and vibration analysis.
18. Imparts maintenance training.

1.7 Principles of Maintenance

They are followed in a system to guide the staff to work efficiently and effectively to achieve the overall objectives of the maintenance system.

Plant management in maintenance work:
The main role of a maintenance function is to provide safe and effective operation of the equipment to achieve the desired targets on time with economic usage of resources.

Production and maintenance objectives:
The plant operation is driven by the production targets. The objective of the maintenance function is to support these targets. The achievement of the desired goals of the production system is to be supported by both the production and maintenance departments to ensure the smooth and successful operation of the industry.

Establishment of work order and recording system:
The maintenance system should have a proper work and recording system. The work order for the maintenance function indicates the nature of the work to be performed and the series of operations to be followed to execute a particular job. It is necessary to maintain proper records and entries to monitor the maintenance function.

Information-based decision-making:
The maintenance objectives are successfully achieved by the use of a reliable information system. This information is used to meet the manpower and spare parts requirements of the industry.

Adherence to planned maintenance strategy:
Sound maintenance management should adhere to the planned maintenance strategy. This also includes the use of manufacturer information on the life and maintenance schedules of the equipment and other material resources available.

Planning of maintenance function:
All the maintenance functions are to be carefully executed through proper planning to ensure the effective utilization of manpower and materials.

Manpower for maintenance:
The manpower requirement of the maintenance system must be carefully evaluated based on the time and motion study. The requirements should also satisfy the need arising in case of overhauls, component replacement, emergency, and unscheduled repair.

Workforce control:
Determining the exact workforce required to meet the maintenance objectives of the system is a difficult task due to the element of uncertainty. Hence, proper control and monitoring of the workforce needs to be ensured.

Role of spare parts:
A good maintenance management system requires appropriate tools. So, the system should have good quality tools available in the required quantities to ensure the proper function of the maintenance work.

Training of maintenance workforce:
Training of the workforce must be an integral part of any good maintenance management system. Training helps the workforce learn about modern techniques, and recent trends in maintenance and to chalk out a strategy to meet the growing demands of the industry.

1.8 Maintenance Planning

Planning maintenance jobs basically deals with answering two questions: 'What' and 'How' of the job, specifically, 'What activities are to be done?' and 'How those jobs and activities are to be done?' While answering these two questions, other supplementary questions are to be answered, e.g., 'Where the jobs are to be done?' and 'Why the job is to be done?', etc., as these will help in developing the 'What' and 'How' of the job. It is very essential that engineering knowledge must be extensively applied to maintenance jobs for the development of appropriate job plans using the most suitable techniques, tools, materials, special facilities, etc. (Braglia *et al.*, 2019). As job planning forms the basic foundations over which the efficiency and cost of actions depend, the persons responsible for job planning should have adequate capabilities, such as knowledge about jobs and available techniques, facilities and resources, analytical ability, conceptual logical ability, and judgmental courage.

Effective planning and scheduling significantly contribute to the following:

- Reduced maintenance cost.
- 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.

Planning Objectives

- Minimizing the idle time of maintenance workers.
- Maximizing the efficient use of work time, material, and equipment.
- Maintaining the operating equipment at a level responsive to the needs of production in terms of delivery schedule and quality.

Basic Levels of Planning Process (Depend on The Planning Horizon)

1. Long-range planning: It covers a period of three to five years and sets plans for future activities and long-range improvement.
2. Medium-range planning: It covers a period of one month to one year.
3. Short-rang planning: It covers a period of one day to one week. It focuses on the determination of all the elements required to perform maintenance tasks in advance.

1. Long Range Planning

It needs to utilize the following:

1. Sound forecasting techniques to estimate the maintenance load.
2. Reliable job standards times to estimate staffing requirements.
3. Aggregate planning tools such as linear programming to determine resource requirements. sets plans for future activities and long-range improvement.

2. Medium-Range Planning

- Specify how the maintenance workers will operate.
- Provide details of major overhauls, construction jobs, preventive maintenance plans, and plant shutdowns.
- Balance the need for staffing over the period covered.

- Estimate required spare parts and material acquisition.

3. Short-Range Planning

- Focus on determining all the elements required to perform maintenance tasks in advance.
- Assess required maintenance tools and skills needed for efficient maintenance of equipment.
- Assess skills required for maintenance personnel.
- Review personnel transfers to and from maintenance organizations assessing and reporting safety hazards associated with the maintenance of equipment.
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- Review personnel transfers to and from maintenance organizations.
- Assess and report safety hazards associated with the maintenance of equipment.

1.9 Management Organization and Structures

• Manning Levels
Manning levels will be dependent upon factors such as asset numbers and types, skill levels, out-sourcing levels, productivity levels, or rosters.

• Technicians
The primary technician skill groups are electricians and mechanical fitters. There may be boilermakers and welders depending on the site and the need. Such staff are responsible for the physical implementation of the maintenance task upon an asset. Remotely-located sites, where the contractors and services have limited availability, will usually use more in-house staff.

• Non-Technical Assistants
Unskilled, non-technical assistants or laborers are also used to assist the skilled staff and/or perform non-technical tasks. Often, operations staff are used for this assistance.

• Procurement and Inventory Management
Often, the engineering department manages the store's inventory and procurement functions, although at some sites the procurement function is done by the finance department. Procurement management is responsible

for maximizing value when purchasing items and ensuring that required items are on hand when needed. Store management is responsible for receiving and issuing items, stock control, store housekeeping, and also ensuring that required items are on hand when needed.

- Planning and Maintenance Data Management

Preventive maintenance practices require considerable planning and scheduling of related activities. There needs to be some capacity within the department to plan and monitor jobs and activities effectively.

- Supervision

Front-line supervision is required to manage the day-to-day activities during a shift, such as timekeeping, day-to-day job planning, liaising with the operations department on a shift basis, allocating jobs to staff, monitoring workflow, coaching and developing, and shift reporting. In the future, it is likely that more responsibility will be devolved to staff (tradespeople/technicians, etc.).

- Maintenance Management

Maintenance management is responsible for managing the department and takes overall responsibility for an asset's lifecycle during its operating life (Alnaggar and Pitt, 2019). Apart from overseeing the maintenance staff, maintenance management usually develops and manages the maintenance budgets, sets targets, makes decisions about what needs to be done, and looks at longer-term strategies.

- Engineering Support

There will usually be people within the engineering management group who can provide engineering support and technical assistance in mechanical and electrical disciplines. They will assist with day-to-day issues as well as project work.

- Quality Control

Often performed by supervision or could be done by peers. However, quality control of completed work is often overlooked.

- Training

All personnel should be trained and competent as appropriate. Management and supervision are responsible for assessing training needs. Often, adequate training is overlooked. Training should be given by in-house or external people depending on requirements.

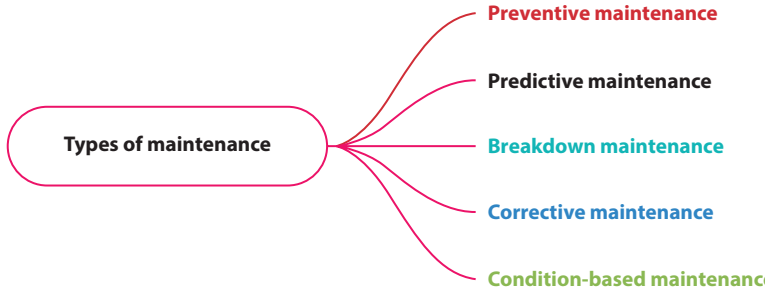

Figure 1.2 Types of maintenance.

1.10 Types of Maintenance (Figure 1.2)

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 (Mustafa, 2021). 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) lasts for its design life. Different approaches have been developed to know how maintenance can be performed to ensure equipment reaches or exceeds its design life. In addition to waiting for a piece of equipment to fail (reactive maintenance), the other approaches are preventive maintenance, predictive maintenance, or reliability-centered maintenance (Poór *et al.*, 2019).

1.10.1 Breakdown (Reactive) Maintenance

Breakdown 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 (Lucke, 2022). Recent studies indicate that this is still the predominant mode of maintenance. The advantages of breakdown 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 or incur capital costs until something breaks. Since we do not see any associated maintenance cost, we could view this period as saving money. In reality, during the time we believe we are saving maintenance and capital costs, we are really spending more money than we would have under a different maintenance approach. We are spending more money associated with capital costs because, while waiting for the equipment to break, we are shortening the life of the equipment resulting

in more frequent replacement. We may incur costs upon failure of a primary device associated with its failure causing the failure of a secondary device. This is an increased cost that we would not have experienced if our maintenance program had been more proactive. Our labor cost associated with the 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 online quickly, we will have to pay maintenance overtime costs. 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 (Mishra and Tyagi, 2022).

Advantages

1. Involves low-cost investment for maintenance.
2. Less staff is required.

Disadvantages

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

1.10.2 Preventive Maintenance

Preventive maintenance can be defined as, "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." Preventive maintenance is a means to increase the reliability of their equipment (Okpalaobi *et al.*, 2022). By simply expending the necessary resources to conduct maintenance activities intended by the equipment designer, equipment life is extended and its reliability is increased. In addition to an increase in reliability, a lot of amounts will be saved over that of a program just using reactive maintenance. Studies indicate that these savings can amount to as much as 12% to 18% on average.

Advantages

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

Disadvantages

1. Catastrophic failures are still likely to occur.
2. Labor intensive.
3. Includes performance of unneeded maintenance.
4. Potential for incidental damage to components in conducting unneeded maintenance.

Depending on the facility's 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 optimal 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.

Preventive maintenance (lubrication, filter change, etc.) will generally run the equipment more efficiently resulting in dollar savings. While we will not prevent catastrophic equipment failures, we will decrease the number of failures. Minimizing failures translates into maintenance and capital cost savings (Karki *et al.*, 2022).

1.10.3 Predictive Maintenance

Predictive maintenance can be defined as "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's physical state. Results indicate current and future functional capability" (Fermín-Cueto *et al.*, 2020).

Basically, predictive maintenance differs from preventive maintenance by basing maintenance needs on the actual condition of the machine rather than on some preset schedule. 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 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 tasks based on quantified material/equipment condition.

There are many advantages to predictive maintenance. A well-orchestrated predictive maintenance program will eliminate catastrophic equipment failures (Dalzochio *et al.*, 2020). A schedule of maintenance activities can be made to minimize or delete overtime costs. It is possible to minimize inventory and order parts, as required, well ahead of time to support the downstream maintenance needs and optimize the operation of the equipment, saving energy costs and increasing plant reliability. Past studies have estimated that a properly functioning predictive maintenance program can provide 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%. Independent surveys indicate the following industrial average savings resultant from the initiation of a functional predictive maintenance program:

1. Return on investment—10 times
2. Reduction in maintenance costs—25% to 30%
3. Elimination of breakdowns—70% to 75%
4. Reduction in downtime—35% to 45%
5. Increase in production—20% to 25%.

Advantages

1. Increased component operational life/availability.
2. Allows for pre-emptive corrective actions.