Chapter 7
Maintaining and Improving Equipment

**Types of Maintenance**

- Reactive Maintenance
- Preventive Maintenance
  - Time-based
  - Condition-based (predictive technologies)
- Proactive Maintenance
  - FEMA analysis
  - Age Exploration
**Reactive Maintenance**

- Fix it when it breaks
- Very expensive; maintenance staff typically work overtime.
- Hasty repairs; typically not high quality.
- Can rarely be planned. That is one of the primary reasons it is so expensive.
- Applicable for a very small subset of maintenance activities
  - Replacement of light bulbs.
  - Inexpensive items, readily available.

**Preventive Maintenance – Time-based**

- Better than reactive; can usually reduce maintenance costs by 50%, primarily because it is planned.
- Assumes that wear-out failure is the typical failure mode (will return to this).
- Since it can be planned, it will increase asset reliability.
- It is the stepping stone to predictive and potentially TPM or RCM (Total Productive Maintenance and Reliability Centered Maintenance).
Preventive Maintenance – Condition-based

❖ Uses predictive technologies to monitor vibration, speed, temperature, sound, etc.

❖ Assumes these variables can be measured and impending failures can be predicted.

❖ Tends to be more effective than preventive maintenance.

❖ Requires capital and effectively trained technicians to take and analyze readings.

❖ Expected to increase as technologies become available (Some say 50% of all R&M activities will be driven by predictive technologies in next ten years).

TPM

❖ Purpose is to obtain the ultimate potential from equipment.

❖ Equipment requirements:
  - Availability: Equipment is in operational condition when needed.
  - Efficiency: Equipment performs at its standard or rated speed.
  - Quality: Equipment produces no non-conformance or defects.

❖ Includes restoration and redesign so that equipment performs better and requires less maintenance than when it was new.

❖ Operators perform basic equipment repairs.

❖ Teams of maintenance staff and engineers redesign equipment to increase reliability, maintainability, and overall performance.
Benefits of TPM (Nakajima)

- Breakdowns reduced by 98%
- Defect rate reduced by 65%
- Labor cost reduced by 30%
  - Maintenance costs reduced by 15 - 30%
  - Energy costs reduced by 30%
- Inventory turns increased by 200% (3 to 6 times per month)
- Improvement ideas increased by 127%

Equipment Losses

- Downtime from setup and adjustments.
- Downtime from breakdowns.
  - These two affect availability
- Idling and minor stoppages
  - Equipment is starved or blocked
- Reduced speed (worn out or needs adjustment)
  - The above two losses affect efficiency
- Defects caused by variability in equipment performance.
- Reduced yield caused by non-optimal operations
  - These last two affect quality
Criteria For Measuring Six Losses

- Maintainability
- Reliability
- Availability
- Efficiency
- Quality Rate
- Overall Equipment Effectiveness

Maintainability

- Effort and cost of performing maintenance
  - Ease of access to equipment for maintenance
  - Skill level required to do the maintenance
  - Availability of getting spare parts and service

\[
MTTR = \frac{\sum \text{(Downtime for Repair)}}{\text{Number of Repairs}}
\]

- Down time for repair includes waiting time for repairs, time spent doing repairs and time spent testing and getting equipment ready to resume operation.
**Repair-related Downtime Versus Repair Time**

<table>
<thead>
<tr>
<th>Machine Stops</th>
<th>Find, wait for repair person</th>
<th>Diagnose Problem</th>
<th>Find spare parts</th>
<th>Repair problem</th>
<th>Test machine</th>
<th>Machine back in service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Repair time</td>
<td></td>
<td>Total Repair-Related Downtime</td>
</tr>
</tbody>
</table>

**Reliability**

- **Definition**
  Probability that equipment will perform properly under normal operating circumstances.

- Probability of successful performance

  \[ R = \frac{\text{Number of Successes}}{\text{Number of Repetitions}} \]

  where number of repetitions is the number of times the equipment does something.

  If the machine produces 100 parts and 96 of them are good, then the unit is 96% reliable.
Patterns of Equipment Failure

- Graphs show conditional probability of failure against operating age

<table>
<thead>
<tr>
<th>Type</th>
<th>% equipment conforming</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Bathtub</td>
<td>4%</td>
</tr>
<tr>
<td>B. Wearout</td>
<td>2%</td>
</tr>
<tr>
<td>C. Gradual rise</td>
<td>5%</td>
</tr>
<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.

Source: “Maxim 4: Most failures are not more likely to occur as equipment gets older” by John Moubray. http://www.aladon.co.uk/p15.html

Example 1: Failure Potential Curve

Suppose we start with 110 components and observe the time periods within which they fail. We observe the following:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Failures</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>15</td>
<td>46</td>
<td>30</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>No. Survivors</td>
<td>110</td>
<td>109</td>
<td>108</td>
<td>107</td>
<td>106</td>
<td>105</td>
<td>104</td>
<td>103</td>
<td>102</td>
<td>101</td>
<td>86</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

Now, the failure potential is a conditional probability. It specifies for an item that has survived up until a given time period, the probability that it will then fail during that time period. It is computed as the number of items that fail in a period, divided by the number of items that started the period. For example, using the above numbers and looking only at period 11, the number of observed failures is 30 and the number of items started is 40, so the failure potential in period 11 is 75%.

Performing the same computation for all periods and rounding to one decimal gives:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Failure Potential</td>
<td>.9 .91 .92 .93 .93 .94 .94 .95 .96 1.94 14.9 53.5 75.0 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notice the failure potential in this case roughly conforms to pattern B on slide 13.
Mean Time Between Failure

- Represents the average time between failures (if can be repaired)
- Time to first failure for equipment that cannot be repaired.
- Assuming a constant failure rate (as in Equation 13)

\[
MTBF = \frac{\text{Total Running Time}}{\text{Number of Failures}}
\]

Reliability, \( R(T) \), is defined as the probability that the item will not fail before time \( T \):

\[
R(T) = e^{-\lambda T},
\]

where
\[
0 \leq R(T) \leq 1.0
\]
\( e \) = natural logarithm base (about 2.718)
\( T \) = specified time,
\( \lambda \) = failure rate = \( 1 / MTBF \)

Example 2: MTBF

Twenty machines are operated for 100 hours. One machine fails in 60 hours and another fails in 70 hours. What is the mean time between failures?

Eighteen of the machines ran for 100 hours, while two others ran for 60 hours and 70 hours each. The total running time is \( 18 \times 100 + 60 + 70 = 1930 \), and

\[
MTBF = \frac{1930}{2} = 965 \text{ hours / failure}
\]
Example 3: Reliability for a Given Time of Operation

What is the reliability of the same machines from example 2 at 500 hours? 900 hours?

\[ \lambda = \frac{1}{965} = .001362 \text{ failure/hour} \]

\[ R(500) = e^{-0.001362 (500)} = 0.596 \]

\[ R(900) = e^{-0.001362 (900)} = 0.394 \]

Nearly a 60% chance that the machine will run 500 hours without failure and about a 40 percent chance that it will run for 900 hours.

Suppose the machine's performance is entirely dependent on one particular component. Each time the component is replaced, the machine's reliability returns to 100%. How often should the component be replaced so the machine's reliability is never less than 90%?

\[ R(T) = e^{-\lambda T} \]

\[ 0.90 = e^{-0.001362 T} \]

Since \( \ln X^n = n (\ln X) \) and \( \ln e = 1 \)

\[ T = -\frac{\ln (0.90)}{-0.001362} \]

\[ T = 101.7 \]

Results from this type of analysis are not necessarily intuitive. If we wanted to increase the reliability to 95%, the results gives 49.5. This is despite the fact that with 20 machines tested, none failed in less than 60 hours, and 18 were still running at 100 hours.

Availability

Definition - proportion of the time equipment is actually available to perform work out of the time it should be available.

One measure: \( A = \frac{MTBF}{MTBF + MTTR} \)
**Availability**

Should include repair and non-repair sources of downtime. Another measure:

\[ A = \frac{\text{Actual Running Time}}{\text{Planned Running Time}} \]

Planned Running Time = total plant time - planned downtime
Actual Running Time = planned running time - all other downtime

This measure of availability might be preferable because it gives incentive to reduce both MTTR and internal setup time.

Setup time and MTTR are often interrelated to the extent that poorly maintained equipment is harder to change over and adjust.

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**Repair downtime Variability**

- Machines with more frequent but less severe breakdowns are better in terms of process stability and inventory cost than machines with less frequent but more severe breakdowns.

- Accurate assessment of availability and variability calls for high data integrity.

- Must show all downtime for internal setups and failures.

  In many companies, downtime of 10 or 20 minutes are not even recorded.


**Efficiency**

Efficiency is a measure of how well a machine performs while it is running.

- Is the machine producing output when it is running?
- Is it producing output at the right speed.

**Rate Efficiency**

Machine is running, but parts do not feed correctly and thus output is impacted.

Suppose a machine runs 535 minutes a day.
Average daily output of the machine is observed to be 830 parts.
Average cycle time is observed to be 0.6 minutes/part.
It should take $830 \times 0.6 = 498$ minutes per day to produce the parts.
Rate efficiency is as follows:

$$RE = \frac{Actual \ Production \ Volume \times \ Actual \ Cycle \ Time}{Actual \ Running \ Time}$$

$$RE = \frac{830 \times 0.6}{535} = \frac{498}{535} \approx 0.93$$

Machine is processing parts only 93% of the time it is running.

**Speed Efficiency and Performance Efficiency**

Speed Efficiency - Example

Suppose a machine is designed to produce a part every 30 seconds (0.5 minutes per part).

The observed time to produce a part is 0.6 minutes per part. Then,

$$SE = \frac{Design \ Cycle \ Time}{Actual \ Cycle \ Time} = \frac{0.5}{0.6} = 0.83$$

Machine is running at 83% of its rated speed.

Overall performance efficiency, $PE = RE \times SE$

For the past two examples, $PE = 0.93 \times 0.83 = 0.78$

If the design cycle time is unknown or if the machine makes different parts with different cycle times then $SE$ is ignored and $PE$ is calculated solely as a function of lost time from interruptions.

$$PE = \frac{Actual \ Running \ Time - Time \ for \ Interruptions}{Actual \ Running \ Time}$$
Quality Rate and OEE

The quality rate is an index of the equipment’s ability to produce output that is non-defective, or conforms to requirements.

\[ Q = \frac{\text{Actual Production Volume} - \text{Defective Output}}{\text{Actual Production Volume}} \]

Overall Equipment Effectiveness (OEE)

\[ \text{OEE} = A \times \text{PE} \times Q \]

Causes of Equipment Problems

- Deterioration
- Equipment is ill-suited for the purpose
- Failure to maintain equipment requirements
- Failure to maintain correct operating conditions
- Lack of skills of operators, maintenance crew, and setup people
PM Program emphasis

- Maintain normal operating conditions
  - Know what normal operating conditions are.
  - Standard conditions should be posted at each machine.
  - De-rating the equipment unless capacity is necessary (life of a bearing is inversely proportional to rotational speed).

- Maintain equipment requirements
  - Lubrication (GM-70% of operators lack of lubrication was major reason for downtime).
  - Tight bolts and fasteners.
  - Use of proper tools and fasteners in machine setup.

PM Program emphasis (Continued)

- Keep equipment and facilities clean and organized
  - 5s
  - Sort, organize, clean, standardize, train and sustain
  - Management must allow the time to do it.

- Monitor equipment daily
  - Keep problems simple so they do not become major issues.
  - Operators are the best resource to perform these checks.

- Schedule preventive maintenance
  - Provides for periodic, scheduled downtime during which experts can inspect, replace parts as necessary and overhaul equipment
Scheduling PM

- Clock or calendar interval
  - Two shift operation with third shift for PM
  - Three shift operation with first and last 30 minutes of each shift for PM
  - Decide which tasks should be performed quarterly, monthly, weekly, etc.

- Cycles of usage
  - Every 1000 hours
  - Every 500 units produced

- Periodic inspection - schedule PM whenever periodic inspections indicate impending or possible malfunction or failure.

Trade-off / PM Versus Breakdown

\[ E(n) = \text{expected time between breakdowns} \]
\[ E(n) = \sum nP_n, \] where
\[ n = \text{time period when a breakdown may occur}, \]
\[ P_n = \text{probability of a breakdown in period } n \]
\[ = \frac{b_n}{\sum b_n} = \frac{\text{Number of machine breakdowns in period } n}{\text{Total number of breakdowns in all periods}} \]

Expected number of breakdowns = \( 1 / E(n) \).

Expected cost of letting \( N \) identical machines breakdown, \( C_B \), is:

\[ C_B = \frac{N \times c_B}{E(n)} \]
\[ c_B = \text{cost of repairing a broken down machine} \]

This is the cost of not performing PM
Trade-off / PM Versus Breakdown

To obtain the cost of performing PM involves determining the costs of performing Routine PM and the costs of repairing machines that breakdown regardless of PM.

c_p = cost of performing PM on a single machine.
N (c_p) = cost of performing PM on N identical machines
B_n = expected number of breakdowns when PM is performed every n periods.

\[ B_n = N \left( P_1 + \ldots + P_n \right) + B_2 P_{n-1} + B_3 P_{n-2} + \ldots + B_n P_1 \]

Therefore, the cost of repair maintenance is \( B_n (c_B) \)

The total expected cost per period of performing PM every n periods, \( C_n \), is the sum of the cost of PM per period and the cost of repair maintenance per period.

\[ C_n = \frac{N \times c_p}{n} + \frac{B_n c_B}{n} \]

when \( C_n < C_B \), then PM every n periods is less costly than letting equipment breakdown.

Example 4: Determining Maintenance Costs

Suppose a group of 25 identical machines is monitored for 5 months, and without M the number of breakdowns in each month is as follows:

<table>
<thead>
<tr>
<th>os. Of Operation before Breakdown, n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>o. of Breakdowns, b</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>probability of Breakdown (P_n)</td>
<td>0.12</td>
<td>0.16</td>
<td>0.12</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

This indicates that the longest time a machine runs before breaking down is 5 months, and that, for example, 4 machines run 2 months before they broke own.

The cost of repairing a machine after breakdown is $500 (c_B), whereas the cost of PM on a machine is $100 (c_p). Preventive maintenance does not eliminate breakdowns.

What is the monthly cost of breakdowns?

If PM is used, how often should it be done?
Solutions:

1. With no PM, the expected time between breakdowns is:
   \[ E(n) = \sum np_n = 1(.12) + 2(.16) + 3(.12) + 4(.2) + 5(.4) = 3.6 \text{ months} \]

   Thus, the expected cost of not performing PM is
   \[ C_B = \frac{NcE(n)}{3.6} = \frac{25 \text{ machines} \times ($500 \text{ per machine})}{3.6} = \$3472.22 \]

2. The expected number of breakdowns with PM performed every \( n \) months, \( B_n \), is
   \[ N \left( P_1 + \ldots + P_n \right) + B_nP_1 + B_nP_2 + \ldots + B_nP_n \]

   \[ B_1 = N (P_1) = 25(.12) = 3 \]
   \[ B_2 = N (P_1 + P_2) + B_2P_1 = 25 (.28) + 3 (.12) = 7.36 \]
   \[ B_3 = N (P_1 + P_2 + P_3) + B_3P_1 + B_3P_2 = 25 (.4) + 3 (.16) + 7.36 (.16) = 11.36 \]
   \[ B_4 = N (P_1 + P_2 + P_3 + P_4) + B_4P_1 + B_4P_2 + B_4P_3 = 25 (.6) + 3 (.12) + 7.36 (.16) + 11.36 (.12) = 17.9 \]
   \[ B_5 = N (P_1 + P_2 + P_3 + P_4 + P_5) + B_5P_1 + B_5P_2 + B_5P_3 + B_5P_4 = 25 (1.0) + 3 (.2) + 7.36 (.12) + 11.36 (.16) + 17.9 (.12) = 30.45 \]

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Solution (Cont.)

<table>
<thead>
<tr>
<th>Months Between PM Service, ( n )</th>
<th>Expected Breakdowns in ( n ) Months, ( B_n )</th>
<th>Expected Breakdown Cost = ( 500B_n )</th>
<th>Expected Breakdown Cost/Month = ( 500B_n/n )</th>
<th>Expected Cost/Month = ( 25 \times ($100/n) )</th>
<th>Expected Total Cost, ( C ) (Breakdown + PM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1500</td>
<td>1500</td>
<td>2500</td>
<td>4000</td>
</tr>
<tr>
<td>2</td>
<td>7.36</td>
<td>3680</td>
<td>1840</td>
<td>1250</td>
<td>3090</td>
</tr>
<tr>
<td>3</td>
<td>11.36</td>
<td>5680</td>
<td>1893</td>
<td>833</td>
<td>2726</td>
</tr>
<tr>
<td>4</td>
<td>17.9</td>
<td>8950</td>
<td>2238</td>
<td>625</td>
<td>2863</td>
</tr>
<tr>
<td>5</td>
<td>30.45</td>
<td>15225</td>
<td>3045</td>
<td>500</td>
<td>3545</td>
</tr>
</tbody>
</table>

Except for PM every month or every 5 months (\( n = 1 \) or 5), the expected cost of PM service is always less than the expected cost of not performing PM (\( \$3472 \)). Using the least costly Schedule of PM every 3 months instead of no PM, expected savings is \( 3472 - 2726 = 746 \)
**Problems With PM Tradeoffs**

- Periodic scheduled replacement of components can actually increase the risk of failure in complex machines and processes.

- If infant mortality failure pattern is appropriate, then replacing components at a given rate increases risk.

- For most equipment the failure pattern is unknown and will always be unknown.
  - Must experience several failures before you can pick up a specific pattern. Companies cannot afford to let component fail.
  - Must rely on periodic inspections and/or monitoring to predict potential failure.

**Manage Maintenance Information**

- CMMS
  - Handles workorders for repair maintenance
  - Maintains PM procedures and schedules
  - Releases workorders for all scheduled preventive, predictive, and repair maintenance.
  - Prepares periodic summary reports

- Typical information for equipment
  - Type of machine - Serial number
  - Date put in service - Manufacturer
  - Dates of upgrades/changes - Location in plant
  - Location of manuals, schematics, drawings, - Spare parts
Predictive Maintenance

- Use periodic, scheduled inspections to determine the replacement requirements (usually by maintenance staff).

- Warning hopefully provides sufficient time to order replacement parts, transfer production to other machines, or schedule tasks.

- Vibration, speed, temperature, sound are example predictors of failure.
  - X-ray radiography identifies stress cracks on a machine
  - Infrared thermography (temperature differences) and ultrasound (sound differences beyond human perception)

- Some equipment is so important that on-line sensors are used.

TPM

- Provide maximum support and service to all users of equipment

- A machine breakdown is seen as a defect

- TPM is a form of continuous improvement. Includes:
  - Educating and involving workers
  - Upgrading and redesigning equipment
  - Build mistake proofing devices into equipment
  - Monitoring equipment performance

- Takes on a life-cycle perspective

- Emphasis and spending switches from procuring new or more equipment to monitoring and upgrading existing equipment.
TPM – Operator’s New Roles

- Perform basic PM tasks and minor repairs. These can be performed more frequently and often more efficiently than the specialists.

- Maintenance staff’s new roles
  - Teaching operators skills in basic maintenance
  - Assisting operators with basic maintenance
  - Restoring deteriorated equipment
  - Assessing weaknesses in equipment design
  - Upgrading equipment
  - Developing new operating and maintenance requirements for equipment

Closing Comments

- Develop in-house capability to redesign equipment, fixtures and tools

- Eliminate human error in operation and maintenance
  - Education and training (operator certification programs)
  - Mistake proofing (lights, sound, automatic machine stop, etc).

- Must do it all over, but have a pilot area and grow the “lessons learned.”