Reliability Strategy and Plan

Major Coverage in Module

• Equipment Asset Management
• Planned Maintenance: Integration of Maintenance Techniques
• Continuous Improvement Techniques and Programs
• Company Examples
Relationship Between Production, Assets, and Maintenance

- **Primary Input**: (Materials, Labor, Energy)
- **Primary Output**: (End Product)

- **Production**
- **Asset**
- **Maintenance**

Equipment Asset Management

- Strategic concept that goes beyond equipment maintenance
- Includes every stage in the lifecycle of production and manufacturing equipment assets.
  - Design
  - Operation
  - Maintenance
  - Repair
Equipment Asset Management

- Reduction in maintenance cost is accomplished by reducing the need for maintenance.
  - Design for the service
  - Fabricate with proper materials
  - Correct installation
  - Assure lubrication
  - Eliminate chronic problems
  - Enforce proper repair procedures

- Includes Preventive Maintenance (PM), Predictive Maintenance (PdM) and even Reactive Maintenance (RM) in an optimum combination.

- Elements such as Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) are used.

Focus of Manufacturing and Maintenance

<table>
<thead>
<tr>
<th>Period</th>
<th>Market and Manufacturing</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre 1945</td>
<td>Assembly Lines Production for stock</td>
<td>Reactive Corrective</td>
</tr>
<tr>
<td>1945 - 1950</td>
<td>Economic expansion Ever increasing demand Investments in more assets</td>
<td>Reactive Corrective</td>
</tr>
<tr>
<td>1960's</td>
<td>More innovations Increased complexity of assets Expanding infrastructure</td>
<td>Preventive</td>
</tr>
<tr>
<td>1970's</td>
<td>Market saturation Paradigm shift from vendor to customer</td>
<td>Preventive Active/proactive</td>
</tr>
<tr>
<td>1980's</td>
<td>Customer is the dominant force MRP / MRP II/JIT</td>
<td>Preventive Proactive</td>
</tr>
<tr>
<td>1990's</td>
<td>Global competition Optimize manufacturing efficiency by MES/ERP/TQM implementation in the workplace Network business objects</td>
<td>Proactive Integration with design and engineering Integration with open business systems Integration with open control systems</td>
</tr>
</tbody>
</table>

Source: SQL Systems Inc.
Maintenance Strategy

Integration of complementary techniques to meet the goals of optimum equipment reliability and availability for the least maintenance and operating cost.
Benefits of a Planned Maintenance System

**BENEFITS**
- Reduce the size and scale of repairs
- Reduce downtime
- Increase accountability for all cash spent
- Reduce number of repairs
- Increase equipment’s useful life
- Increase operator, mechanic, and public safety
- Increase consistency and quality of output
- Reduce overtime
- Increase equipment availability
- Reduce number of backup and standby units
- Increase control over parts and reduce inventory level
- Improve information available for equipment specification
- Lower maintenance costs (better use of labor/materials)
- Lower overall cost/product unit

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**Reactive Maintenance (RM)**

- Also known as breakdown, run to failure maintenance.
- Maintenance is performed only after the equipment fails. “If it ain’t broke, don’t fix it” “When it breaks, we’ll fix it”
- Little time, effort, or expense is allocated for maintenance until it is absolutely necessary.
- When this is the sole type of maintenance practiced:
  - High percentage of unplanned activities
  - High replacement part inventories
  - Inefficient use of maintenance effort
- A purely reactive maintenance strategy ignores the many opportunities to influence equipment survivability.
- Typical examples are electronic circuit boards and light bulbs.
- Justifiable in particular circumstances:
  - Does not produce critical delays;
  - Does not sacrifice safety;
  - Does not significantly increase costs.
### Decision Flow Chart for Preventive Maintenance (PM)

1. Is monitored, scheduled maintenance or inspection required for safety, insurance or regulation?  
   - **No**
2. Will the breakdown be more costly than prevention?  
   - **No**
3. Is equipment in the critical path for manufacturing?  
   - **No**
4. Is backup equipment unavailable?  
   - **No**
5. Will the breakdown adversely affect delivery or customer service?  
   - **No**
6. Will the breakdown further damage the equipment?  
   - **No**

**REACTIVE MAINTENANCE JUSTIFIED**

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### Preventive Maintenance (PM)

- Also known as Time-based or Interval-based Maintenance.
- Maintenance activities are performed on a calendar or operating time interval basis to extend the life of the equipment and prevent failure.
- Performed without regard to equipment condition.
- Assumes that the condition of the equipment and its need for maintenance is correlated with time. This means that most items can be expected to operate reliably for a period “X”, and then wear out.
Age-related Failures

Typical graph of single-piece and simple items such as tires, brake pads, compressor blades, etc.

- Predictable relationship between age and failure is true in some instances:
  - Equipment that comes in direct contact with product
  - Equipment with visual signs of wear and corrosion

Patterns of Equipment Failure

- Graphs show conditional probability of failure against operating age

<table>
<thead>
<tr>
<th>Type</th>
<th>% equipment conforming</th>
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<tbody>
<tr>
<td>A. Bathtub</td>
<td>4%</td>
</tr>
<tr>
<td>B. Wearout</td>
<td>2%</td>
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<tr>
<td>C. Gradual rise</td>
<td>5%</td>
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<tr>
<td>D. Initial increase</td>
<td>7%</td>
</tr>
<tr>
<td>E. Uniform failure</td>
<td>14%</td>
</tr>
<tr>
<td>F. Infant Mortality</td>
<td>68%</td>
</tr>
</tbody>
</table>

Source: Aladon Ltd.
Preventive Maintenance

- Failure rate (failure/time) is used as a guide to establish task periodicities.
  - MTBF = reciprocal of failure rate only in the special case of exponential life model (constant failure rate case)
- It provides only the average age at which failure occurs, not the most likely age.
- Can result in unnecessary maintenance.
- PM can be costly and ineffective when it is the sole type of maintenance practiced.

Preventive Maintenance (cont.)

- Preventative maintenance is only effective in the wear-out phase.
  - If you are in the constant failure phase, and you replace a part you often move back to the “infant mortality” phase, with a higher failure rate.
What Maintenance Tasks Are Performed?

- Checking and cleaning
- Inspecting
- Adjustments
- Lubrication
- Parts replacement and servicing
- Calibration
- Repair of components and equipment

Examples of PM

- Car maintenance
  - Change oil per instructions in the manual
  - Undercoating the car with rust-proofing
  - Schedule regular tune-ups
- Equipment with direct product contact
  - Machine tooling, screw conveyors, furnace refractories, pump impellers, etc.
Predictive Maintenance (PdM)

- Also known as Condition-Based Maintenance.
- Uses non-intrusive testing techniques, visual inspection and performance data to assess machinery condition.
- Replaces arbitrarily timed maintenance tasks with maintenance that is scheduled when warranted by equipment condition.

Benefits of Predictive Maintenance

- Helps reduce cost and improve reliability:
  - Frequency based preventive maintenance can be delayed if PdM monitoring shows it is not necessary yet;
  - Equipment with indicators of probable failure prior to scheduled PM activity are identified and scheduled for maintenance prior to failure;
  - Equipment with conditions that if not repaired will lead to catastrophic failure are detected and repaired at a fraction of the catastrophic failure repair cost.
Benefits of Predictive Maintenance

- Improves mean-time-to-repair due to prediction of failure
- Reduces inventory levels due to the avoidance of premature parts replacement and the ability to predict parts requirements
- Improves loading of resources and provides reduced overtime levels due to reduced emergency maintenance
- Gives the engineer/technician insight into the location and cause of the impending failure, reducing diagnosis time if the equipment is permitted to run to failure

Methods to Assess Condition of Systems/Equipment

- Includes intrusive and non-intrusive methods
  - Vibration Analysis
  - Tribology and Lubrication
  - Thermal Imaging and Temperature Measurement
  - Flow Measurement
  - Electrical Testing and Motor Current Analysis
  - Leak Detection
  - Valve Operation
  - Corrosion Monitoring
  - Process Parameters
  - Visual Observations
### TECHNOLOGIES

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<tr>
<td>![technologies](source: NASA)</td>
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### APPLICATIONS

| Source: NASA |

**Vibration Monitoring and Analysis**

- One of the most commonly used techniques.
- Helps determine the condition of rotating equipment and structural stability in a system.
- Applicable to all rotating equipment; e.g., motors, pumps, turbines, compressors, engines, bearings, gearboxes, shafts, etc.
- Conditions monitored: wear, imbalance, misalignment, mechanical looseness, bearing damage, belt flaws, cavitation, fatigue, etc.
**Infrared Thermography (IRT)**

- Application of infrared detection instruments to identify pictures of temperature differences
- It is a non-contact technique
- Attractive for identifying hot/cold spots in energized electrical equipment, large surface areas such as boilers and building walls, and other areas where "stand off" temperature measurement is necessary.

**Lubricant and Wear Particle Analysis**

- Is performed for three reasons:
  - To determine the mechanical wear condition
  - To determine the lubricant condition
  - To determine if the lubricant has become contaminated
- There are a wide variety of tests that will provide information regarding one or more of these areas.
- Standard analytical tests include: visual and odor, viscosity, % solids/water, spectrometric metals, infrared spectroscopy, particle counting, analytical ferrography, etc.
Passive (Airborne) Ultrasonics

- Airborne ultrasonic devices operate in a frequency range of 20kHz-100kHz and heterodyne the high frequency signal to the audible range to allow the operator to hear changes in noise associated with leaks, corona discharges, and other high frequency events.

- Examples include bearing ring and housing resonant frequency excitation caused by insufficient lubrication and minor defects.

Non-Destructive Testing (NDT)

- Evaluates material properties and quality of manufacture for high-value components or assemblies without damaging the products or its function.

- Examples are: radiography, ultrasonic testing (imaging), magnetic particle testing, dye penetrant, hydrostatic testing and electromagnetic induction testing
Non-Destructive Testing (NDT)

Radiography (or X-Ray):
- Detection of deep-surface defects.
- One of the most powerful NDT techniques available in industry.
- Depending on the strength of the radiation source, can provide a clear representation of discontinuities or inclusions in material several inches thick.
- Applicable to metal components including weld points.

Ultrasonic Testing (Imaging) (UT):
- Detection of deep sub-surface defects
- Alternative of complementary technique to radiography.
- Based on the difference in the wave reflecting properties of defects and the surrounding material

Non-Destructive Testing (NDT)

Ultrasonic Testing (cont.)
- Applicable to same components as X-Ray testing. Specialized applications for plastics or composite materials are common.
- Preferred method over radiography due to expense and safety precautions required by radiography.

Magnetic Particle Testing (MT):
- Detection of shallow sub-surface defects.
- Useful during localized inspections of weld areas and specific areas of high stress or fatigue loading
- The major advantage is its portability and speed of testing.
- Applicable to materials that conduct electric current and magnetic lines of flux.
- Most effective in welded areas.
Non-Destructive Testing (NDT)

Dye Penetrant (DP):
- Detection of surface defects in non-porous materials.
- Allows large areas to be quickly inspected.
- Simplest NDT technique in which to gain proficiency

Hydrostatic Testing:
- Method for detecting defects that completely penetrate pressure boundaries.
- Typically conducted prior to delivery or operation of completed systems or sub-systems that act as pressure boundaries.
- Applicable in components and assembled systems that contain fluids or gases.

Non-Destructive Testing (NDT)

Electromagnetic Induction Testing or Eddy Current Testing:
- Provides a portable and consistent method for detecting surface and shallow sub-surface defects in metal components, such as cracks, seams, holes or lamination separation).
- A set of magnetizing coils are used to induce electrical currents into the component being tested.
- Used for monitoring the thickness of metallic sheets, plates and tube walls. Also coating thickness.
- In more production oriented applications, this technique can determine material composition, uniformity and thickness of materials being produced.
Most Commonly Used PdM Techniques

- Vibration monitoring → rotating equipment
- Oil analysis → detect residual metal particles
- Thermography → identifying plant “hot spots”
- Shock pulse measurement → bearings
- Ultrasonics X-ray scanning → spot leaks and faults

Predictive and Proactive Maintenance

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear-out Failures</td>
<td></td>
</tr>
<tr>
<td>Random Failures</td>
<td></td>
</tr>
<tr>
<td>Premature Failures</td>
<td></td>
</tr>
</tbody>
</table>

Condition Monitoring identifies early detection of degradation for Predictive Maintenance

Proactive maintenance reduces the risk of failure
Proactive Maintenance (PAM)

- Improves maintenance through better design, installation, maintenance procedures, workmanship, and scheduling.

- Employs the following basic techniques to extend machinery life:
  - Specifications for new/rebuilt equipment
  - Precision rebuild and installation
  - Failed-Part Analysis (FPA)
  - Root-Cause Failure Analysis (RCFA)
  - Reliability Engineering
  - Rebuild certification/verification
  - Age exploration
  - Recurrence Control

Failed-Part Analysis (FPA)

- Involves visually inspecting failed parts after their removal to identify the root causes of their failures

- More detailed technical analysis may be conducted when necessary to determine the root cause of a failure.

- Example: Failed-bearing analysis provides methods to categorize defects such as scoring, color, fretting, and pitting and to relate those findings to the most probable cause of failure
Root-Cause Failure Analysis (RCFA)

- Proactively seeks the fundamental causes that lead to facility and equipment failure.
- Goals are:
  - Find the cause of the problem quickly, efficiently, and economically
  - Correct the cause of the problem, not just its effect
  - Provide information that can help prevent the problem from recurring
  - Instill a mentality of “fix forever”

Age Exploration (AE)

- Provides a methodology to vary key aspects of the maintenance program to optimize the process.
- The AE process examines the applicability of all maintenance tasks in terms of:
  - Technical content: Review tasks to ensure that all identified failure modes are addressed and that the existing tasks produce the desired amount of reliability
  - Performance interval: The task performance interval is continuously adjusted until the rate at which resistance to failure declines is determined.
  - Task grouping: Tasks with similar periodicity are grouped together to minimize time spent on the job and outages
**Characteristics of Proactive Maintenance**

- Uses feedback and communications to ensure that changes in design or procedures are rapidly made available to designers and managers
- Employs a life-cycle view to maintenance and supporting functions
- Ensures that nothing affecting maintenance occurs in isolation
- Employs a continuous process of improvement
- Integrates functions which support maintenance into maintenance program planning
- Uses root-cause failure analysis and predictive analysis to maximize maintenance effectiveness
- Adopts an ultimate goal of fixing the equipment forever
- Periodic evaluation of the technical content and performance interval of maintenance tasks (PM and PdM)

**Summary of Different Maintenance Techniques**

<table>
<thead>
<tr>
<th>Description</th>
<th>Benefits</th>
<th>Shortcomings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactive</strong></td>
<td>Fix or replace a device when it breaks</td>
<td>Suitable for non-critical and low cost equipment</td>
</tr>
<tr>
<td><strong>Preventive</strong></td>
<td>Scheduling maintenance activities based on arbitrary time intervals</td>
<td>Reduces reactive maintenance</td>
</tr>
<tr>
<td><strong>Predictive</strong></td>
<td>Assesses the equipment's health through diagnostics testing and/or on-line monitoring</td>
<td>Predicts when a device is likely to fail</td>
</tr>
<tr>
<td><strong>Proactive</strong></td>
<td>Uses information provided through predictive methods to find and isolate the source of equipment problems</td>
<td>Prolong operating life of equipment</td>
</tr>
</tbody>
</table>
Implementation of Planned Maintenance

• Step 1: Evaluate equipment and understand current conditions

• Step 2: Restore deterioration and correct weaknesses.

• Step 3: Build an information management system.

• Step 4: Build a preventive maintenance system.

• Step 5: Build a Predictive maintenance system.

• Step 6: Evaluate the planned maintenance system.

Step 1: Evaluate Equipment and Understand Current Conditions

1. Prepare or update equipment logs

2. Evaluate equipment: Establish evaluation criteria, prioritize equipment, and select planned maintenance equipment and components

3. Define failure ranks

4. Understand situation: measure number, frequency, and severity of failures; MTBFs; maintenance costs; breakdown maintenance rates, etc.

5. Set maintenance goals (indicators, methods of measuring results)
Step 1: Evaluate/Understand Current Conditions

• To decide which equipment receives planned maintenance, prepare equipment logs and prioritize equipment.

• Equipment logs are raw data for evaluating equipment. Must have design data and show equipment’s operating and maintenance history.

• Evaluate each piece of equipment in terms of its effect on safety, quality, operability, maintainability, etc.

• Rank equipment (as A, B, or C, for example) and perform maintenance on all units ranked A or B, as well as those for which zero failure is a legal requirement.

Step 1 (Cont.)

• Obtain data on failure numbers, frequencies, and severities, and on MTBFs, MTTRs (mean time to repair), maintenance costs, etc.

• Set goals for reducing these through planned maintenance.

• Rank failures as major, intermediate, or minor depending on their effect on equipment.

• Obtain data on failure numbers, frequencies and severities, MTBFs, etc.

• Set goals for reducing these through planned maintenance.
### Example Criteria for Evaluating Equipment

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Evaluation Criterion</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety: Effect of failure on people and environment</td>
<td>Equipment failure poses explosion risk or other hazards: equipment failure causes serious pollution</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Equipment failure might adversely affect the environment</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Other equipment</td>
<td>C</td>
</tr>
<tr>
<td>Quality: Effect of failure on product quality</td>
<td>Equipment failure has a major effect on quality (could lead to product contamination or abnormal reactions and produce out-of-spec product)</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Equipment failure produces quality variations that can be put right by the operator comparatively quickly</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Other equipment</td>
<td>C</td>
</tr>
<tr>
<td>Operation: Effect of failure on production</td>
<td>Equipment with major effect on production, without standby provision, whose failure causes previous and subsequent processes to shut down completely</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Equipment failure causes only partial shutdown</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Equipment failure has little effect or no effect on production</td>
<td>C</td>
</tr>
<tr>
<td>Maintenance: Time and cost of repair</td>
<td>Equipment takes 4+ hours or costs $2,400+ to repair, or fails three or more times per month</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Equipment can be repaired in under 4 hours at a cost of between $240 and $2,400 or fails less than three times/month</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Equipment costs less than $240 to repair or can be left unrepaired until a convenient opportunity arises</td>
<td>C</td>
</tr>
</tbody>
</table>

Source: Nippo Zosen Co., PM Prize Lecture Digest

### Examples of Planned Maintenance Goals

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Improvement Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failures by equipment ranking</td>
<td>A equipment ......0</td>
</tr>
<tr>
<td></td>
<td>B equipment ......1/10 of indicator during baseline period</td>
</tr>
<tr>
<td></td>
<td>C equipment ......1/2 of indicator during baseline period</td>
</tr>
<tr>
<td>Failures by failure ranking</td>
<td>Major failures ...... 0</td>
</tr>
<tr>
<td></td>
<td>Intermediate failures ...... 1/10 indicator during baseline period</td>
</tr>
<tr>
<td></td>
<td>Minor Failures ...... 1/2 indicator during baseline period</td>
</tr>
<tr>
<td>Equipment failure severity</td>
<td>Failure downtime $x \ 100$ operating time (For A equipment......0.15 or less)</td>
</tr>
<tr>
<td>Equipment failure frequency</td>
<td>Failure stops $x \ 100$ operating time (For A equipment......0.1 or less)</td>
</tr>
<tr>
<td>Planned maintenance achievement rate</td>
<td>Planned M. jobs completed $x \ 100$ total planned maintenance jobs scheduled (90% or more)</td>
</tr>
</tbody>
</table>
Step 2: Reverse Deterioration and Correct Weaknesses

1. Establish basic conditions, reverse deterioration and abolish environments causing accelerated deterioration.

2. Conduct focused improvement activities to correct weaknesses and extend lifetimes.

3. Take measures to prevent identical or similar failures from occurring.

4. Introduce improvements to reduce process failures.

Step 2: Reverse Deterioration and Correct Weaknesses (Cont.)

• Equipment exposed to accelerated deterioration for many years can fail unexpectedly at irregular intervals.

• The first step in the planned maintenance program is to restore accelerated deterioration, correct major weaknesses, and restore equipment to its optimal condition.

• This is achieved by operations and maintenance working together in the spirit of cooperation
Step 2: Program for the Production Department

1. Deterioration prevention:
   - Operate equipment correctly
   - Maintain basic equipment conditions (cleaning, lubrication)
   - Make adequate adjustments (during operation and setup)
   - Record data on breakdowns and other malfunctions
   - Collaborate with maintenance department to study and implement improvements

2. Deterioration measurement (using the 5 senses)
   - Conduct daily inspections

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3. Equipment restoration
   - Make minor repairs (simple parts replacement and temporary repairs)
   - Report promptly and accurately on breakdowns and other malfunctions

• Maintaining basic equipment conditions and daily inspection cannot be addressed by the maintenance staff alone. They are most effectively handled by those closest to the equipment --- the operators.
Step 3: Build an information management system

1. Build a failure data management system

2. Build an equipment maintenance management system (machinery-history control, maintenance planning, inspection planning, etc.)

3. Build an equipment budget management system

4. Build systems for controlling drawings, technical data, etc.

Step 3: Building an Information Management System

- Building a failure data management system will assist teams in determining failure frequency, downtime, etc. for individual processes or types of equipment.

- The information helps prioritize improvements and prevent recurrence.

- The system should include the following data:
  - date and time of failure
  - failure rank
  - equipment model
  - failed component
  - nature of failure
  - cause of failure
  - action taken
  - effect on production
  - time and number of personnel required for repair
Step 3: Building an Information Management System

- Data should be analyzed and made available at regular intervals in the form of periodic failure summaries and equipment failure lists.

- A computerized maintenance management system (CMMS) cannot function effectively if major and intermediate failures persist. Therefore, construct a failure data management system, first.

- Build the equipment maintenance management system when major and intermediate failures no longer recur.

Step 3: Computerized Maintenance Budget Management

- Must generate the following kinds of information:
  - Budget summaries for different types of maintenance work that compare budgeted and actual expenditure
  - Work and materials usage schedules providing information on work plans, costs, projected materials usage, etc.
  - Job priority lists that include information on maintenance work priorities, projected downtimes, costs, etc.
  - Charts that compare predicted downtime losses with maintenance costs and help measure maintenance effectiveness (cost of maintaining equipment vs. predicted losses from failure)
Step 3: Controlling Technical Information and Drawings

- A technology management system should control all information that relates to:
  - maintenance (including design standards)
  - technical reports
  - important literature
  - checking standards
  - mechanical design calculation programs
  - equipment diagnosis criteria, etc.

- Design the drawing control system to file and retrieve maintenance drawings, equipment logs, detailed drawings of parts to inspect, piping layouts, flow diagrams, catalogs, etc.

Step 4: Build a Preventive Maintenance System

1. Prepare for periodic maintenance (control standby units, spare parts, measuring instruments, lubricants, drawings, technical data, etc.)

2. Prepare preventive maintenance system flow diagram (see next page).

3. Select equipment and components to be maintained, and formulate a maintenance plan.

4. Prepare or update standards (material standards, work standards, inspection standards, acceptance standards, etc.).

5. Improve shutdown maintenance efficiency and strengthen control of subcontracted work.
Step 4: Selecting Equipment and Components for Preventive Maintenance

- Assess the equipment designated for planned maintenance and select equipment for PM from:
  - Equipment that, by law, requires periodic inspection
  - Equipment with maintenance intervals determined by experience
  - Equipment that requires regular checking due to its importance to the process
  - Equipment with an established replacement interval based on the serviceable life of its components
  - Important equipment for which it is difficult or impossible to detect or correct abnormalities during operation
Step 4. Preparing Maintenance Plans

- Base maintenance plans on mid-range (5 year) production plans
- Detail the plant/section shutdown maintenance along with the preventive maintenance for individual equipment items
- Include plans for “opportunity maintenance” (maintenance performed on machines whenever they are shut down for other reasons)

Step 4: Formulating Preventive Maintenance Standards

- To ensure that people perform preventive maintenance accurately and efficiently, formulate the following kinds of standards:
  - Material selection standards
  - Work estimating standards
  - Spare-parts control standards (standby units, general parts, tools and testing equipment)
  - Lubricant control standards
  - Lubricant supply control standards
  - Safety standards
Step 4: Improving the Efficiency of Shutdown Maintenance

- Standard practice in many process industries
- Can consume up to half of a company’s annual maintenance budget because it includes equipment modification, cost of stopping and restarting the plant, as well as the cost of maintaining equipment that cannot be opened during normal operation
- Can also include the implementation of investment projects
- Involves almost every department within the company (safety, purchasing, accounting, production, engineering, and maintenance)

Step 4: Work Breakdown Structure for Shutdown Maintenance

- Prepare an on-site work operation sheet in network form
  - A bar type operation sheet conceals the relationships among different tasks and the effect of delays on the overall project while a network diagram clearly shows the relationships among different tasks and critical path can be checked constantly.
- Prepare a network diagram (PERT or CPM)
- Shorten the process
- Reduce shutdown maintenance costs
Step 5: Build a Predictive Maintenance System

1. Introduce equipment diagnostics (train diagnosticians, purchase diagnostic equipment, etc.)

2. Prepare predictive maintenance system flow diagram

3. Select equipment and components for predictive maintenance, and expand gradually

4. Develop diagnostic equipment and technology

Characterized by a combination of three tasks:

- Surveillance: monitoring machinery condition to detect incipient problems
- Diagnosis: isolating the cause of the problem
- Remedy: performing corrective action

If the last task is not performed, then the monitoring efforts (gathering data and performing analysis) are wasted.
**Step 5: Equipment Selection**

- Review of equipment performance histories
  - Criticality of each machine
  - Types of failures
  - Outlook for continued failures
- Select a manageable number of machines
- Determine what, how, when and where to measure
  - Choose parameters that best indicate machine condition and failure progression
  - Choose appropriate instruments and techniques for measuring
  - Make decisions about how often to monitor and where on the equipment to take measurements

Source: IRD Mechanalysis, Inc.
Step 5: Frequency of PdM tasks should be based on the failure period (or P-F interval)

• The frequency of PdM tasks has nothing to do with the frequency of failure and nothing to do with the criticality of the item.

• The frequency of PdM is based on the fact that most failures do not occur instantaneously, and that it is often possible to detect that the failure is occurring during the final stages of deterioration.

Step 5: Frequency of PdM tasks should be based on the failure period (or P-F interval)

• The amount of time to elapse between the point where the potential failure occurs and the point where it deteriorates into a functional failure is known as the P-F interval.

• The P-F interval governs the frequency with which the predictive task must be done. The checking interval should be less than the P-F interval if we wish to detect the potential failure before it becomes a functional failure.
Step 5: Set up a PdM Process

- Develop systems for establishing inspection schedules and handling data
- Develop program for training personnel
- Put in place a structured means of communication to relay information about equipment condition to those planning and scheduling repair activities
- Set the levels or limits that represent normal operating conditions for all parameters to be monitored
- Map out monitoring routes
- Give identification numbers to the machines
- Mark points to be monitored on the machines

Step 5: Determining acceptable condition limits

- Obtain baseline measurements to establish the condition of the machinery
- Compare actual measurements to the standards set
- While baseline measurements are being taken, machines operating outside established limits will be found.
- Investigate, diagnose and correct faults before machines are included in program
- Begin periodic monitoring
Step 5: *Periodic Condition Monitoring*

- Entails taking measurements on a schedule; collecting, recording, and trending (charting) the data
- Analyze the trended information to detect progressive problems and identify faults that require corrective action
- As the program continues, reassess points being monitored and original limits set

Step 6: *Evaluate the Planned Maintenance System*

1. Evaluate the planned maintenance system

2. Evaluate reliability improvement; number of failures and minor stops, MTBF, failure frequency, etc.

3. Evaluate maintainability improvement: preventive maintenance rate, predictive rate, MTTR, etc.

4. Evaluate cost savings: decrease in maintenance expenditures, improvement in distribution of maintenance funds
Continuous Improvement Techniques and Programs

- **Reliability Centered Maintenance (RCM)**
  
  On-going process which determines the optimum of reactive, preventive, predictive and proactive maintenance practices in order to provide the required reliability at the minimum cost

- **Total Productive Maintenance (TPM)**
  
  Plant improvement methodology which enables continuous and rapid improvement of the manufacturing process through the use of employee involvement, employee empowerment, and closed-loop measurement of results

---

Reliability Centered Maintenance (RCM)

- **Reliability Centered Maintenance**
  - Reactive Maintenance
    - Small items
    - Non-critical
    - Inconsequential
    - Unlikely to fail
    - Redundant
  - Preventive Maintenance
    - Subject to Wearout
    - Consumable Replacement
    - Failure pattern known
  - Predictive Maintenance
    - Random failure
    - Patterns not subject to wear
    - PM induced failures
  - Proactive Maintenance
    - RCFA
    - FMEA
    - AE

---
Historical Evolution of RCM

- RCM finds its roots in the early 1960’s.
- Initial development was done by the North American civil aviation industry.
- Airlines realized that many of their maintenance philosophies were not only too expensive but actually dangerous. Industry re-examined everything they were doing to keep their aircraft air-borne.
- In the mid-1970’s the US Department of Defense commissioned a report on the subject from the aviation industry. This report was written by Stanley Nowlan and Howard Heap (United Airlines) and published in 1978. It is still one of the most important documents available today.

The work demonstrated that a strong correlation between age and failure did not exist. Therefore, the basic premise of preventive (time-based) maintenance was false for the majority of the equipment.

Development of new technologies in the late 1980s made it possible to determine the actual condition of equipment, and not rely upon estimates of when it might fail based upon age (condition-based monitoring).
RCM Analysis

- What does the system or equipment do?
- What functional failures are likely to occur?
- What are the likely consequences of these functional failures?
- What can be done to prevent these functional failures?

RCM decision logic tree based on the answers to these questions

| Will failure of the facility or equipment item have a direct and adverse effect on safety or critical mission operations? |
|---|---|
| Is the item expendable? |
| Yes | No |
| Yes | No |
| Yes | No |

| Is there predictive technology (e.g. vibration testing or thermography) that will monitor the condition and give sufficient warning (alert/alarm) of an impending failure? |
|---|---|
| Yes | No |

| Is there an effective PM task that will minimize functional failure? |
|---|---|
| Yes | No |

| Is establishing redundancy cost and priority-justified? |
|---|---|
| Yes | No |

<table>
<thead>
<tr>
<th>Accept risk</th>
<th>Install redundant unit(s)</th>
<th>Install PM task and schedule</th>
<th>Define PdM task and schedule</th>
</tr>
</thead>
</table>

Source: NASA
RCM Principles

- RCM is function oriented
  Seeks to preserve system or equipment function
- RCM is system focused
  More concerned on maintaining system function than individual component function
- RCM is reliability centered
  Relationship between operating age and the failures experienced is important
- RCM acknowledges design limitations
  Maintenance can, at best, achieve and maintain the level of reliability for equipment which is provided by design. RCM recognizes that maintenance feedback can improve original design
- RCM is driven by safety and economics
  Safety first, then cost-effectiveness

RCM Principles

- RCM defines failure as any unsatisfactory condition
  Loss of function (operation ceases) or loss of acceptable quality (operation continues)
- RCM uses a logic tree to screen maintenance tasks
- RCM tasks must be effective
- RCM tasks must be applicable
  The tasks must reduce the number of failures or ameliorate secondary damage
- RCM acknowledges 3 types of maintenance and run-to-failure
  PM, PdM, and failure-finding (one of the several aspects of proactive maintenance)
- RCM is a living system
  It gathers data from the results achieved and feeds this data back to improve design and future maintenance. This feedback is an important part of the Proactive Maintenance element of the RCM program
**RCM Goals and Objectives**

- Identify for each system and equipment the failure modes and their consequences
- Determine the most cost-effective and applicable maintenance technique to minimize the risk and impact of failure

**Example RCM Analysis**

- Brief example of the RCM methodology and the type of data required to conduct an RCM analysis
- Develop an equipment data sheet which includes both vendor and CMMS identification numbers.
- Additional information included:
  - Number of units installed
  - Item description
  - Function(s)
  - Functional Failures
  - Failure Modes
  - Failure Effects
  - Historical data
**Definitions**

- **Functional Failures**
  
  Descriptions of the various ways in which a system or subsystem can fail to meet the functional requirements designed into the equipment.

- **Failure modes**
  
  Equipment and component-specific failures that result in functional failure of the system or subsystem.

  Not all failure modes or causes warrant preventive or predictive maintenance because the likelihood of their occurring is remote or their effect is inconsequential.

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**RCM Information Sheet**

May be started at either the component, subsystem, or system level.

For example, a chilled water system would have four RCM information sheets:

<table>
<thead>
<tr>
<th>Function</th>
<th>Functional Failures</th>
<th>Failure Modes</th>
<th>Maintenance (M) or Operations (O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss of flow</td>
<td>Motor failure</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pump failure</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catastrophic leak</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blocked line</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valve out of position</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td>Insufficient flow</td>
<td>Pump cavitation</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drive problem</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blocked line</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valve out of position</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrumentation</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Chilled water temperature too high</td>
<td>Chiller failure</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low refrigerant</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fouled heat exchanger</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrumentation problem</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling tower problem</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valve out of position</td>
<td>Both</td>
<td></td>
</tr>
</tbody>
</table>

1. System Data Sheet

Source: NASA
Each of the individual components which make-up the chilled water system would have a sheet similar to Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Functional Failure</th>
<th>Failure Mode</th>
<th>Source of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>Motor will not turn</td>
<td>Insulation failure</td>
<td>Voltage spike</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open winding</td>
<td>Phase imbalance</td>
</tr>
<tr>
<td>Motor</td>
<td>Motor will not turn</td>
<td>Burnt rotor</td>
<td>Insulation contamination</td>
</tr>
<tr>
<td></td>
<td>Wrong speed</td>
<td>Excessive vibration</td>
<td>Excessive temperature</td>
</tr>
<tr>
<td>Bearings</td>
<td>Motor will not turn</td>
<td>Bearing seized</td>
<td>Fatigue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improper lubrication</td>
<td></td>
</tr>
<tr>
<td>Motor controller</td>
<td>Motor will not turn</td>
<td>Contractor failure</td>
<td>Mainline contact failure</td>
</tr>
<tr>
<td></td>
<td>Wrong speed</td>
<td>VFD malfunction</td>
<td>Loss of electrical power</td>
</tr>
<tr>
<td>Overloads/fuse</td>
<td>Motor will not turn</td>
<td>Device burned out</td>
<td>Excessive current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excessive torque</td>
<td></td>
</tr>
<tr>
<td>Shaft/coupling</td>
<td>Pump will not turn</td>
<td>Shaft/coupling</td>
<td>Fatigue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sheared</td>
<td></td>
</tr>
</tbody>
</table>

2. Electric Motor Failures Sheet

A table similar to table 3 should be prepared to select the maintenance strategy to be followed in order to address each failure mode and its root cause. This sheet will be extensive for even the simplest of systems.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Mechanism</th>
<th>Reason</th>
<th>Root Cause</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing seized</td>
<td>Lubrication</td>
<td>Contamination</td>
<td>Seal failure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insufficient</td>
<td>Oil leak</td>
<td>Procedural</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy load</td>
<td></td>
<td>Procedural</td>
</tr>
<tr>
<td></td>
<td>Fatigue</td>
<td>Metallurgical</td>
<td>Inherent</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excessive</td>
<td>Imbalance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface distress</td>
<td>Installation</td>
<td>Procedural</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contamination</td>
<td>See lubrication</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Storage</td>
<td>Procedural</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Welding</td>
<td></td>
</tr>
</tbody>
</table>

3. Failure Mode Identification Sheet
Table 4 provides an abbreviated Root Cause Failure Sheet for electric motor stators

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Mechanism</th>
<th>Reason</th>
<th>Root Cause</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation</td>
<td>Age</td>
<td>Inherent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environment</td>
<td>Chemical attack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overheating</td>
<td>Excessive current</td>
<td>Power quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase imbalance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short on/off cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overloaded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contamination</td>
<td>Environment</td>
<td>Moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improper lube</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process related</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue</td>
<td>Excessive vibration</td>
<td>Lack of winding support</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase imbalance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Imbalance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Misalignment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resonance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Root Cause Failure Sheet

Use of Formal RCM

- Due to the extensive up front effort required, a formal rigorous RCM analysis should be for:

  Case 1:
  - Systems and components that are truly unique
  - Where consequences of failure are completely unacceptable
  - Failure modes are not understood.

  Case 2:
  - Iterative process has not produced the desired level of reliability
  - Life cycle cost for maintaining the desired level of reliability is excessive
Key Success Factors for Implementing RCM

- Clear project goals
- Management support and a commitment to introduce a controlled maintenance environment
- Union involvement
- Good understanding of RCM philosophy by plant staff
- Pilot RCM applications to demonstrate success and build support
- Sufficient resources for both the review and subsequent implementation of recommendations
- Clear documentation of results to facilitate acceptance of recommendations
- Integration with PdM maintenance capability
**Total Productive Maintenance (TPM)**

- Cross-functional team activities to eliminate unnecessary or unplanned downtime and equipment-related quality problems, and improve machine operability and maintainability.
- Rigorous preventive maintenance program to control deterioration -- carried out cooperatively by operations and maintenance personnel.
- Training to upgrade operations and maintenance skills among production and maintenance personnel.
- Team activities to improve maintenance management and maintenance operations efficiency (maintenance planning, visual systems, etc.)
- Information systems to support the development of new equipment that is easier to operate, adjust and maintain, with lower life-cycle costs and higher reliability.
Strategies for Implementing TPM

1. Provide for small group activities (autonomous maintenance)
2. Perform planned maintenance
3. Implement early equipment management
4. Involve everyone through continuous training
5. Maximize equipment effectiveness

Autonomous Maintenance

Autonomous maintenance includes any activity performed by the production department that has a maintenance function and is intended to keep the plant operating efficiently in order to meet production plans.

Goals:

• Prevent equipment deterioration through correct operation and daily checks
• Bring equipment to its ideal state through restoration and proper management
• Establish the basic conditions needed to keep equipment well-maintained
Establishing Basic Equipment Conditions Eliminates Causes of Accelerated Deterioration

Failure

Natural Deterioration (inherent lifetime)

Accelerated Deterioration (artificially induced)

Extend Lifetimes

Eliminate Causes

Corrective Maintenance

Prevent errors by improving operability
Improve maintainability and repair quality
Improve safety and reliability

Establishment of basic conditions

Cleaning: eliminate all dust and dirt
Lubricating: keep lubricants clean and repaired
Tightening: keep nuts and bolts secure

The Importance of Cleaning

Cleaning is a form of inspection in TPM. Its purpose is not merely to clean but expose hidden defects or equipment abnormalities.

Harmful Effects of Inadequate Cleaning

<table>
<thead>
<tr>
<th>Failure</th>
<th>Dirt and foreign matter penetrates rotating parts, sliding parts, pneumatic an hydraulic systems, electrical control systems, and sensors, etc., causing loss of precision, malfunction, and failure as a result of wear, blockage, frictional resistance, electrical faults, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality defects</td>
<td>Quality defects are caused either directly by contamination of the product with foreign matter or indirectly as a result of equipment malfunction.</td>
</tr>
<tr>
<td>Accelerated deterioration</td>
<td>Accumulated dust and grime make it difficult to find and rectify cracks, excessive play, insufficient lubrication, and other disorders, resulting in accelerated deterioration.</td>
</tr>
<tr>
<td>Speed losses</td>
<td>Dust and dirt increase wear and frictional resistance, causing speed losses such as idling and under performance.</td>
</tr>
</tbody>
</table>
Daily Checking

Ensures that abnormalities are detected and dealt with as soon as possible.

**Lubrication Storage**
- Are lubricant stores always kept clean, tidy, and well-organized by thorough application of the 5S principles?
- Are lubricant containers always capped?
- Are lubricant types clearly indicated and is proper stock control practiced?

**Lubrication Inlets**
- Are grease nipples, speed-reducer lubricant ports, and other lubricant inlets always kept clean?
- Are lubricant inlets dustproofed?
- Are lubricant inlets labeled with the correct type and quantity of lubricant?

**Oil level Gauges**
- Are oil-level gauges and lubricators always kept clean, and are oil levels easy to see?
- Is the correct oil level clearly marked?
- Is equipment free of oil leaks, and are oil pipes and breathers unobstructed?

**Automatic Lubricating Devices**
- Are automatic lubricating devices operating correctly and supplying the right amount of lubricant?
- Are the oil or grease pipes blocked, crushed or split?

**Lubrication Condition**
- Are rotating parts, sliding parts, and transmissions (e.g., chains) always clean and well-oiled?
- Are the surroundings free of contamination by excess lubricant?

---

**Checkpoints for Nuts and Bolts**

**Slight Defects**
- Are any nuts or bolts loose?
- Are any nuts or bolts missing?

**Bolt lengths**
- Do all bolts protrude from nuts by 2-3 thread lengths?

**Washers**
- Are flat washers used on angle bars and channels?
- Are tapered washers used where parts are subject to variation?
- Are spring washers used where parts are subject to vibration?
- Are identical washers used on identical parts?

**Attachment of Nuts and Bolts**
- Are bolts inserted from below, and are nuts visible from the outside?
- Are devices such as limit switches secured by at least two bolts?
- Are wing nuts on the right way around?

- True daily inspection means being alert enough to spot anything out of the ordinary while operating the equipment or patrolling the plant and being able to deal it with and report it correctly.

- Requires easily-understood standards and high operator skills.
Steps to Implementing Autonomous Maintenance

1. Perform initial cleaning
2. Address contamination sources and inaccessible places
3. Establish cleaning and checking standards
4. Conduct general equipment inspection
5. Perform general process inspection
6. Systematic autonomous maintenance
7. Practice full self-management

Planned Maintenance System Showing Allocation of Responsibility

- **PM**
  - Specialized maintenance
  - Autonomous maintenance

- **PdM**
  - Specialized maintenance
  - Autonomous maintenance

- **RM**
  - Specialized maintenance
  - Autonomous maintenance

- **Planned servicing**
  - Complete/Partial shutdown maintenance
  - Periodic servicing
  - Periodic inspection
  - Periodic checking

- **Opportunity maintenance**
  - Alarms
  - Continuous monitoring
  - Trend monitoring
  - Interlocks

- **Periodic diagnosis**
  - OSI
  - SDI

- **Daily checking and diagnosis**
  - Detecting signs of abnormality

OSI: On-stream inspection (non-destructive)
SDI: Shutdown inspection
An operations group can assume about one-fifth of the work performed by the maintenance group.

Early Equipment Management

- Good equipment management techniques improve the use of capital assets and extend their life cycle.
- The objective is to maximize the return on a company’s total investment in equipment.
- Individuals and groups must understand their role in equipment management, so that they know how their activities impact the total life cycle of the equipment.
- Traditionally, the equipment management function is divided into five phases: Specification; Procurement; Startup or Commissioning; Operation, and Disposal.
Typical Phases of Equipment Management

<table>
<thead>
<tr>
<th>Phase</th>
<th>Responsibility</th>
<th>Costs</th>
<th>Analytical Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td>Management and engineering</td>
<td>Costs are minimal, typically less than 5% of total life-cycle cost. However, this is the phase where the majority of the life-cycle cost is defined. Poor specification and design leads to higher total life-cycle costs.</td>
<td>High effort. Most of the technical effort spent on the equipment is in the specification phase. Too much effort is spent on controlling the purchase cost and not enough on controlling the operational cost.</td>
</tr>
<tr>
<td>Procurement</td>
<td>Purchasing with engineering reservin</td>
<td>Costs can appear to be high, but are typically only a small percentage of the operating cost.</td>
<td>Most effort is spent on contract terms and vendor prices. Little effort is spent on ensuring continuing vendor support and incentive-based performance guarantees.</td>
</tr>
<tr>
<td>Startup</td>
<td>Launch team consisting of representatives from engineering, production, and maintenance with assistance by the vendor if dictated by the contract for purchase</td>
<td>Costs can be relatively high. Most of the launch cost is typically due to delays in the startup schedule representing lost opportunity when production is delayed.</td>
<td>This is end of engineering involvement. Engineering and the vendor are motivated to rush through the effort to get to the next project. Most analytical effort is spent on redesigns or fixes to original design errors. The fixes are typically tactical and not strategic.</td>
</tr>
<tr>
<td>Operation</td>
<td>Production and maintenance</td>
<td>Costs are by far the largest of any phase, typically as high as 80% of the total life-cycle cost. These costs are rarely analyzed or controlled as equipment performance tends to steadily decline.</td>
<td>Little or no analytical resource is available. Engineering is working on projects, maintenance is fighting fires, and production is pressed for schedule compliance.</td>
</tr>
<tr>
<td>Disposal</td>
<td>Maintenance</td>
<td>Costs in terms of lingering liabilities can be enormous. Costs can be minimal if sufficient up-front engineering is performed.</td>
<td>Little or no analytical work or planning is performed unless there are hazards associated with disposal.</td>
</tr>
</tbody>
</table>

Source: Productivity Inc.

TPM Equipment Management Life Cycle

Small Group Cross-functional Activities

Specification | Procurement | Startup | Operation | Disposal
Engineering | Purchasing | Team | Production/Maint. | Maintenance

Company Policies and Rules

Source: Productivity Press
Early Equipment Management and Maintenance Prevention (MP) Design

- During equipment specification and procurement, TPM focuses on lowering total life-cycle cost through the use of Maintenance Prevention design.

**Maintenance Prevention Design:**

Minimizes future maintenance costs and deterioration losses of new equipment by taking into account (during planning and construction) maintenance data on current equipment and new technology and by designing for high reliability, maintainability, economy, operability, and safety.

Training to Boost Operating and Maintenance Skills

- Basic policy is to develop specialist skills through an active program of on-the-job training and self-development, supported by off-the-job training.

- Equipment-competent operators must acquire the following abilities:
  - To detect equipment abnormalities and effect improvements
  - To understand equipment structure and functions and be able to discover the causes of abnormalities
  - To understand the relationship between equipment and quality and be able to predict quality abnormalities and discover their causes
  - To understand and repair equipment
Maintenance Skills Training

- Maintenance professionals must be able to:
  - Instruct operators in correct handling, operating and daily maintenance of equipment
  - Correctly assess whether equipment is operating normally or not
  - Trace the causes of abnormalities and restore normal operation correctly
  - Improve equipment and component reliability, lengthen equipment lifetimes
  - Understand equipment diagnostics and use and standardize them
  - Optimize the preceding activities and make them as cost-effective as possible

Maximize Equipment Effectiveness

- Primary measure of performance in TPM is overall equipment effectiveness (OEE) and overall plant effectiveness (OPE).

- OEE measures the effective utilization of capital assets by expressing the impact of equipment related losses. Eight types of equipment/plant losses are tracked:
  - **Shutdown loss:** is the time lost when production stops for planned annual shutdown maintenance or periodic servicing.
  - **Production adjustment loss:** is time lost when changes in supply and demand require adjustment in production plans.
  - **Equipment failure loss:** is time lost when a plant/equipment stops because equipment loses its specified functions


Maximizing Equipment Effectiveness (Cont.)

- Process failure losses: is when a plant/equipment shuts down as a result of factors external to the equipment, such as changes in the physical or chemical properties of the substances being processed.

- Normal production losses: are rate losses that occur during normal production at plant/equipment startup, shutdown, and changeover.

- Abnormal production losses: are rate losses that occur when a plant/equipment operate at less than ideal speed.

- Quality defect losses: include time lost in producing rejectable product, physical loss in scrap, and financial losses due to product downgrading.

- Reprocessing losses: are recycling losses that occur when rejected material must be returned to a previous process/equipment to make it acceptable.

Overall Plant Effectiveness

- Is the product of the availability, performance rate, and quality rate.

- Is a comprehensive indicator of a plant's condition that takes into account operating time, performance and quality.

  - Availability: is the operating time expressed as a percentage of the calendar time

  \[
  \text{Availability} = \frac{\text{Calendar time} - (\text{shutdown loss} + \text{major stoppage loss})}{\text{Calendar time}} \times 100
  \]

  Shutdown losses = Shutdown maintenance loss + production adjustment loss

  Major stoppage loss = equipment failure loss + production failure loss
Overall Plant Effectiveness (Cont.)

- **Performance rate:** Expresses the actual production rate as a percentage of the standard production rate. The standard production rate is equivalent to a plant’s design capacity and is the intrinsic capacity of a particular plant.

  
  The actual production rate is expressed as an average.

  Performance rate = $\frac{\text{Average actual production rate}}{\text{Standard production rate}} \times 100\%$

- **Quality rate:** Expresses the amount of acceptable product (total production less downgraded product, scrap, and reprocessed product) as a % of total production

  Quality rate = $\frac{\text{Production quantity} - (\text{quality defect loss} + \text{reprocessing loss})}{\text{Production quantity}} \times 100\%$

---

OEE Example Calculation

Calendar Time: 24 hours x 30 days  
Operating Time: 24 hours x 27 days

A. Availability = $\frac{24 \times 27}{24 \times 30} \times 100\% = 90\%$

<table>
<thead>
<tr>
<th>Actual Production Volume</th>
<th>Days</th>
<th>Volume</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Standard Production Volume</td>
<td>6</td>
<td>1000</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>800</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1000</td>
<td>12000</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>27</td>
<td></td>
<td>23900</td>
</tr>
</tbody>
</table>

Actual Production Rate = 23900/27 = 885 tons/day

B. Performance Rate = 885/1000 = .885

C. If 100 ton of rejectable product are produced, then Quality Rate = 23800/23900 = .996 = C

D. OEE = 0.90 x 0.885 x 0.996 = .793 or 79.3%
Overall Plant Effectiveness

- World Class Maintenance Requires:
  - Availability ≥ 90%
  - Performance Efficiency ≥ 95%
  - Rate of Quality Products ≥ 99%
  - In-order-to yield an OEE ≥ 85%

OPE and the Structure of Losses

Availability = \[ \frac{\text{Calendar time} - (1) - (2) - (3) - (4)}{\text{Calendar time}} \times 100\% \]

Performance rate = \[ \frac{\text{Average actual production rate}}{\text{Standard production rate}} \times 100\% \]

Quality rate = \[ \frac{\text{Production amount} - (7) - (8)}{\text{Production amount}} \times 100\% \]

Overall Plant Effectiveness = Availability x Performance rate x Quality rate

Source: Productivity Inc.
Company Examples
Eastman Chemical Company

Reliability Journey

Integration to Life Cycle Cost

R&D

RBM Implementation

Strategic Plan

RBM

Reactive

Preventive

Predictive

Proactive

Focus

Organizational Linkage

Education

Managing Results

Case for Change

Culture

Principles

Results Expected

Managing Results

Strategic Plan

Benchmarking

Measures

Organization

Goals

Strategy

E. I. Dupont

- Widely recognized for outstanding safety record as well as its vigorous approach to benchmarking.
- Learned of TPM processes before most other North American companies.
- Organized an internal staff function, the Corporate Maintenance Leadership Team (CMLT), responsible for helping plants improve equipment management.
- Decided that maintenance needed to be view strategically in order for it to support overall corporate goals.
- Developed a vision of success and the establishment of a process to achieve that vision.
- Established an internal award system that recognizes excellence in equipment management
3M Company
Excellence in Maintenance

Advanced Planning and Scheduling System

Performance Tracking and Measurement System

Employee Involvement

Predictive Maintenance

Excellence in Maintenance

Preventive Maintenance

Maintenance Conscious Engineering

Employee Education Training & Development

Computerized Maintenance Management System