Chapter 2
Maintenance in Manufacturing Environment: An Overview

Abstract Maintenance is one of the major activities in manufacturing as it highly influences production quality and quantity and directly affects production cost and customer satisfaction. As new manufacturing technologies emerge and global communication advances, new maintenance practices are developed to cope with these changes. The role of maintenance in maintaining asset value over time is getting more visible at the business level with the increase in its acquisition and maintenance costs. In this chapter, various manufacturing systems are introduced along with their distinctive features that influence maintenance strategies and practices. Maintenances management concepts, philosophies, policies, and practices in manufacturing are briefly described and discussed in this chapter.

Keyword Maintenance concepts · Strategies · Manufacturing systems

Maintenance in its narrow meaning includes all activities related to maintaining a certain level of availability and reliability of the system and its components and its ability to perform at a standard level of quality. It includes activities related to maintaining spare part inventory, human resources and risk management. In a broader sense, it includes all decisions at all levels of the organization related to acquiring and maintaining high level of availability and reliability of its assets. Maintenance is becoming a critical functional area in most types of organizations and systems such as construction, manufacturing, transportation, etc. It is becoming a major functional area that effects and affected by many other functional areas in all types of organizations such as production, quality, inventory, marketing and human resources. It is also getting to be considered as an essential part of the business supply chain at a global level.

Maintenance plays a major role in the success of organizations in various sectors. However, maintenance in the manufacturing sector attracted special attention puts maintenance in manufacturing in a leading position of development in maintenance. This attention is mainly due to the special features of the manufacturing sector. In this chapter, types of manufacturing systems are classified and

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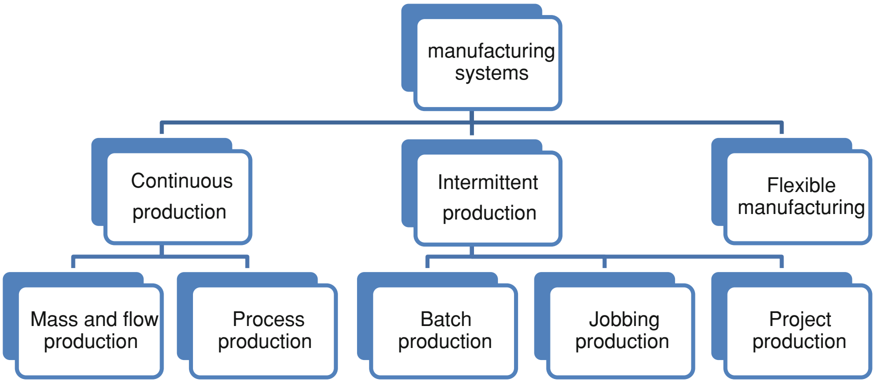

Fig. 2.1 Types of manufacturing systems

its different types are introduced. Features that distinct manufacturing from other sectors are discussed along with their influence on maintenance strategies. Finally, maintenance concepts and strategies are briefly introduced.

2.1 Types of Manufacturing Systems

The oldest type of manufacturing system is the custom manufacturing where a person or a machine makes a certain product tailored to a specific need. A shoemaker is an example of this system. Modern manufacturing have intermittent, continuous or flexible production systems as shown in Fig. 2.1.

Intermittent production is where more than one of the same product is being made in a short amount of time. There are structures of intermittent systems including batch production, jobbing production, project production.

In Batch production a group of similar products (batch) are produced stage by stage over a series of workstations. Batch production has a relative low initial set up cost for single production line used to produce several products. This feature makes attractive for small businesses who cannot afford to run continuous production lines. In addition, batch production reduces the risk of unpredictable and seasonal demands. Inefficiencies associated with batch production is the main drawback of batch production as equipment must be stopped between batches for a while (idle time) to re-configured and tested.

Jobbing production is where firms produce items that meet the definite requirements of the client as a one-off. These items are designed differently, and are tailored to the needs of each individual client. They include tailoring, plumbing, film production and new transport systems installation.

In Project production a complex sets of interrelated activities (project) are performed within a given period of time and estimated budget to make a product characterized by its immobility during production. Examples of such products are;

ships, locomotive, aircrafts buildings and bridges. The product is located in a fixed position where production resources are moved to it. Network planning techniques, such as PERT and CPM, are usually utilized for scheduling and controlling the implementation of the project.

The most flexible and responsive to changes manufacturing system is the flexible manufacturing system (FMS). It absorbs sudden large scale changes in production volume, capacity and capability. FMS produces a product just like intermittent manufacturing and is continuous like continuous manufacturing. Flexibility is coming from either the ability to produce new products (machine flexibility) or from the ability to use multiple machines to perform the same operation (routing flexibility). Usually, FMS consist of highly automated CNC machines connected by sophisticated material handling system and a central computer that controls material movements and machine flow. The main advantage of FMS is its high flexibility in managing manufacturing resources. The resulting gains are numerous including:

- Reduced manufacturing cost,
- Greater labor productivity,
- Greater machine efficiency,
- Improved quality,
- Increased system reliability,
- Shorter lead times.

However, FMS implementation requires a large initial capital and substantial pre-planning. It also requires high skilled labor.

Continuous manufacturing is the type of manufacturing system that uses an assembly line or a continuous process to manufacture products. It is used for products that are made in a similar manner. In this type of manufacturing system the product moves and processed along the production line. Continuous processing is a method used to manufacture or process materials that are either dry bulk or fluid continuously through a certain chemical reaction or mechanical or heat treatment. Continuous usually means several months or sometimes weeks without interruption. Some common continuous processes are; Oil refining, Chemical and petrochemicals plants, sugar mills, blast furnace, power stations, and saline water desalination and cement plants. Continuous processes use process control to automate and control operational variables such as flow rates, tank levels, pressures, temperatures and machine speeds.

Different maintenance approaches are usually adopted for different types of manufacturing systems. Shut down maintenance is commonly used for major overhauls in continuous manufacturing systems. Shutting down and starting up continuous processes typically results in waste or degraded products and it usually takes several hours for production to resume in full capacity. Strict procedure should be followed for shutting down and starting up continuous manufacturing processes to protect personnel and equipment. In contrast, discrete or semi-continuous manufacturing processes can be easily shut down and restarted and can be operated for one or two shifts if necessary. Flexible manufacturing systems give higher flexibility for planned and unplanned maintenance activities compared to other types of manufacturing systems.

2.2 Maintenance in Manufacturing

Maintenance in the manufacturing environment is one of the most complicated types of maintenance in comparison to construction, transportation and service business. Manufacturing is becoming highly competitive with extremely high pressure in reducing cost and increasing value of assets and improving the quality of outcomes (products). Manufacturing systems has grown over the years to be parts of global networks and supply chains. All of these changes in the manufacturing business have put maintenance in a great pressure on developing more effective and efficient operations.

Other special feature of manufacturing environment that makes it distinct from other environment is its complicated interrelation with large number of stakeholders, internal and external. The management structure in manufacturing environment is usually highly structured with many several decision layers and many parallel functional areas. Marketing, purchasing, production, engineering, and maintenance are common functional areas that usually share the benefit of the manufacturing facilities in different objectives that in many cases are conflicting with each other and hence proper synchronization is essential for the success of the global manufacturing business. External beneficiaries (stakeholders) include contractors, technology and spare part providers, customers, and upstream and downstream customers in the supply chain. Coordination and may be integration is essential for globally competitive business environment. Manufacturing facilities are in the heart of all of this complicated interrelation which makes maintenance a critical role player in this environment.

Maintenance in manufacturing deals with highly technical equipment that needs special types of expertise with limited choices of technology providers. As such maintenance in manufacturing requires highly sophisticated level of planning and operations more than any other business environment. Developing internal expertise in these technologies is becoming more and more expensive and choice for outsourcing is limited. Various maintenance strategies are adopted regarding in-house versus outsourcing for higher asset value, and more productivity operations.

Manufacturing facilities usually have long term physical interaction with limited number of people that are usually well trained to handle major production equipment. However, those people are exposed to health and safety hazards resulting from ill maintained facilities and equipment. As such maintenance plays a major role in keeping healthy environment locally within the facility, and the global environment. Waste resulting from manufacturing processes can be reduced and controlled through proper maintenance and asset management practices. Health and safety of people within the manufacturing facility can be well improved and

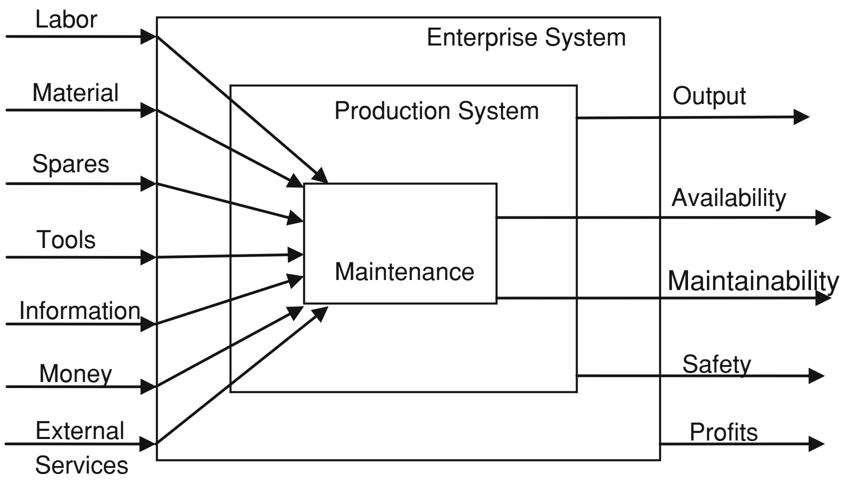

Fig. 2.2 Input output model of the enterprise

sustained through well planned and managed maintenance. The issue of health and environment in manufacturing is highly critical compared to other businesses as it is considered to be one of the main sources of environmental hazards in the current industrial arena. This needs clear and global understanding of maintenance as a part of a large system that works together for the benefit of the whole organization. One such view is introduced by Visser [1] as shown in Fig. 2.2.

Maintenance is in the heart of the production system that is part of a global enterprise. The success of the enterprise is highly dependent on the output of the production system in terms of quantity, quality, and safety. Such output cannot be obtained without a highly effective and efficient maintenance system that maintains high rate of manufacturing equipment availability with long term maintainability that keeps high level of asset value. Such maintenance system is composed of plans and operations that guarantees material, spares, tools, human and financial resources availability in the right time with the right quality and quantity. External resources and outsourcing some activities are some strategies that may be utilized as needed in the right way.

2.3 Maintenance Management

The main decisive factor for maximizing manufacturing asset value in terms productivity, reliability, cost, etc. is maintenance management, the body of the organization that is in charge of planning, implementing, controlling, and improving maintenance activities. Maintenance management is often considered as a centralized functional unit within the overall organizational structure in

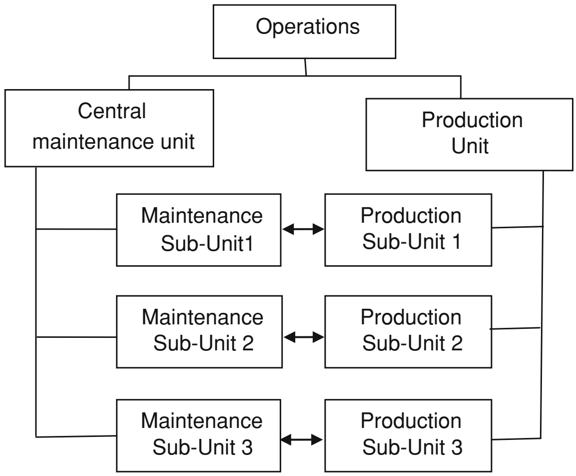

Fig. 2.3 Hybrid maintenance organizational structure

parallel with other functional units such as, production, Decentralized maintenance units is another common structure adopted by large organizations with multiple production units. The decision of adopting centralized or decentralized management structure is usually mad at the high management level taking into consideration, the size of the organization, the complexity of its operations, and the organization culture. Each structure has its advantages and disadvantages. Advantage of centralized over decentralized are: Centralized structure is more efficient in utilization of specialized human resources and equipment. Decentralized structure provides higher accessibility and responsiveness and more quality results. Small and medium size organizations prefer centralized structure because of cost and limited amount of work. Large size organizations vary between the two choices. A third common option is a hybrid structure that keeps maintenance units (group) at each production unit linked to a central maintenance unit as shown in the Fig. 2.3. This structure preserves close access and high level of specialization and interaction with production while utilizes collective expertise and support in the central unit with less cost.

Maintenance management involves planning, organizing, and controlling responsibilities. Maintenance planning is done at three levels, strategic, tactic and operations. The maintenance strategic planning level is to establish the alignment with higher business level plans. The details of this level of planning are covered in Chap. 3. Tactical and operational plans include the following elements:

1. Maintenance philosophy
2. Maintenance load forecasting
3. Maintenance capacity
4. Maintenance scheduling.

Maintenance philosophy is the step of designing on the general maintenance concept selected from known best practices as the maintenance philosophy for the organization. Total productive maintenance and reliability based maintenance concepts are two widely spread concepts that are discussed in Sect. 2.3. The selected concept is supported with right combinations of maintenance strategies such as preventive maintenance, condition based maintenance, and shutdown maintenance. Brief discussion on these strategies is introduced in Sect. 2.4.

Maintenance forecasting is a major part of planning concerned with estimating the current and future amount of maintenance work and type needed. Maintenance load forecasting is a complex task that involves a lot of uncertainties and influenced by many factors such as the age of the equipment, the rate of use, usage climate, and skills of workers.

Capacity planning is the translation of the maintenance load into resource needed to meet the forecasted load. Resources include, number and skills of craftsmen, maintenance tools, labor, material, spare parts, etc.

Maintenance scheduling is the process of assigning resources for tasks to be accomplished at a certain time in a certain frequency. Scheduling of tasks should take into account production schedules, optimization of resources and reducing costs. Scheduling is discussed in Chap. 3 in detail.

The organizing responsibility of maintenance management includes:

1. Job design
2. Time standards
3. Project management.

Job design involves defining for each major maintenance job, the work content, the method of maintenance the required skills and the needed tools.

Time standards are determined for major components of major maintenance jobs following the scientific approach. This helps in controlling maintenance tasks and efficient utilization of resources. It is also useful for planning and scheduling maintenance activities and forecasting workload.

Project management is used for optimizing and controlling major complex time consuming maintenance operations, such as shutdown maintenance projects for large plants. Critical Path Method (CPM) and Program Evaluation and Review (PERT) are common project management tools.

Controlling activities of maintenance management include the following:

1. Work Control
2. Inventory Control
3. Cost Control
4. Quality Control.

Work control is done using work order system in an integrated data base system for controlling reporting and analyzing. Intelligent maintenance systems are developed and integrated with ERP systems are commonly used and proven to be efficient and effective.

Inventory control is an important element of maintenance management that ensures the availability of spare parts and tools in the right quantity at the right time. Ordering and re-ordering quantities taking into consideration costs and lead times are built into automated information systems to assist management in this task by raising red flags at reorder points.

Cost control involves tracing all cost components of maintenance activities that include direct maintenance costs, lost production, equipment degradation, backups, and over maintenance costs.

Quality control of maintenance work involves assuring that the maintenance work is following standards and producing the expected results. Control is done by the supervision and testing final outcomes following a predetermined control procedure.

2.4 Maintenance Concepts and Strategies

Several maintenance concepts were developed in different parts of the world that are usually based on cultural and philosophical backgrounds. These trends encompass other strategies and technologies of maintenance. Some of these concepts are briefly introduced below:

2.4.1 Total Productive Maintenance

Total Productive Maintenance (TPM) is developed from the preventive maintenance methodology introduced from the USA and further developed and implemented in many Japanese companies since 1971. It is then spread throughout the world.

TPM is defined as a system of maintaining and improving the integrity of production and quality systems through the machines, equipment, processes and employees that add business value to the organization [2]. Total Productive Maintenance (TPM) is a proactive and cost-effective approach to maximize equipment effectiveness using the principles of teamwork, empowerment, 'zero breakdowns' and 'zero defects'.

TPM is designed to maximize equipment effectiveness (improving overall efficiency) by establishing a comprehensive productive-maintenance system covering the entire life of the equipment, spanning all equipment related fields (planning, use, maintenance, etc.) and, with the participation of all employees from top management down to shop-floor workers, to promote productive maintenance through motivation management or voluntary small-group activities. TPM provides a comprehensive company-wide approach to maintenance management, which can be divided into long-term and short-term elements. In the long-term, efforts focus on new equipment design and elimination of sources of lost equipment time and typically require the involvement of many areas of the organization. In this chapter, we focus on the short-term maintenance efforts that are normally found at the plant level of the organization. In the short-term, TPM activities include an autonomous maintenance program for the production department and a planned maintenance program for the maintenance department.

TPM improves many aspects such as operational performance, safety, cleanliness, employee morale and customer satisfaction to achieve excellence in business performance [3]. Some of the key objectives of TPM are:

- Focus and improve people management to minimize the targeted losses.
- Develop the policy, strategy and early management activities to ensure easy maintenance of the equipment.
- Develop the autonomous maintenance system to empower the production operators to take care of the conditions and effectiveness of the equipment.
- Develop a planned maintenance of the machine and equipment.
- Provide training and education to the operators and maintenance personnel to upgrade their equipment-related knowledge and skills.
- Establish safety practices and also prevent adverse environmental effects.
- Reduce the wastage of organizational resources.

Research show strong positive impact of TPM on multiple dimensions of maintenance performance [4]. In addition to controlling costs, TPM can improve dimensions of cost, quality, and delivery and it can be a strong contributor to the strength of the organization.

There are seven major elements of TPM as follows [5]:

1. housekeeping on the production line,
2. cross-training of operators to perform maintenance tasks,
3. teams of production and maintenance personnel,
4. operator involvement in the maintenance delivery system,
5. disciplined planning of maintenance tasks,
6. information tracking of equipment and process condition and plans,
7. Schedule compliance to the maintenance plan.

The main barriers to implementing TPM are lack of top management commitment, lack of middle management support and employee resistance to change. Changing the environment to suit TPM is a challenging task in the public sector undertakings, where apart from normal business constraints, managers deal with stiffer government control, large and unwieldy operations, wary unions and bleeding bottom lines.

2.4.2 Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) was initiated by the commercial aviation industry and then adopted by the U.S. military in the 1970s and then by the U.S. commercial nuclear power industry (in the 1980s) followed by other commercial industries and fields in the early 1990s. The following brief introduction is adopted from http://www.ebme.co.uk/articles/management/327-reliability-centred-maintenance-rcm in addition to other recent sources from the literature.

RCM is defined by the technical standard SAE JA1011, as "an engineering framework that enables the definition of a complete maintenance regime. It regards maintenance as the means to maintain the functions a user may require of machinery in a defined operating context". It is an industrial improvement approach focused on identifying and establishing the operational, maintenance, and capital improvement policies that will manage the risks of equipment failure most effectively. Within the manufacturing context, RCM is a systematic approach for understanding the function of the manufacturing system and the failure modes of its components, and choosing the optimum course of action that would prevent the failure modes from occurring or to detect them before occurring.

The primary principles upon which RCM is based are the following:

- Function oriented. It seeks to preserve system or equipment function.
- Device group focused. It is concerned with maintaining the overall functionality of a group of devices rather than an individual device.
- Reliability centred. It uses failure statistics in an actuarial manner to look at the relationship between operating age and the failures. RCM is not overly concerned with simple failure rate; it seeks to know the probability of failure at specific ages.
- Acknowledges design limitations. Its objective is to maintain the inherent reliability of the equipment design, recognizing that changes in reliability are the province of design rather than maintenance. Maintenance can only achieve and maintain the level provided for by design.
- Driven by safety and economics. Safety must be ensured at any cost; thereafter, cost-effectiveness becomes the criterion.
- Defines failure as any unsatisfactory condition. Therefore, failure may be either a loss of function (operation ceases) or a loss of acceptable quality (operation continues).
- Uses a logic tree to screen maintenance tasks. This provides a consistent approach to the maintenance of all kinds of equipment.
- Tasks must be applicable. The tasks must address the failure mode and consider the failure mode characteristics.
- Tasks must be effective. The tasks must reduce the probability of failure and be cost effective.
- Acknowledges two types of Maintenance tasks and Run-to-failure. The tasks are Interval (Time- or Cycle-)-Based and Condition-Based. In RCM, Run-to-Failure is a conscious decision and is acceptable for some equipment.
- A living system. It gathers data from the results achieved and feeds this data back to improve future maintenance. This feedback is an important part of the Proactive Maintenance element of the RCM program.

RCM develops maintenance standards for ensuring that a system or device meets its designed reliability or availability, even in the procurement and installation phases.

RCM analysis determines the type of maintenance appropriate for a given equipment item. It results in a decision of whether a particular piece of equipment should be reactively maintained ("Accept Risk" and "Install Redundant Units"), predicatively maintained ("Define PM Task and Schedule") or predicatively maintained ("Define Predictive Testing and Inspection Task and Schedule"). Successful implementation of RCM results the following benefits:

1. Increased reliability leading to fewer equipment failures and, therefore, greater availability for patients and lower maintenance costs.
2. Reduction in total of total maintenance cost as failures are prevented and preventive maintenance tasks are replaced by condition monitoring.
3. Increasing Efficiency and Productivity as a result of the RCM approach to maintenance that ensures that the proper type of maintenance is performed on equipment as needed.
4. Reducing lifecycle costs including acquisition phase and operation phase since decisions made early in the acquisition cycle profoundly affect the life-cycle cost. Savings of 30–50 % in the annual operations and maintenance costs are often obtained overtime through the implementation of a balanced RCM program.
5. Improving maintenance sustainability as RCM planning involves decisions made at all phases of equipment life cycle.

2.4.3 Maintenance Strategies

Maintenance can be performed in two major types: corrective or preventive as shown in Fig. 2.4. Corrective maintenance, similar to repair work, is undertaken after a breakdown when obvious failure has been located. Preventive maintenance (PM) is intended to reduce the probability of failure or degradation of functioning of an item and is carried out at predetermined intervals, predetermined PM, or according to a prescribed condition, Condition Based Maintenance (CBM).

Predetermined maintenance is scheduled based on the number of hours in use, the number of times an item has been used, according to prescribed dates, etc. The question remains which equipment should be preemptively maintained and at what times? Condition based maintenance, on the contrary, does not use predetermined intervals and schedules. It monitors the condition of components and systems (diagnostic) in order to determine a dynamic preventive schedule. It can also use forecasted condition of the machine (prognostic) for that purpose. A comparison of different maintenance approaches is shown in Table 2.1. In practice, combination of these approaches is used for different components within the same manufacturing environment.

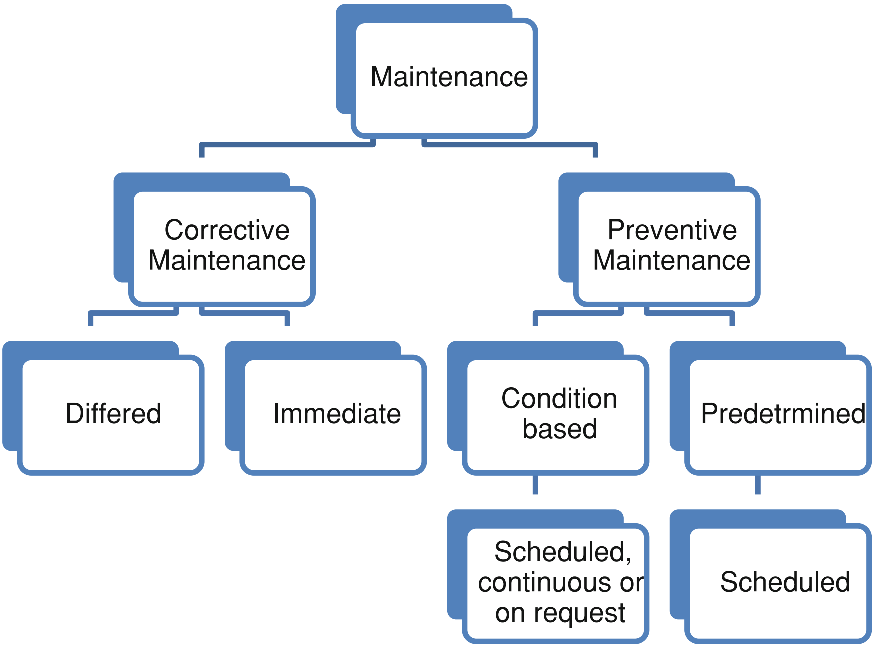

Fig. 2.4 Types of maintenance (extracted from Niu, G., et al.)

A brief description of each maintenance strategy is introduced next.

1. Corrective maintenance (also called reactive, breakdown, or operate to failure maintenance) may be defined as the remedial action carried out due to failure, or deficiencies discovered during preventive maintenance, to repair an equipment/item to its operational state. The action can be repairing, salvaging, rebuilding or overhauling. Usually, corrective maintenance is an unscheduled maintenance action, basically composed of unpredictable maintenance needs that cannot be preplanned on the basis of occurrence at a particular time. The action requires urgent attention that must be added, integrated with, or substituted for previously scheduled work items. However, corrective maintenance should be utilized only in non-critical areas where capital costs are small, consequences of failure are slight or does not affect the comprehensive system function, no safety risks are immediate, and quick failure identification and rapid failure repair are possible. In such cases, the maintenance can be deferred until a suitable time.
2. Scheduled Preventive Maintenance (PM) is a scheduled or fixed time maintenance service to detect and prevent potential failures and extend the life of equipment. It includes activities such as cleaning, lubricating, adjustment, and replacement of minor parts. It is used for reducing unexpected failure of critical

Table 2.1 Maintenance strategies (extracted from Niu et al.)

Corrective	Preventive		
Run-to-fail	Predetermined	Predictive	
Maintenance approaches			
Fix when it breaks	Scheduled maintenance	Condition based maintenance diagnostics	Condition based maintenance prognostics
No scheduled maintenance	Maintenance based on a fixed time schedule	Maintenance based on current condition	Maintenance based on forecasting of remaining equipment life
	Intolerable failure effect and possibility of preventing the failure effect	Maintenance scheduled based on evidence of needs	Maintenance need is projected as probable within mission time
	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	Forecasting of remaining equipment life based on actual stress loading
	Failure mechanism is time based, age or usage	Gradual degradation from the onset of failure	Gradual degradation from the onset of failure

equipment and to promote better safety, health and working environment conditions for the workforce. It helps in increasing the life span of assets and eliminates unnecessary replacements. However, PM should be planned and performed in a highly delicate manner to avoid damage of the equipment or nearby equipment during inspection, repair, adjustment, or installing or reinstalling of parts.

Timing of PM should also be optimized to reduce risks of failure during or after PM and to minimize total costs of PM while maximizing total benefits. Computer and mathematical models are developed for that purpose. In general, the frequency of PM is determined by the type of equipment, its age, its condition, and the consequences of failure. Optimization models exist for various preventive maintenance policies including replacement and inspection.

Consider an example of a replacement policy where a component is replaced after operating for a time t. During this time, minor repairs are performed in case of unexpected component failures. The replacement preventive maintenance brings back the system to as good as new condition, while minimum repair does not change the failure rate of the system. The objective in this case is to find the optimum replacement time t^* (period) that minimizes the total cost of replacement and minimum repairs. Considering t as the cycle time of replacement, we may consider minimizing the expect cost per unit time UEC(t) as follows:

$$\mathrm{UEC(t)} = \frac{\text{Total expected cost}}{\text{expected cycle time}}$$

Assuming random component failures of failure rate r(t), the expected number of failures E[N(t)] during time period (0, t) is given by Barlow and Hunter [6] as follows:

$$E[N(t)] = H(t) = \int_0^t r(t)dt,$$

This makes the expected unit time cost modeled as follows:

$$\mathrm{UEC(t)} = \frac{\mathrm{C_p + C_f H(t)}}{\mathrm{t}},$$

where, C_p is the total cost of replacement and C_f, the cost of each minimum repair. Now solving the equation with respect to t gives the optimum time for replacement t^* that gives the minimum cost per unit time.

Other models for more complicated situations can be found in the literature of PM optimization.

3. Condition based maintenance (CBM) was introduced to try to maintain the correct equipment at the right time. CBM is based on using real-time data to prioritize and optimize maintenance resources. Observing the state of the system is known as condition monitoring. Such a system will determine the equipment's health, and act only when maintenance is actually necessary. Developments in recent years have allowed extensive instrumentation of equipment, and together with better tools for analyzing condition data, the maintenance personnel of today are more than ever able to decide the right time to perform maintenance on some piece of equipment. Ideally condition-based maintenance will allow the maintenance personnel to do only the right things, minimizing spare parts cost, system downtime and time spent on maintenance. http://en.wikipedia.org/wiki/Condition-based_maintenance.

The most common condition monitoring techniques are vibration analysis, oil analysis, thermography, ultrasonics, electrical effects monitoring and penetrants. Vibration analysis techniques are used to monitor the performance of mechanical equipment that rotates, reciprocates, or other dynamic actions. Examples include gearboxes, roller bearings, motor, fans, generators and reciprocating engine. Oil analysis looks at its chemical composition and its content of foreign material. Iron based wear particles in lubrication oils determines the specific component that is wearing and the type and extent of wear. Changes in lubricant properties, including viscosity, flash point, pH, water content, etc. reflect the condition of the equipment.

Thermography measures surface temperature variations using infrared camera to determine poor electrical connections and hot spots furnace and kiln refractory wear and critical boilers and turbine component overheating. Ultrasonics are used to detect cracks, gaps, build ups, erosion, and corrosion in welds, coatings, piping, tubes, structures, shafts, etc. Electrical effect monitoring is used for corrosion detection. Electrostic and liquid-dye penetrants are used to detect cracks and discontinuities on surfaces.

In reality, reliable and effective CBM faces some challenges. First, initiating CBM is costly. Often the cost of instrumentation can be quite large, especially if the goal is to monitor equipment that is already installed. Second, it is not always easy to implement CBM due to variables such as complexity of the environment, the inner structure of equipment, obscure failure mechanisms, etc.

The advantages of CBM over predetermined preventive maintenance:

- Improved system reliability
- Decreased maintenance costs
- Decreased number of maintenance operations causes a reduction of human error influences.

Its disadvantages are:

- High installation costs, for minor equipment items often more than the value of the equipment
- Unpredictable maintenance periods cause costs to be divided unequally
- Increased number of parts (the CBM installation itself) that need maintenance and checking.

Today, due to its costs, CBM is not used for less important parts of machinery despite obvious advantages. However it can be found everywhere where increased reliability and safety is required, and in future will be applied even more widely.

4. Shutdown maintenance is a planned stoppage of production for conducting a comprehensive maintenance of equipment or plant with the purpose of restoring the processes to its original state. Shutdown is a common practice in continuous type of production systems and it is given different names in different industries such as, shutdown, shut-in, down-turn, turnaround, or outage. During the shutdown period a large complement of work is scheduled into a relatively short period of time. The period might extend to several weeks causing a large amount of planned production loss. Scheduled shutdowns, however, can provide unique opportunities to a maintenance department not normally available during standard operation or even during short shutdown periods. Lost capacity can be restored to an overtaxed facility during an extended shutdown. Major equipment overhauls can be performed to help prevent future unscheduled shutdowns. Long term preparation for the shutdown maintenance involves external contractors, technology providers, and customers.

Typically oil refineries go through shut down maintenance every 4 years for 42 days with around 300,000 man-hours with around 80 % success rate [7]. Power plant shutdown maintenance projects are larger in duration and man power requirement, while shutdowns in petrochemical industries are more frequent but smaller in terms of duration and man-hour requirement.

Shutdown maintenance is usually divided into four phases [8]:

a. Initiation: In this phase detailed planning of all aspects of the project is done. This includes, work scope, pre shut down work, procurement of material, quality and safety programs, project organization, cite logistics, etc.
b. Preparation: This phase includes the task of defining the work scope in the form of a list of tasks and activities that need to be done during shutdown maintenance. The success of this type of maintenance depends on the clarity of the work scope. In many cases the work scope is usually loosely defined drawn from past experience, inspection reports, and historical estimates. This scope fluctuation causes work force staffing changes during the TAM execution. Several methodologies are reported in the literature for developing clear and concise work scope. Another task in this phase is preparation of the job packages, selection of contractors, defining safety procedure, etc. in addition to the budget.
c. Execution is the phase concerned with conducting the work and monitoring its progress in accordance with time, cost and quality.
d. Termination is the phase of closing the project, assessing performance and documenting lessons learned.

5. Other maintenance types or activities are done within the above major maintenance strategies include the following:

- Opportunity maintenance is an activity conducted when an opportunity arises while performing another major maintenance job. An example of an opportunity is a shutdown maintenance period utilized to carry out known maintenance tasks.
- Overhaul is a comprehensive examination and restoration of a piece of equipment to an acceptable condition
- Fault finding is the task of assessing the level of failure onset.
- Design modification is carried out in coordination with the engineering department or technology provider to improve the operational performance of equipment through design changes. Maintenance exposes the equipment to design faults and improvement opportunities that when carried out improves the overall performance of the system.
- Replacement of equipment instead of fixing it upon failure or replacing the equipment following a predetermined plan regardless of its condition at the time.

2.5 E-Maintenance

E-maintenance is wide spread in the industry since the early 2000, referring to the integration of information and communication technologies with the maintenance strategy following the success of e-business and the e-manufacturing in business and production. Muller et al. [9] define e-maintenance as "Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, tether-free, wireless, infotronics, technologies), e-maintenance activities (operations or processes) such e-monitoring, e-diagnosis, e-prognosis, etc."

The emergence of e-maintenance contributed to increase maintenance efficiency, responsiveness, and proactivness and to optimize maintenance related work flow. It also integrated maintenance with the other functions of the e-enterprise. E-maintenance increases accessibility of multi origin data of different types and facilitates remote analysis, prognostics and decision making.

Muller et al. [9] identified three categories of capabilities or advantages of e-maintenance:

1. Maintenance type and strategies:

   - E-maintenance provides users, operator, manager, or expert, with remote accessibility to factory's equipment condition allowing them to take remote actions such as monitoring, diagnosing, de-bugging, fixing, controlling, etc. This capability allows remote decision making and expert consultation without physical attachment to the plant.
   - E-maintenance provides the opportunity of connecting geographically dispersed subsystems and stakeholders which allows cooperative/collaborative maintenance. This capability contributes to accelerating maintenance processes and simplifies it design (lean process).
   - E-maintenance allows immediate intervention by operator in response to programmable alerts and seeks on-line expertise for optimum solution to the situation.

2. Maintenance support and tools.

   - E-maintenance utilizes new development in sensor technology, ICT, signal processing and other similar technologies, in better understanding of causes of failure and system disturbances for improved engineering designs and production techniques.
   - E-maintenance provides a transparent and automated information exchange platform with different stakeholders.
   - E-maintenance enables high quality of after-sales service in terms of response time and quality consultation and interventions.

3. Maintenance activities

   - E-maintenance provides experts with the opportunity of on-line fault diagnosis and share their share their expertise with each other.

- With e-maintenance provides remote operators rapid interaction with experts and source designers for repairing and trouble shooting. This results a reducing down times.
- The multisource knowledge and data environment allows efficient knowledge capitalization and management.

2.6 Intelligent Prognostics

Prognosticsis an engineering discipline focused on predicting the health of a system or a component and hence it's remaining useful life. The predicted health is used for deciding on action to be taken for retaining its original state or contingency mitigation. The science of prognostics is based on the analysis of failure modes, detection of early signs of wear and aging, and fault conditions. These signs are then correlated with a damage propagation model. Prognostics issued in different applications such as maintenance management and transportation. In manufacturing maintenance is used in combination of condition-based maintenance.

Intelligent Prognostics is a natural evolution of predictive maintenance utilizing remote networking technologies combined with big data modeling with sophisticated imbedded systems. Lee et al. [10] define intelligent prognostics as "a systematic approach that can continuously track health degradation and extrapolating temporal behavior of health indicators to predict risks of unacceptable behavior over time as well as pin pointing exactly which components of a machine are likely to fail".

Technical approaches to building models in prognostics can be categorized broadly into data-driven approaches, model-based approaches, and hybrid approaches. Model base prognostics may include data collected from model-based simulations under normal and degraded conditions. Models are built based on different random load conditions or modes. In the absence of valid, reliable and accurate system models, the trajectory of a developing fault is monitored and the time to reach a predetermined state of intervention is predicted. This is the data-driven prognostic approach. The hybrid approach utilizes both data driven and model based approaches to generate more accurate and reliable results. For more details, see [10].

Maintenance will continue to utilize more tools of Prognostics and integrating it with other intelligent and communication technology. The trend of developing more generic predictive and intelligent maintenance systems for different industrial applications will continue. Intelligent prognostics is the base of the e-maintenance concept that links maintenance with the rest of the production system.

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