Maintenance Engineering and Maintainability: An Introduction

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Abstract: Maintenance is another important aspect of system performance after reliability. There are several facets of the the maintenace management and in this introductory chapter, we would like to have these surveyed. Broadly speaking, maintenance is the process of maintaining equipment in its operational state either by preventing its transition to a failed state or by restoring it to an operational state following a failure. This leads to various types of maintenace activities that can be planned to realize the objective of maitenance, such as preventive, predictive or corrective. Recent developments in the maintenace engineering and management are also discussed in this chapter.

46.1 Introduction

The Oxford dictionary meaning of "to maintain" is to "cause something to continue" or "to keep something in existence at the same level". Therefore, maintenance does extend the useful life of a product or system. Also the necessity of "upkeep" arises to oppose the forces of degradation. The degradation can be due to deterioration caused by environment to which the equipment is exposed or due to deterioration of equipment arising from its actual use. From British Standard BS4778-3.1:1991 or BS 3811:1993 (or MIL-STD-721B), one settles for the definition of maintenance as: "Maintenance is the process of maintaining an item in an operational state by either preventing a transition to a failed state or by restoring it to an operational state following failure". Therefore, the primary aim of maintenance system is to prolong the state of functioning of equipment or a system by not allowing it to deteriorate in condition.

There is an interesting philosophical paper by Rao [25], who postulates 14 laws for the subject of universal theory of failures. But more interesting and of concern to maintenance engineers is the section on anatomy of failures in this article, which makes it an interesting reading, particularly in relation to fault and failure and the warning time to failures as catastrophic failures do not occur instantaneously without a warning time. This allows us to take proactive measures to avoid them.

46.1.1 Maintenance System

An effective maintenance system involves three separate entities of work, *viz.*, maintenance, inspection and verification, which can be done by different groups in the same company or different companies specifically subcontracted for the purpose.

Maintenance Task: Maintenance tasks [12,13,15] are generally of two types, *viz.*, *planned* and *unplanned*. The *planned maintenance* can be *preventive* or *corrective* (including deferred maintenance) whereas the *unplanned maintenance* is mainly *corrective*, which includes any *emergency maintenance*. Again the preventive maintenance can be *scheduled maintenance* and the other can be based on condition of the equipment- known as *condition-based maintenance*. Therefore, the form of the maintenance can be:

1. *Pre-planned maintenance:* This includes early maintenance tasks such as cleaning, greasing, lubricating, zero-setting and recording key measurements. This is often conducted by non-maintenance staff and observed equipment deterioration that cannot be corrected will be reported to regular maintenance staff. This is also called First-line maintenance.
2. *Planned maintenance:* This is also known as scheduled maintenance and its timing and scope are both known in advance.
3. *Shutdown maintenance:* It is a planned maintenance but is carried out when production or plant is shut down.
4. *Breakdown maintenance:* This is carried out when equipment fails to meet its desired function. This may involve repairs, replacements or adjustments as considered necessary.
5. *Emergency maintenance:* This is carried out only when either inspection or breakdown maintenance has identified its necessity.

Inspection: All plant machines, equipment and structures are subjected to regular inspection scheduled to detect performance or safety problems and to ensure that all items receive necessary maintenance.

Verification: Verification is a process, not a measurement, and it has two primary objectives:

- To check that the maintenance work is being done
- To confirm that maintenance standards have not been compromised.

Verification is usually done or supplemented by (in addition to in-house verification) a third party (to be completely impartial or fair). One of the key parameter to verify if the maintenance was up to the standard is to determine availability of the system since the maintenance is result dependent and the test lies in *effectiveness* than *efficiency*.

46.1.2 Maintenance Philosophy

Based on the timing and the work contents involved in the maintenance task, different maintenance philosophies [13, 15] can be put in the following categories. *viz.*,

1. Timing known, Content known: Preplanned Maintenance (PPM), Planned Shut downs, Routine Inspections, Schedules Change-outs fall in this category.
2. Timing known, Content unknown: Statutory Surveys, Third Party Inspections, Condition-based maintenance
3. Timing unknown, Content known: Anticipated Maintenance work, Contingency work awaiting shutdown, Run to destruction
4. Timing unknown, Content unknown: Breakdown maintenance, immediate Repairs arising from inspection, Run to failure.

From the point of view of work management, activities falling in category 1 are most welcome and in category 4 are least welcome. It is always advantageous to shift work to a more manageable category. By using effective maintenance regime, the intention should be to keep category 4 as empty as possible. it is worthwhile to observe that in “run to failure”, in which equipment is run till it fails and repairs are carried out but work content is unknown. However, in “run to destruct” category, in which equipment is run till it fails and is discarded, a replacement is required thus work content is known. Also by careful evaluation of maintenance histories and shutdown programmes the timing uncertainty in category 3 can be minimized. Such work followed by full job preparation can provide a fast response when situation finally requires it. Also the requirements in category 2 can be anticipated with care once operations are routinely established.

Out of all maintenance work preplanned maintenance (category 1) is most widely used but it is often argued that this method requires work to be done that is not necessary since it is done on the basis of calendar irrespective of machine condition.

Run to destruct (category 3) the equipment is usually used until it fails and is discarded or replaced. The works requires switching off the machinery or isolate it, remove or replace the old unit and connect the new unit. Work management is straight forward as materials technical content is all known.

Breakdown maintenance (category 4) is simple and can be applied quickly with limited resources and information but work arising from unexpected breakdown is difficult to manage and may involve high costs. Breakdown maintenance is not safe and may sometimes involve danger to life.

46.1.3 Maintenance Scope Changed with Time

Over the past several decades starting from the pre-World War II period, the concept and scope of maintenance has changed considerably, more than any other management discipline. These changes can basically be attributed to the advent of more complex designs of systems requiring new maintenance techniques.

This is resulting in change in the concept of maintenance organization and responsibilities. There is a tremendous increase in the number, size and variety of physical assets (plants, equipment and buildings), which have be maintained.

There is a rapidly growing awareness of product quality affecting maintenance activities and of the extent to which equipment failure can affect safety and the environment, coupled with the requirement of achieving high plant availability at reduced costs. With the increase in complexity and sophistication, coupled with organizational changes have resulted in changes the maintenance work is carried out today. These changes are testing attitudes and skills in all sectors of industry to their limits. Management and engineers [7,11] are beginning to adopt completely new ways of thinking and strategies towards maintenance, so that they can evaluate them sensibly and apply those likely to be useful to them and their companies. In fact, the changes that have taken place during this period are well documented by Moubray [14], who split this period into three distinct periods (which Moubray [14] calls as *generations I, II and III*) and are summarized in Table 46.1.

Table 46.1: Changing Maintenance Requirement over Time

Characterized by	Period		
	From 1930 to 1950	From 1950 to 1975	From 1975 to present
Expectations of Maintenance	-Failure-based Maintenance	-Higher Plant Availability -Longer equipment Life -Lower Costs	-Higher Plant Availability and reliability -Greater Safety and Better Quality -Environmental friendly -Longer Life -Greater Cost Effectiveness
Pattern of Failure	Old Age Failures	Infant Mortality and old Age	Various Patterns of Hazard Rates
Maintenance Techniques	-Reactive Maintenance -Fix it when it broke	-Calendar-Based Maintenance -Scheduled Overhauls -Systems for planning and controlling work - Big but slow computers	- Condition Monitoring -Design for reliability and maintainability -Hazard Studies -Small but fast computers -Expert Systems -Multi-skilling and teamwork

During the period 1930 to 1950 (first generation), industry was not so mechanized, so downtime did not matter much to them. The maintenance was conducted only when equipment actually failed. The work was more “fix it” than maintenance. Moreover, most equipment was simple and was usually over-designed, which made it reliable and easy to repair. This meant that the prevention of equipment failure was not considered their priority by the management. Therefore, there was no need for systematic maintenance [2,14] of any sort beyond occasional cleaning, servicing and lubrication. Obviously, the skill requirement was also lower than it is today.

But things did change dramatically during and after the World War II. Wartime pressure accelerated mechanization and by 1950's, machines became more complex and numerous. As the industry became more and more dependent on them, the concern for the uptime of these machines became the priority of the industry and the management considered it advantageous and in their interest to prevent equipment failures. This became the rallying point for the concept of preventive maintenance with the realization that performing regular maintenance and refurbishment could keep equipment operating longer between failures. This came to be known as *Periodic Maintenance*, or *Calendar Based Maintenance* or *Preventive Maintenance* (PM). The goal was to have most of the equipment be able to operate most of the time until the next scheduled maintenance outage. This approach provided more control over the maintenance schedule; however, the system was still susceptible to failure between maintenance cycles.

However, even by 1960's, this concern was mainly confined to the overhauls of equipment done at fixed intervals. But as the cost of maintenance increased the necessity of maintenance planning and control systems was felt. In fact, the amount of capital tied up in fixed assets increased enormously and the necessity of maximizing the life of these assets was felt more acutely.

As the downtime reduced output, it affected the productive capability of physical assets by increasing operating costs and interfering with customer service and by 1970's, this was further aggravated by the worldwide move towards just-in-time systems, where reduced stocks of work-in-progress meant that quite small breakdowns could stop the whole plant. Instead of waiting for a machine to fail before working on it, or performing maintenance on a machine regardless of its condition (PM), the idea of performing maintenance on equipment only when it indicates impending faults – *Predictive Maintenance* (PdM) – took hold and the idea of using PdM to perform maintenance on machines only when they exhibit signs of mechanical failure had come to be known as *Condition Based Maintenance* (CBM). This process of maintenance has become more *proactive* than *reactive* in their maintenance tasking.

However in recent times with extensive automation, reliability, availability and safety of production processes have become serious issues as the failures can affect our ability to sustain satisfactory quality standards and may have severe environmental consequences. This necessitates the integrity of our physical assets - one which goes beyond cost and becomes a matter of survival for the organization. Today, as the dependence on physical assets is growing, to secure maximum return on their investment, they must be kept in efficiently working condition for as long as we can.

Moreover, the cost of maintenance is also rising, in absolute terms and as a proportion of total expenditure. In some industries, it is the highest or the second highest element of operating costs. Consequently, in last thirty years it has moved from almost nowhere to the top of the cost control priority. Also it is becoming apparent that there is less and less connection between the operating age of the assets and how likely they are to fail.

In recent times, there has been tremendous growth in the maintenance concepts and techniques. The change in emphasis includes:

- Decision support tools, such as hazard studies, failure modes and effects analyses and expert systems
- New maintenance techniques, such as condition monitoring or CMMS
- Designing equipment with emphasis on reliability and maintainability

- A major shift in organizational thinking towards participation, team-working and flexibility.

A major challenge facing maintenance people nowadays is not only to learn what these techniques are, but to decide which are worthwhile and which are not in their own organizations. If we make the right choices, it is possible to improve asset performance and at the same time contain and even reduce the cost of maintenance. If we make the wrong choices, new problems are created while existing problems only get worse.

In fact RCM provides a framework which enables users to respond to these challenges, quickly and easily. Since every physical asset is put into service because someone wants it to do something, they expect it to fulfill a specific function or functions. When an asset is maintained, obviously the state we wish to preserve is the one in which it continues to do whatever its users want it to do.

Of recent, emphasis is being placed on *core business* by several major companies of the world and under this thinking; companies are transferring previously in-house functions to external specialist companies. Use of experts or specialists and reasons for choosing *in-house* teams *on-site* accommodated teams or *manned-up* technicians brought from outside for the completion of a job, is becoming routinely common these days. Subcontracting for maintenance job is also becoming quite common in the globalizing world of trade these days and the number and size of companies engaged in maintenance work is growing very fast.

46.2 Approaches to Maintenance

There are several approaches to maintenance, and different approaches are applicable based on the expected use and maintenance schedule of an item. Economic considerations are tightly related to maintenance and system lifecycle; it is clear that failure to consider design's effects on maintenance, and vice versa, can have adverse affects on profit. Therefore, design and maintenance must be simultaneously planned in order to ensure an efficient and cost-effective operation over the life of a product.

Maintenance has been categorized based on the nature and purpose of the maintenance work and its frequency. Generally, there are four types of maintenances in use, *viz*., preventative, corrective, predictive and fault-finding.

Maintenance can also be classified according to the degree the maintenance work is carried out to restore the equipment in relation to its original state. This leads to the following categorization:

Perfect Maintenance: is one which restores the equipment to *as good as new* condition.

Minimal Maintenance: results in equipment having the same failure rate as it had before the maintenance action was initiated. This is called- *as bad as old* state.

Imperfect Maintenance: is one in which the equipment is not restored to *as good as new* but relatively *younger* (a state in between *as good as new* and *as bad as old*).

Worse Maintenance: This type of maintenance results (unintentionally) in an increase of equipment's failure rate or actual age but does not result in break down.

Worst Maintenance: This type of maintenance results (unintentionally) results in equipment's breakdown.

In the foregoing classification maintenance can be preventive (PM) or corrective (CM) and accordingly the PM or CM would be belong to one of the above categories. The have been discussed in nicely in several texts [20, 22, 24].

In this handbook, we have included Chapter 47 and Chapter 48 on some aspects of maintenance modelling and optimization as well as on the trends on maintenance technology and management.

46.2.1 Preventive Maintenance

Preventative maintenance, as the name itself indicates, is a schedule of planned maintenance aimed to prevent future breakdowns and failures of a system that is functioning properly. In fact, preventive maintenance is performed to prevent equipment failure before it actually occurs and to keep the equipment working and/or extend the life of the equipment. Usually, it is performed on equipment on a regular basis based on the expected life of the equipment and the frequency of the maintenance is generally constant. Preventive maintenance is a schedule of planned maintenance actions aimed at the prevention of breakdowns and failures since the primary objective of preventive maintenance is to prevent the failure of equipment before it actually occurs. For example, lubrication of mechanical systems is done after a certain number of operating hours or replacement of lightning arresters in jet engines after a certain number of lightning strikes. It is designed to enhance the equipment reliability by replacing worn components before they actually fail. Preventive maintenance activities include equipment checks, partial or complete overhauls at specified periods, oil changes, lubrication and so on. In addition, workers can record equipment deterioration so they know which worn out parts to replace or repair before they can cause system failure. The technological advances in tools for inspection and diagnosis have enabled even more accurate and effective equipment maintenance. The ideal preventive maintenance program would prevent *all* equipment failure before it occurs.

Preventive maintenance [17] is a logical alternative of choice if the following two conditions are satisfied:

- The equipment in question has an increasing hazard rate. In other words, the hazard rate of the equipment increases with time, implying a wear-out situation Preventive maintenance of a component that is assumed to have an exponential distribution (which implies a constant failure rate) does not make sense!
- The overall cost of the preventive maintenance action must be less than the overall cost of a corrective action. The overall cost for a corrective action includes ancillary tangible and/or intangible costs, such as downtime costs, loss of production costs, lawsuits over the failure of a safety-critical item, loss of goodwill, *etc*.)

As stated earlier, if the unit has an increasing failure rate, then a carefully designed preventive maintenance program may improve system availability. Otherwise, the costs of preventive maintenance might actually outweigh the benefits. It is important to make it explicitly clear that if a component has a constant failure rate (*i.e*. defined by an exponential distribution), then preventive maintenance of the component will have no effect on the component's failure occurrences.

In fact, the objective of a good preventive maintenance program is to either minimize the overall costs (or downtime, *etc*.) or meet a reliability/ availability goals. In order to achieve this, an appropriate interval of time must be determined for the scheduled maintenance. One way to do that is to use the optimum age replacement model, where the model satisfies the conditions mentioned previously, *viz.*,

- The unit is exhibiting behavior associated with a wear-out mode. That is, the failure rate of the unit is increasing with time.
- The cost for planned replacements is significantly less than the cost for unplanned replacements.

Long-term benefits of preventive maintenance include:

- Improved system reliability.
- Decreased cost of replacement.
- Decreased system downtime.
- Better spares inventory management.

Thus long-term effects and cost comparisons usually favor preventive maintenance over performing maintenance actions only when the system fails.

46.2.1.1 Maintenance Policies

The literature is full of numerous maintenance models [22] that have been presented by researchers using various assumptions and cost structures but all of them can be broadly categorized under certain maintenance policies. These policies, however, are with regard to single equipment.

Age-dependent PM Policy: Under this policy, PM is carried out at some predetermined age or repaired (CM) upon failure. PM or CM can be perfect, minimal or imperfect.

Periodic PM Policy: Under this policy, equipment’s PM is carried out at fixed time intervals regardless its failure history.

Failure Limit Policy: Under this policy the PM is performed only when the failure rate (or some index of performance) reaches a predetermined level and the intervening failures are repaired when they occur.

Sequential PM Policy: Under this policy, equipment's PM is carried out at unequal time intervals, which go on becoming shorter with the age.

Repair Limit Policy: Under this policy, two cases arise, *viz., repair cost limit policy* and the other is *repair time limit policy*. Under the former, the repair cost is assessed when the equipment fails and repair is performed only if the repair cost is less than a predetermined limit, otherwise the equipment is replaced, whereas under the repair time limit policy, the limit is set on the repair time instead of cost.

Repair Number Counting Policy: Under this policy, the equipment is replaced at k^{th} failure and the first *(k-1)* failures are removed by minimal repair. Upon replacement the process repeats.

As said before, the foregoing maintenance policies were applicable to single equipment with increasing failure rate. Recently, there has been increasing interest in multi-equipment maintenance models. In fact maintenance of a multi-equipment system differs from that of single equipment in that there exists *economic* or *failure* dependence. Due to former, the PM non-failed subsystems can be performed at reduced cost while the failed subsystems are being repaired. In case of failure dependence or *correlated failures*, failure of one of the subsystem may affect the functioning of other subsystems. In case of a system with number of subsystems or equipment, the following maintenance policies are applicable:

Group Maintenance Policy: Under this policy there are three different cases:

T-Age group Replacement Policy: The units or equipment are replaced when the system is of age m-Failure group policy: this calls for a system inspection after m- failures have occurred

m-Failure and *T-Age Policy*: This policy combines the advantages of *m*-failure and *T-age* policy and calls for a group replacement when the system is of age *T* or when *m*-failures have occurred, whichever comes first. This policy requires inspection at either the fixed age *T* or the time when m-failures have occurred, whichever comes first. At inspection, all failed equipment are replaced with new ones and all functioning equipment are serviced so that they become as good as new.

Opportunistic Maintenance Policies: Under this policy in multi-component system, it is possible to do PM of non-failed equipment at a reduced additional cost while failed equipment is being repaired. There are many variations the in strategy under this category.

Warranty Models: Maintenance needs to be incorporated in the warranty models so that if warranted equipment fails, the failed components that caused the equipment failure will be replaced and in addition PM can be carried out to reduce the chances of failure in future. Therefore, warranty policies [23] with integrated PM should be preferable.

It can easily be shown that the corrective replacement costs increase as the replacement interval increases. In other words, the less often we perform PM, the higher will be the corrective costs. Obviously, the longer we let a equipment operate, its failure rate increases to a point where it is more likely to fail, thus requiring corrective actions. However, just the opposite is true for the preventive replacement costs. The longer we wait to perform PM, less shall be the costs. On the other hand, if we do PM too frequently, the costs would go up. If we combine both costs, it is easy to realize that there is an optimum point that minimizes the costs. In other words, one must strike a balance between the risk (costs) associated with a failure while maximizing the PM interval analysis.

Generally, preventive maintenance (PM) is considered beneficial but it must be mentioned that there are risks of equipment failure and human errors committed while performing PM, just as in any other maintenance operation. This logic dictates that it would cost more for regularly scheduled downtime and maintenance than it would normally cost to operate equipment until repair is absolutely necessary. This may be true for some components; however, one should compare not only the costs but the long-term benefits and savings associated with preventive maintenance. Without preventive maintenance, for example, costs for lost production time from unscheduled equipment breakdown will be incurred. Also, preventive maintenance results in savings due to an increase of effective system service life.

There are several excellent references available for preventive maintenance modelling and analysis but the books by Nakagawa [20], Wang and Pham [22] and Jardine and Tsang [24] stand out distinctly. The book by Jardine and Tsang [24] presents different optimal replacement policies and models, spare parts provisioning besides discussing optimal inspection policies under various conditions. Besides capital equipment replacement decisions and maintenance resource requirements are also presented. Nakagawa and Wang and Pham [20,22] describes perfect and imperfect preventive maintenance models and several optimum preventive maintenance policies. Inspection models with different types of units such as standby, storage and different types of failures such as extended failures (catastrophic, partial or degraded) and intermittent failures. Faults revealed or unrevealed are also considered. In fact both these books present an up-to-date status of various models that have been available so far.

In this handbook, we have included Chapter 49 by Nakagawa on Replacement and Preventive Maintenance models.

46.2.2 Predictive Maintenance

Predictive maintenance (PdM) or condition based maintenance (CBM) is carried out only after collecting and evaluating enough physical data on performance or condition of equipment such as temperature, vibration or particulate matter in oil *etc*. by performing periodic or continuous (on-line) equipment monitoring. Analysis is then performed on the collected data to prepare an appropriate maintenance plan. PdM technologies used to collect information of equipment condition can include infrared, acoustic (partial discharge and airborne ultrasonic), corona detection, vibration analysis, sound level measurements, oil analysis and other specific online tests.

The basic aim in PdM [18] is to perform maintenance at a scheduled point in time when the maintenance activity is most cost effective but before the equipment fails in service. Most PdM inspections are performed while equipment is in service, thereby minimizing disruption of normal system operations. This type of maintenance is generally carried out on mechanical systems where historical data is available for validating the performance and maintenance models for the systems and the failure modes are known. Predictive maintenance (PdM) helps determine the condition of in-service equipment in order to predict when maintenance should be performed. The *predictive* component of the term predictive maintenance comes from the goal of predicting the future trend of the equipment's condition. This approach uses principles of statistical process control to determine at what point in the future maintenance activities will be appropriate.

In fact, for condition monitoring or predictive technique any relevant means is acceptable to determine equipment condition, and to predict potential failure, which may even include the use of the human senses (appearance, sound, feel, smell *etc*.), machine performance monitoring, and statistical process control techniques. But the other sophisticated technologies used in monitoring include:

- Vibration Measurement and Analysis
- Acoustic Emission (Ultrasonics)
- Oil Analysis
- Infrared Thermography
- Motor Current Analysis

These will be explained in some details in the following paragraphs.

46.2.2.1 Vibration Measurement and Analysis

This technology owes its popularity to Fast Fourier Transform (FFT) technique developed in 1964, when spectrum analyzers became available that could be used with special transducers to measure machine vibrations. When portable FFT-based data collectors became available around 1980, the use vibration as a tool for machinery fault diagnosis went a sea change and found its applications in the petrochemical, electrical power, paper and other process industries. Today, *On-line Vibration Analysis System* (rather than portable analyzers) is widely used for monitoring vibrations with piezoelectric accelerometers as vibration probes and computer-based specialized data acquisition systems for collecting, storing and archiving FFT data. The on-line dynamic vibration monitoring system enables mechanical fault detection at the earliest detectable time. But the system installation costs are usually high because of the capital cost of the hardware as well as the installation labour. However, vibration analysis is the most appropriate solution on high speed rotating machines and can be the most expensive part of a PdM program. It still remains the most widely used method for detecting rubbing in rotating machines such as electrical power generating turbines through changes in amplitude and phase of the 1X (rotating frequency) vibration component.

46.2.2.2 *Acoustic Emission*

Acoustic emission (AE), particularly, for bearing diagnosis is becoming quite indispensable. Sometimes acoustical analysis may also be done at sonic or ultrasonic levels. Sonic technology is useful for mechanical equipment whereas ultrasonic equipment is useful for detecting electrical problems. Ultrasonic testing is a relatively new predictive technology. It is capable of detecting sounds that lie outside the human hearing range, and are indicators of failing mechanical conditions. As a result, ultrasonic testing has become an essential part of predictive maintenance program. Ultrasonic inspections can help detect leaking gases or fluids in heat exchangers, compressors, and valves. This technique not only locates leaks in steam traps and valves, but can also be helpful in detecting certain electrical faults, such as arching and corona.

46.2.2.3 *Oil Analysis*

Oil analysis in relevant cases can be more reliable technique in predictive maintenance. The early use of oil analysis dates back to the early 1940s by the railway companies in the Western United States, where the technicians used simple spectrographic equipment and physical tests to monitor locomotive engines. When diesel locomotives came in use, oil analysis practices by railways became very frequent. By the 1980s oil analysis formed the basis of condition-based maintenance (CBM) in most railways in North America.

Lubricating oil contains a good deal of information about the envelope in which it circulates. Wear of metallic parts, for example, produces a lot of minute particles, which are carried by the lubricant. Wear means the loss of solid material due to the effects of friction of contacting surfaces. These small metal particles can give information about the machine parts that are wearing, and can be detected by various methods, such as atomic emission spectrometry. Determination of larger particles can be done using optical or electronic microscopy, or ferrography. The acidity of oil can indicate whether the oil has been oxidized as a result of operation at high temperature, if there is a high percentage of moisture, or due to oil having been in service for long.

The viscosity of the oil is also an important parameter and must be in conformity with the requirements of the machine. The alkalinity or the loss of alkalinity of the oil proves that the oil is in contact with some inorganic acids such as sulphuric or nitric acid. Oil undergoes destructive changes in property when it is subjected to oxygen, combustion gasses and high temperatures. Viscosity change, as well as additive depletion and oxidation occur to degrade the oil.

Several methods are used to analyze oil condition and contamination. These analyses may include spectrometry, viscosity analysis, dilution analysis, water detection, acid number assessment, base number assessment, particle counting, and microscopy. Oil and wear particle analysis is a combination of spectrometric, ferrographic, and filter analysis. Oil and wear particle analysis can detect abnormal wear modes particularly in aviation systems, long before the wear can cause any serious damage.

The oil data modelling and analysis can be of great help in fault detection procedure and we have included Chapter 50 in this handbook on this aspect.

46.2.2.4 Infrared (IR) Thermography

Infrared (IR) thermography is used to detect temperature changes in bearings and shafts. The IR thermographic analysis detects abnormal temperatures that may signify corrosion, damaged wiring, loose connections, and/or insulation breakdown and hot spots. Infrared monitoring and analysis help reduce unexpected electrical and mechanical equipment (from high to low speed equipment) failures. This vital information can alert in advance of the catastrophic failures and is considered cost-effective technique of monitoring.

46.2.2.5 Motor Current Analysis

Motor Diagnostic technologies have become more prevalent through the 1990's in recent time. The technologies include: Motor Circuit Analysis (MCA) and Motor Current Signature Analysis (MCSA) applied to both energized and de-energized electric motor systems. Motor current analysis techniques are non-intrusive methods of detecting mechanical and electrical problems in motor driven rotating equipment. Motor Current Monitor (MCM) uses the electric motor of the equipment as a sensor and the information about the equipment is extracted from the line current of the motor. The MCM first learns the motor-based system for a certain period of time and acquires and processes the motor data. These data are stored in the internal database and a reference model, which consists of parameters and their means and standard deviations, is established. Now, during actual monitoring the data being acquired is compared with the results stored in the internal database. If the acquired data is significantly different from the reference model, it indicates a fault level that is determined by the magnitude and the time duration of the difference. This approach is used for diagnostics of electrical equipment, especially with rotating components. The main advantages lie in its being a noninvasive methodology for diagnosing health and operations of motor-actuated valves, generators, electric motors, and other types of electric equipment.

With new, inexpensive RF components and integration techniques, along with advances in microprocessor technology, it is possible to provide an economic solution for wirelessly monitoring motor operating parameters - such as temperature, vibration, current, *etc*. - for all classes of motors. The generic technology will find applications in areas where motors, pumps, gearboxes or drive chains need to be monitored on a continuous basis, such as fluids processes in chemical industries, motor generator systems, serial trunk conveyor systems, and general line production in manufacturing industries.

Motor Current Signature Analysis (MCSA) is a technique used to determine the operating condition of AC induction motors without interrupting production. MCSA techniques can be used in conjunction with vibration and thermal analysis to confirm key machinery diagnostic decisions.

MCSA works on the principle that induction motor circuits can actually be viewed as a transducer. By clamping a Hall Effect current sensor on either the primary or the secondary circuit, fluctuations in motor current can be observed. It has been observed that if a high resistance exists, (for example due to broken rotor bars) harmonic fluxes are produced in the air gap. These fluxes induce current components in the stator winding that can cause modulation of the supply current at ± the number of motor poles times slip. Available signal processing techniques can help extract the modulating frequency and represent the amplitude relationship of modulating frequency to line frequency. This relationship allows one to estimate the presence and severity of the defect.

46.2.2.6 Problems in Condition Monitoring

Although many organizations use sophisticated techniques for condition monitoring these days, there are still many problems that remain unresolved. For example, it is known that the main determinant of frequency of condition monitoring is the lead time to failure (or PF interval), which is the time at which an incipient failure can first be detected, until functional failure occurs. For example, in case of a bearing, PF interval is the time interval from when overall bearing vibration levels reach an alarming limit, until the bearing seizes completely. In order to be sure that the failure is detected prior to the functional failure; the bearing must be monitored at a frequency less than the PF Interval. But PF interval can hardly be determined accurately. For instance, in case of a bearing, the PF Interval may vary depending on the type of bearing installed, the severity of its operating cycle, the type of lubrication applied, ambient temperature conditions, the type of failure detected and many other factors.

Even today, the PF Interval can only be approximately estimated. Any error tends to be on the conservative *(i.e.,* too frequent) side. However there are cases of bearing failures that have occurred undetected, despite these bearings being monitored at these conservative frequencies. However, the situation is not that bad as smart sensor technology will greatly reduce the complexity of linking the outputs of these sensors to current process control systems thereby more and more equipment can be monitored continuously, on-line, and the control room operators will be able to assess quickly and easily, the current condition of the bearings or alignment or balance or gears on a particular machine. Several expert systems for fault diagnosis are available today. However, at present, these expert systems are still essentially rule-based systems, and like all rule-based systems, the results are only as good as the rules that have been established within the system.

Several articles have been published on the performance monitoring of steam turbines, using measurements of temperature, pressure, power output and other techniques to determine the turbine condition, and the specific faults that may require attention. In future, it is likely that this type of monitoring will be used on large Diesel engines, pumps and other sophisticated equipment. It is expected that sophisticated techniques such as ultrasonic flow measurement will be used to assist with the cost-effective application of performance monitoring techniques to a wider range of equipment.

The major trends, one may expect to see in future are:

- The development of smart sensors, and other low-cost on-line monitoring systems that will permit the cost-effective continuous monitoring of important equipment
- The increasing provision of built-in vibration sensors as standard features in large motors, pumps, turbines and other large equipment items
- Increasingly sophisticated condition monitoring software, with rapidly developing *expert* diagnosis capabilities
- Increasing integration, and acceptance for interfacing condition monitoring software with CMMS and Process Control software
- More focus on the applications of condition monitoring technologies to improve equipment reliability and performance, rather than just to predict component failure.
- A reduction in the cost of applying condition monitoring technologies.

In any case, adoption of PdM in the maintenance of equipment can result in substantial cost savings and higher system reliability. This approach offers cost savings over routine or time-based preventive maintenance because tasks are performed only when considered necessary, in contrast to time and/or operation count based maintenance where a piece of equipment gets maintained whether it needs it or not. Time based maintenance is labor intensive, ineffective in identifying problems that develop between scheduled inspections and is not cost effective.

46.2.3 Failure-Finding Maintenance

Failure-finding maintenance involves checking a (quiescent) part of a system to see if it is still working. This is often performed on subsystems of a system dedicated to safety -- protective devices. This is an important type of maintenance check because failures in safety systems can have more catastrophic effects, if other parts of the system fail. Inspections are usually carried out in order to uncover hidden failures (also called dormant failures). In general, no maintenance action is performed on the component during an inspection unless the component is found failed, in which case a corrective maintenance action can be initiated.

46.2.4 Corrective Maintenance

Corrective maintenance consists of the actions taken to restore a failed equipment or system to operational state. This maintenance usually involves replacing or repairing the component that caused the failure of the overall system. Corrective maintenance is performed at unpredictable intervals because a component's failure time is not known *a priori*. The equipment becomes operational after corrective maintenance or repairs have been performed. Corrective maintenance is actually carried out in three steps:

Diagnosis of the fault: The repairmen must take time to locate the fault or failed parts or otherwise satisfactorily assess the cause of the equipment or system failure.

Repair or replacement of faulty components: Once the cause of equipment failure has been established, action is taken to remove the cause, usually by replacing or repairing the components that caused the equipment to fail.

Verification of the repair action: After the faulty components have been repaired or replaced, the repair crew must verify that the system is again successfully operating.

The total time taken to repair the equipment is called *down time*, as during this period the equipment is not available or operating. By the same logic, the *uptime* of an equipment or system is the time during which it is available or operating. Further, a *cycle time* is the sum of *uptime* and *downtime*. In fact a repairable or maintainable equipment or system undergoes several such cycles of *operating state* and *down state* during its entire *life time* before it is discarded or decommissioned.

Actually downtime is the sum of the *administrative time*, *logistic time* and the *actual repair time*. The *administrative time* is the time spent in organizing repairs and is the time lost between the occurrence of a fault and the instant repairmen initiate repair action. This should exclude the *logistic time,* which is the portion of down time during which the repair activity is suspended or delayed on account of non-availability of spare parts or replacements.

The *actual repair time* or *active repair time* is the time during which the repairmen are working on the equipment to affect the repairs. This time in fact is the sum of the time to locate the fault or faults and for identification of the fault, fault correction time, and finally the time taken for testing and recommissioning the equipment. It is apparent that the *repairability*, which is the probability that the equipment or system will be restored to operable state within a specified *active repair time*, depends on the training and skill of the repair crew as well as on the design of the equipment. For example, the ease of accessibility of components in equipment has a direct effect on the active repair time. However, the human factors (covered in chapter 40 of this handbook) to a large extent govern the duration of active repair time.

46.2.4.1 Maintainability

In contrast with the repairability [4,13,19], *maintainability* is defined as the probability that the equipment or a unit will be restored to operable state within a specified downtime and depends on all the elements of downtime, *viz., administrative*, *logistic* and *active repair* times. The downtime is a random variable and has its own distribution called as repair distribution. If the repair distribution is exponentially distributed and we denote maintainability by $M(t)$, it will be given by:

$$M(t) = 1 - e^{-\mu t}$$

where μ is the repair rate and t denotes the time to repair or rather down time. One can also compute the mean of the repair distribution (*MTTR*) as:

$$MTTR = 1/\mu$$

If we change the repair distribution to Lognormal, Weibull or Gamma *etc*, the expression for maintainability and mean time to repair would also change. One can find a discussion of repair time distributions in texts like [4,8,9,10].

From the point of view of assessing the performance of such a repairable equipment which undergoes several cycle of uptimes and downtimes, a question that naturally arises is how much percentage of time on an average (over its entire life), the equipment is available or operating. Thus averaging over a long period of time, one can assess the performance of a repairable or maintained equipment or system and this average characteristic is called *steady state availability* or *inherent availability* or just *mean uptime ratio.*

46.2.4.2 Availability

Statistically speaking the uptimes and downtimes are random variables and will have their distributions. Based on these distributions, one can compute *mean uptime* and *mean downtime.* Actually mean uptime reflects how good the inherent design or built-in reliability is and mean downtime reflects how good the maintainability is? If the steady state availability (SSA) is to be kept high, one should try to design for high value of mean uptime (MUT) and mean down time (MDT) to be as low as possible since SSA is the ratio of mean uptime to *mean cycle time* which is the sum of mean uptime and mean downtime. There can be several combinations of MUT and MDT which can offer the same value of availability. Thus availability is dependent on reliability and maintainability and by clever manipulation one can get the desired value of availability. But the life cycle costs must not be lost sight of while designing maintained equipment or system.

There are other measures of performance of the maintained equipment such as *point availability* and *interval availability*.

Point availability is defined as the probability that the equipment or system is available at a given point of time and the *interval availability* is defined as the expected fraction of an interval of specified length that the equipment or system is in an up state. Naturally if the interval becomes very large, the interval availability would approach steady state availability. There are other measures such as *frequency of failures* and *mean duration of failure* of interest in case of maintained systems. The frequency of failures can also be further classified as interval frequency and steady state frequency. The interval frequency of failure is defined as the expected number of times a failure state encountered in a specified interval; whereas the steady state frequency of failure or simply the frequency of failure is defined as the expected number of times a failure state is encountered over a long period of time.

46.2.4.3 Assessment Techniques

For quantitative analysis of performance measures like reliability, availability or any other measures mentioned in earlier section, it is necessary to have the following information about the equipment or system:

- System configuration: such as number of units, identical or non-identical, series, parallel, standby, nature of redundancy such as warm, cold or active *etc*.
- Failure and repair data: Failure modes, failure and repair distributions.
- Repair strategy: number of repair crews, independent repair facilities inspection or overhaul schedules *etc*.

Once the above information is available, one can proceed using any of the following techniques:

- State Space Approach or Markov Method
- Block Diagram Approach
- Conditional Probability Approach
- Monte Carlo Approach

The detailed information on these approaches can be found in references quoted above or in [4]. However Markov method appears to be more popular technique to analyze maintained systems although it suffers the disadvantage of the dimensionality of the formulation even for moderately sized system. But with the fast computing facilities having large memories available, this should not be considered as a disadvantage any more. In any case, one can always decompose a large problem into manageable sized problems and also use a combination of solution techniques rather than using just one technique.

46.2.4.4 Availability Trade-offs

In designing repairable systems, it is generally desired to optimize system availability subject to some cost constraints. Alternatively, a designer may be specified a value of availability to achieve and determine the optimal pair of mean time between failures (MTBF) and the mean time to repair (MTTR) while minimizing the cost of the system. These formulations are discussed in Chapter 32 of this handbook and the several models are discussed in texts like [1, 8]. However, it is necessary to have some relationship between the variables MTBF and cost and MTTR *versus* cost before any tradeoff can take place. Also the lower and upper limits on MTBF and MTTR should be established from practical considerations as well as the state-of-the-art of the available technology. This will help establish the feasibility pairs for MTBF and MTTR.

46.3 Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) is an approach that helps in deciding what maintenance tasks must be performed at any given point of time. RCM methodology [3,5,6,16,21] was initially used in the aviation industry during 1960s to reduce maintenance costs and to increase the safety and reliability. Today it is used in a variety of industries, and has benefits applicable to dependable embedded systems. In fact RCM covers a wide range of steps, starting from the product design phase to the deployment and maintenance of a system. The first step in applying RCM techniques is to establish the user's expectations about various characteristics of the system on which RCM will be performed. Then, all the modes that the system can fail in must be identified, and an FMEA or FMECA is performed to identify root causes of these failure modes. From that information, an appropriate combination of types of maintenance is selected, and an appropriate schedule of those maintenance actions is planned. The maintenance plan is then implemented, and data is collected to refine and improve the maintenance schedule.

The RCM is a systematic process of preserving a system's or asset's function by selecting and applying effective preventive maintenance (PM) tasks. However, it differs from PM in focusing on function rather than equipment. RCM governs the maintenance policy at the level of plant or equipment type. In general, the concept of RCM is applicable to large and complex systems such as large passenger aircraft, chemical plants, oil refineries and electrical power stations *etc*.

The main features of RCM are:

- The focus is on the preservation of system function;
- Identification of specific failure modes to define loss of this function;
- Prioritizating the failure modes, as not all functions or functional failures have the same importance; and
- Identification of effective and applicable PM tasks that will prevent, and discover or detect the onset of appropriate failure modes based on cost-effective options.

The following process is pursued to RCM:

1. The objectives of maintenance with respect to a particular asset are defined by the functions of the asset and its associated desired performance standards.
2. Functional failures are identified.
3. Failure modes, which are likely to cause loss of each function, are also identified.
4. Failure effects are assessed.
5. Failure consequences are quantified to identify the criticality of failure in terms of the following categories: Hidden failure; Safety and environmental; operational and non-operational.
6. Functions, functional failures, failure modes and criticality are analyzed to identify opportunities for improving performance and/or safety.
7. Preventive tasks are established. These may be one of three main types: scheduled on-condition tasks, which employ condition-based or predictive maintenance; scheduled restoration; and scheduled discard tasks.

Although the main aim of using RCM is to reduce the total costs associated with system failure and downtime, evaluating the returns from an RCM program solely by measuring its impact on costs may hide many other less tangible benefits such as:

- Improving the system availability
- Optimizing spare parts inventory
- Identifying component failure significance and hidden failure modes and previously unknown, failure scenarios
- Providing training opportunities for system engineers and operations personnel
- Identifying areas for potential design enhancement
- Providing detailed review and improvement where necessary

The RCM implementation generally involves high initial costs and quite often results in successful investment but there have been some cases of unsuccessful implementations, which makes a prior economic evaluation of RCM an important step before it is adopted. In fact, RCM should not be undertaken if the financial benefits cannot be demonstrated to outweigh the involved costs. However, the financial benefits and costs associated with RCM are difficult to assess due to the fact that areas of savings are vague as there are no clear cause and effect relationships in the evaluation process. Costs can easily be identified than benefits. Costs include initial outlays primarily for training, and ongoing costs, including maintenance and support personnel, and expenditures associated with the maintenance introduced as a result of RCM findings. Benefits can also be identified through a series of steps. Firstly, one can start by identifying the current problems that can be resolved through RCM. Secondly, by estimating how much improvement would result through the adoption of RCM for the identified problems. Lastly, one should quantify each of the improvements in the larger sense of company's performance (profits, plant availability, personnel cost, *etc*.). When that quantification is done, then the economic benefits of RCM can be evaluated to see if its adoption is justified or not.

The value of RCM lies in the fact that it recognizes that the consequences of failures are far more important than their technical characteristics. In fact, it recognizes that the only reason for doing any kind of proactive maintenance is not to avoid failures per se, but to avoid or at least minimize the consequences of failures. In fact, the RCM process classifies these consequences into the following four groups:

- *Hidden failure consequences*: Hidden failures have no direct impact, but they may lead to multiple failures with often catastrophic consequences. (Often these failures are associated with protective devices which are not fail-safe.)
- *Safety and environmental consequences:* A failure has safety consequences if it has potential to injure or kill someone. It has environmental consequences if it breaches any environmental standard.
- *Operational consequences:* A failure has operational consequences if it affects production, product quality, customer service or operating costs or cost of repairs.
- *Non-operational consequences:* Failures belonging to this category nether affect safety nor production, but involve only the direct cost of repair.

46.4 Total Productive Maintenance

It is a well-known fact that in many factories, the operating time is less than 50% of the gross available hours per year; it is obviously shows that the assets are not being used to the fullest extent. This is partly due to *scheduled downtime*, which includes holidays, no production planned due to limited load, spare capacity to cope with volume flexibility *etc*. The other part is caused by the fact that the production is not wholly efficient. The reasons for this can be categorized into losses, which can be influenced during development and production phase. The total productive maintenance is a proactive equipment maintenance strategy designed to improve overall equipment effectiveness .It actually breaks the barrier between maintenance department and production department of a company.

Total Productive Maintenance: It is an approach to optimize the effectiveness of production means in a structured manner.

TPM focuses on improving the planned loading time. The gap (losses) between 100% and actual efficiency can be categorized into three categories: Availability, Performance and Yield (Quality Rate).

Availability losses: These include breakdowns and changeovers situations when the line is not running while it should be.

Performance losses: These are basically due to speed losses and small stops/idling/empty positions when the line is running, but is not providing the quantity it should.

Yield losses: These occur when the line producing products, but there are losses due to rejects and start-up quality losses.

These losses lead to the Overall Equipment Effectiveness (OEE) indicator, which tells you how efficiently the planned production process is. TPM helps to improve the OEE by providing a structure to quantify these losses, and by subsequently giving priority to the most important ones. TPM provides concepts and tools to achieve both short and long term improvements.

Total Productive Maintenance is not the same as a maintenance department that repairs breakdowns (breakdown maintenance). TPM is a critical adjunct to lean manufacturing. If machine uptime is not predictable and if process capability is not sustained, we cannot produce at the velocity of sales. One way to think of TPM is *deterioration prevention* and *maintenance reduction*, not fixing machines. For this reason many people refer to TPM as *Total Productive Manufacturing* or *Total Process Management*. TPM is a proactive approach that essentially aims to prevent any kind of slack before occurrence. Its motto is "*zero error, zero work-related accident, and zero loss*." TPM has five goals:

1. Maximize equipment effectiveness.
2. Develop 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.
5. Promote TPM through motivational management.

For this concept to function properly, the machines must be ready when we need them and they must be shut down in such a fashion as to be ready the next time. Key measures include efficiency while running and quality. Overall Equipment Effectiveness (or OEE) tells us how TPM is working, not just the typical measures of uptime and throughput. OEE is actually the product of availability, performance efficiency and the quality rate. Operators know what maintenance tasks are theirs; they also know what tasks are appropriate for the skilled trades' maintenance crew. TPM is a philosophy that helps create ownership of the manufacturing process among all employees. Teamwork is vital to the long-term success of TPM. The maintenance group performs equipment modification that would improve its reliability. These modifications are then incorporated into new equipment. The work of the maintenance group is then to make changes that will lead to maintenance prevention. Thus *preventive maintenance* along with *Maintenance prevention* and *Maintainability Improvement* are grouped as *Productive Maintenance*. The aim of productive maintenance is to maximize plant and equipment effectiveness to achieve the optimum life cycle cost of production equipment.

Nippondenso of Japan was first to implement TPM. It had already had quality circles which involved the employees in changes. Therefore, all employees took part in implementing Productive maintenance. Based on these developments Nippondenso was awarded the distinguished plant prize for developing and implementing TPM, by the Japanese Institute of Plant Engineers (JIPE). Thus Nippondenso of Toyota group became the first company to obtain the TPM certification.

TPM identifies 16 types of wastes (Muda) and then works systematically to eliminate them by making improvements (Kaizen). TPM has 8 pillars of activity, each being set to achieve a "*zero*" target. These pillars are:

1. Focused improvement (*Kobetsu-Kaizen*): for eliminating waste.
2. Autonomous maintenance (*Jishu-Hozen*): in autonomous maintenance, the operator is the key player. It involves daily maintenance activities carried out by the operators themselves that prevent the deterioration of the equipment.
3. Planned maintenance: for achieving zero breakdowns.
4. Education and training: for increasing productivity.
5. Early equipment/product management: to reduce waste occurring during the implementation of a new machine or the production of a new product.
6. Quality maintenance (*Hinshitsu-Hozen*): This is actually "*maintenance for quality*". It includes the most effective quality tool of TPM: "*poka-yoke*", which aims to achieve zero loss by taking necessary measures to prevent loss.
7. Safety, hygiene, and environment: for achieving zero work-related accidents and for protecting the environment.
8. Office TPM: for involvement of all parties to TPM since office processes can be improved in a similar manner as well.

46.5 Computerized Maintenance Management System

Computerized Maintenance Management System (CMMS) is also known as *Enterprise Asset Management* (EAM). A CMMS is a stand alone computer program to manage maintenance work, labour and inventory in a company, whereas EAM not only does all the above functions what a CMMS does but also integrates with the company financial, human resource, material management and other ERP (Enterprise Resource Planning) applications. In the past, stand alone CMMS had an advantage over EAM in terms of features, ease of use and functionality. .

A CMMS maintains a computer database of an organization's complete maintenance operations. This database is intended to help maintenance staff do their jobs more effectively (for example, determining which storerooms contain the spare parts they may need) and to help management make informed decisions such as calculating the cost of maintenance for each piece of equipment used by the organization and in allocation of resources judiciously. This information can also be helpful in dealing with third parties. For instance, if the organization is involved in a liability suit, the database information available with the CMMS can be used as an evidence to support that proper safety maintenance was performed. CMMS can be used by any organization that must perform maintenance on equipment and property. Some CMMS products focus on particular industry sectors (*e.g.*, the maintenance of vehicle fleets or health care facilities etc). Other products aim to be more general. To identify CMMS vendors, search for CMMS using any Internet search engine can be made.

Different CMMS packages offer a wide range of capabilities. A typical package may have the following features:

- Work orders: Scheduling jobs, assigning personnel, reserving materials, recording costs, and tracking relevant information such as the cause of the problem, record of downtime, and suggestions for further action required
- Preventive maintenance (PM): Keeps track of PM inspections and jobs, including step-by-step instructions or check-lists, lists of materials required, and other pertinent details. Typically, the CMMS schedules PM jobs automatically. Different software packages offer different techniques for reporting when a job should be performed.
- Asset management: Recording data about equipment and property including specifications, warranty information, service contracts, spare parts, purchase date, expected lifetime, *etc* that might be of help to management or maintenance workers.
- Inventory control: Management of spare parts, tools, and other materials including the specification of materials required for particular jobs, records of where materials are stored, determining when more materials should be purchased, tracking shipment receipts, and taking inventory.

CMMS can produce status reports and documents giving details or summaries of maintenance activities. The more sophisticated the package is, the more analysis facilities are possible. Many CMMS packages can also be hosted by the company selling the product on an outside server, or LAN based, meaning that the company buying the software hosts the product on their own server. CMMS packages are closely related to Facility Management System packages (also called Facility Management Software).

By adding some powerful reliability management tools, one can manage the information around maintenance, reliability and ultimately - physical asset management (PAM). In fact it can begin with the selection, implementation, data accuracy, failure coding, asset hierarchy, work order history, user adoption, training, enforcement, reporting, Key Performance Indicators (KPIs), dashboards, budgeting, planning, scheduling, mobile options, material management and many more factors will determine the result one can get with CMMS or EAM

Last but not the least, one must realize that these software systems are simply automating the underlying maintenance process - so if one is having a poor maintenance process - adding CMMS will not make it better.

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