**Maintenance**

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**LEARNING OBJECTIVES**
After completing this supplement, you should be able to:

**LO 1** Explain what maintenance is, its importance in production systems, and the range of maintenance activities.

**LO 2** Describe preventive maintenance and determine the economic amount of preventive maintenance.

**LO 3** Discuss breakdown (emergency) maintenance.

**LO 4** Decide when to replace a machine or a group of components.
LO1 INTRODUCTION

Maintaining the production capability of an organization is an important function in any production system. **Maintenance** encompasses all the activities that relate to keeping facilities and equipment in good working order and making necessary repairs when breakdowns occur so that the system can perform as intended.

Maintenance activities are often organized into two categories: (1) buildings and grounds, and (2) equipment maintenance. Buildings and grounds is responsible for the appearance and functioning of buildings, roads, parking lots, lawns, fences, and the like. Equipment maintenance is responsible for maintaining machinery and equipment in good working condition and making all the necessary repairs. In this supplement we will mainly focus on equipment maintenance.

The goal of maintenance management is to keep the production system in good working order at minimum cost. There are several reasons for wanting to keep equipment and facilities in good operating condition, such as to:

1. avoid production disruptions (down time), including slowdowns and reduced yield
2. maintain high quality and safety
3. avoid missed delivery dates

Organizations have two basic options with respect to maintenance. One option is reactive: it is to deal with breakdowns when they occur. This is referred to as **breakdown (emergency) maintenance**, i.e., repair or replacement only after failure. The other option is proactive: it is to reduce or avoid breakdowns through a program of lubrication, bolt tightening, cleaning, inspection, and replacement of worn parts. This is referred to as **preventive maintenance**.

**Example 5-1**

The historical frequency of breakdowns of a machine per month is shown in the following table. The cost of a breakdown repair is $1,000 and the cost of preventive maintenance is $1,250 per month (daily inspections, cleaning, lubrication, tightening bolts, and possible parts changes). If preventive maintenance is performed, the probability of machine breakdown is negligible. Should the manager use preventive maintenance, or would it be cheaper to repair the machine only after it breaks down?

<table>
<thead>
<tr>
<th>Number of Breakdowns</th>
<th>Frequency of Occurrence</th>
<th>Expected Number of Breakdowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.20</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>2</td>
<td>.40</td>
<td>.80</td>
</tr>
<tr>
<td>3</td>
<td>.10</td>
<td>.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

The expected number of breakdowns without preventive maintenance is 1.40 per month:

\[
\text{Expected cost of breakdown repair} = 1.40 \text{ breakdowns/month} \times $1,000/\text{breakdown} = $1,400 \text{ per month.}
\]

Therefore, preventive maintenance would cost $1,250 per month. Preventive maintenance would yield a savings of $150/month.

Maintenance managers try to make a trade-off between these two basic options that will minimize their combined cost. With no preventive maintenance, breakdown and repair/replacement costs would be tremendous. Furthermore, costs of lost production and wages
while equipment is not in service must be factored in. So must the cost of injuries or damage to other equipment. However, beyond a certain point, the cost of preventive maintenance exceeds its benefit.

As an example, if a person never had the oil changed in his or her car, and never had the brakes or tires inspected, but simply had repairs done when absolutely necessary, preventive costs would be negligible but repair costs would be quite high, considering the wide range of parts (engine, steering, transmission, tires, brakes, etc.) that could fail. In addition, there would be the uncertainty of when failure might occur (e.g., on the highway, during rush hour, or late at night). On the other hand, having the oil changed every morning would obviously be excessive because automobiles are designed to perform for much longer periods without oil changes. The best approach is to seek a balance between preventive maintenance and breakdown (emergency) maintenance. The same concept applies to maintaining production systems: strike a balance between prevention costs and breakdown costs. This concept is illustrated in Figure 15S-1.

The age and condition of equipment, the degree of technology involved, the type of production process, and similar factors enter into the decision of how much preventive maintenance is desirable. Thus, in the example of a new automobile, little preventive maintenance may be needed since there is slight risk of breakdowns. As the car ages and becomes worn through use, the desirability of preventive maintenance increases because the risk of breakdown increases. Thus, when tires and brakes begin to show signs of wear, they should be replaced before they fail; dents and scratches should be periodically taken care of before they begin to rust; and the car should have its oil changed after exposure to high levels of dust and dirt. Also, inspection and replacement of old critical parts that tend to fail should be performed before a long trip to avoid disruption of the trip and costly emergency repair bills.

A fundamentally different approach is to redesign the item in order to prevent failures from occurring. This is done by increasing the reliability of the equipment. This approach is part of reliability-centred maintenance (RCM). In RCM, for each equipment, its major functions are identified, then major possible failure problems are determined. Next, major causes of each failure (also called failure mode) are identified, and finally various ways (including preventive maintenance) are used to reduce the effect of each major cause. For more details, see e.g., http://www.weibull.com/basics/rcm.htm.

A study was performed by a maintenance engineer in Xcel Energy, the Midwest U.S. utility, based in Minneapolis. In each electrical distribution substation, there is a battery that will operate a relay switch when electricity is interrupted or there is a surge. The system includes a battery charger...
and cables. Dominant failure problems for the battery system are (1) the cable does not conduct electricity, (2) the battery loses its capacity, and (3) the battery charger does not charge the battery. For each critical failure problem, dominant failure causes (modes) are identified, and a maintenance program is suggested to reduce the effect of failure mode. For example, for “cable does not conduct electricity,” major causes are loose connection and corrosion. For “loose connection,” annual electrical resistance test is prescribed, whereas for “corrosion,” the preventive maintenance of cleaning and grease-coating the connections every quarter is prescribed.

RCM should be the ultimate goal of every maintenance system. However, many organizations lack the basics of maintenance management: identifying important maintenance jobs, scheduling the preventive maintenance jobs effectively, and performing the necessary maintenance effectively and efficiently.

**Example S-3**

Simpson Tacoma Kraft company (near Seattle) is a paper mill that needed to cut costs (like the other paper mills) when the current recession began. Maintenance had become reactionary. Relationship with the operations department was not good. Only 20 percent of planned jobs and 30 percent of emergency jobs in a week could be performed internally, resulting in excessive use of contractors. In the spring of 2009 the plant manager called for the re-assessment of the maintenance function. A consulting firm was brought in. They interviewed most staff. A program of change was instituted. The relationship between maintenance and operations needed to be improved. Tradesmen (a pipefitter, an electrician, a machinist, and an instrument technician) were employed as maintenance work planners. Weekly metrics (efficiency, equipment availability, etc.) were developed. Now, operations and maintenance supervisors meet every day. Written guidelines for most repair jobs have been developed, standardizing maintenance processes and establishing quality norms. The store’s staff prepares kits of necessary parts for maintenance jobs so that technicians don’t have to waste time looking for parts. Now, the number of maintenance jobs performed in a week has almost doubled. Next step is equipment failure analysis (i.e., RCM).

### LO 2 PREVENTIVE MAINTENANCE

The goal of preventive maintenance is to reduce breakdowns and avoid the associated costs. Those costs can include loss of output; idle workers; schedule disruptions; injuries; damage to other equipment, products, or facilities; and unexpected repairs, which may involve maintaining inventories of spare parts, repair tools and equipment, and repair specialists.

Most preventive maintenance is periodic (others are condition based). Periodic preventive maintenance can be scheduled according to the availability of maintenance personnel and to avoid interference with operating schedules. Managers usually schedule preventive maintenance using some combination of the following:

1. The result of planned inspections that reveal a need for maintenance
2. According to the calendar (passage of time)
3. After a predetermined number of operating hours (or miles for vehicles)

An important issue in periodic preventive maintenance is its frequency. As the time between periodic maintenance increases, the cost of preventive maintenance per unit time decreases while the risk (and cost) of breakdowns increases. The goal is to strike a balance between the two costs.

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Given preventive maintenance (PM) interval $L$, if a breakdown occurs before $L$, then a breakdown maintenance cost will be incurred, and the machine will be repaired and the next time between breakdowns (TBB) will start. On the other hand, if there is no breakdown before $L$, then a PM cost will be incurred at time $L$. We determine $L$ so that expected cost of each consequence is equal, i.e.,

\[
\text{Breakdown cost} \times \text{Prob}(TBB < L) = \text{Preventive cost} \times \text{Prob}(TBB \geq L)
\]

\[
\text{Breakdown cost} \times \text{Prob}(TBB < L) = \text{Preventive cost} \times (1 - \text{Prob}(TBB < L))
\]

\[
(\text{Preventive cost} + \text{Breakdown cost}) \times \text{Prob}(TBB < L) = \text{Preventive cost}
\]

\[
\text{Prob}(TBB < L) = \frac{\text{Preventive cost}}{(\text{Preventive cost} + \text{Breakdown cost})} \quad (15S-1)
\]

That is, choose $L$ so that the probability that time between breakdowns is smaller than $L$ is equal to Preventive cost/(Breakdown cost + Preventive cost). Note that this marginal cost method is similar to that used in the single period model of Chapter 12.

Suppose that the time before breakdown is Normally distributed and has a mean of three weeks and a standard deviation of .60 week. If breakdown cost averages $1,000 and a preventive maintenance costs $250, what is the optimal preventive maintenance interval?

**Solution**

Begin using formula 15S-1 by calculating the right-hand-side:

\[
\frac{\text{Preventive cost}}{\text{Preventive cost} + \text{Breakdown cost}} = \frac{250}{250 + 1000} = .20
\]

Find the number of standard deviations from the mean represented by an area under the Normal curve of .20 (from the left tail) using Appendix B, Table B. It is $-0.84$. Use this value of $z$ to calculate the preventive maintenance interval:

\[
\text{Mean} + z \times \text{(standard deviations)} = 3 - 0.84 \times 0.60 = 2.496 \text{ (round to 2.5 weeks)}
\]

Ideally, preventive maintenance (especially replacing of worn-out parts) should be performed just prior to a breakdown because this will result in the longest possible use of equipment without a breakdown. **Predictive or condition-based maintenance** is based on historical records (to predict when a piece of equipment or part is about to fail) and ongoing monitoring of equipment condition (temperature, pressure, rates of flow, vibration, noise, humidity, and changes in electrical and mechanical characteristic of critical equipment) that will indicate impending damage to equipment. A good predictive maintenance relies on complete records for each piece of equipment (date of installation, operating hours, and dates and types of repairs) and instruments to monitor the health of each equipment.

The management of Temple-Inland’s newest mill in Maysville, Kentucky, wanted to cut the unscheduled downtime to less than 1 percent. The mill’s standard maintenance check was a walk-through by operators followed by a walk-through by maintenance staff. Problems were written in a notepad but not recorded in a computer so it was difficult to identify trends. Looking for a better solution, management purchased EXP software from Ivara. Now, operators walk through the mill, measuring the condition of equipment (100 or so measurements altogether) and entering them in the computer using hand-held devices. The data is checked by the software, which will trigger an alarm for any measurement that is out of the range. Typical problems (about 6 per day) include too much vibration, low oil, and leaking seal.

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Some Japanese companies use the operators themselves to perform basic preventive maintenance on their machines, rather than maintenance technicians/engineers. Called total productive maintenance (TPM), this approach is consistent with JIT/lean, where employees are given greater responsibility for quality, productivity, and the general functioning of the system.

Training of employees in proper operating procedures and in how to keep their equipment in good operating order—and providing the incentive to do so—are a major part of TPM. More and more, North American organizations are taking a cue from the Japanese and transferring routine maintenance (e.g., cleaning, tightening bolts, inspecting) to the users of equipment, in an effort to give them a sense of responsibility and awareness of the equipment they use (to cut down on abuse and misuse of the equipment) and to reduce the total cost of maintenance (for more details, see e.g., http://www.plant-maintenance.com/articles/tpm_intro.shtml).

**LO 3 BREAKDOWN (EMERGENCY) MAINTENANCE**

The risk of a breakdown can be greatly reduced by an effective preventive maintenance program. Nonetheless, occasional breakdowns still occur. Even organizations with good maintenance practices have to be prepared for breakdowns. Of course, organizations that rely less on preventive maintenance have an even greater need for effective ways of dealing with breakdowns.

Unlike preventive maintenance, management cannot schedule the breakdowns but must deal with them as they occur. The following provisions are used to deal with breakdowns:

1. Standby or backup equipment that can be quickly brought into service.
2. Inventories of spare parts that can be installed as needed, thereby avoiding lead times involved in ordering parts, and buffer inventories of work-in-process, so that other equipment will be less likely to be affected by short-term downtime of a particular piece of equipment.
3. Operators who are able to deal with emergencies (e.g., know how to lock up equipment), and perform at least some minor repairs on their equipment.
4. Maintenance staff who are well trained and readily available to diagnose and correct problems with equipment.

The degree to which an organization pursues any or all of the above provisions depends on how important a particular piece of equipment is to the overall production system. At one extreme is equipment that is the focal point of a system (e.g., printing presses for a newspaper, or vital operating parts of a car, such as brakes, steering, transmission, ignition, and engine). At the other extreme is equipment that is seldom used because it does not perform an important function in the system, and equipment for which substitutes are readily available.

**LO 4 REPLACEMENT**

When breakdowns become frequent and/or costly, the manager is faced with a trade-off decision in which costs are an important consideration: What is the cost of replacement compared with the cost of continued maintenance and repair? This question is sometimes difficult to resolve, especially if future breakdowns cannot be readily predicted. Historical records may help to project future experience. Most of us are faced with a similar decision with our automobiles: when is it time for a replacement?

Another situation when replacement before failure may be economical is in group replacement of components. There may be cost savings in replacing all the components together before most of them start to fail. The following example illustrates this situation.
The maintenance manager for a large factory is wondering if he should have all the 3,000 fluorescent light bulbs, used to illuminate the plant, replaced together in order to save labour costs. There are three light bulbs in a fixture (1,000 fixtures). They are lit about 4,000 hours a year. The light bulbs have a rated life of 25,000 hours with a standard deviation of 5,000 hours (a light bulb’s life is Normally distributed). If all the light bulbs are replaced together, it will take 12 minutes per fixture, whereas if a light bulb is changed individually when it fails, it will take 20 minutes (because the ladder has to be brought from storage and returned there after the work). Labour cost is $15 per hour. Each light bulb costs $1.35 (note that group replacement will also result in price breaks due to the large-quantity purchase but we ignore this fact here). What is the optimal group replacement interval (in years) for the light bulbs?

The average life of a bulb in years of usage is $25,000 / 4,000 = 6.25$ years with standard deviation of $4,000/5,000 = .8$ year. Because a bulb’s life is Normally distributed, it will most likely last 3 years. So, we will start with 3 years as group replacement year and add one more year until group replacement cost per year starts to increase.

<table>
<thead>
<tr>
<th>Replace After</th>
<th>Age at Replacement</th>
<th>Group Replacement Cost</th>
<th>Prob. of Failing Before Group Replacement</th>
<th>Individual (Failed) Replacement Costs</th>
<th>Total Cost</th>
<th>Cost per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 years</td>
<td>12,000 hours</td>
<td>$15(12/60)(1,000) + $1.35(3,000) = 7,050</td>
<td>$\text{Prob } [z &lt; (12 – 25)/5] = .0047$</td>
<td>$3,000(.0047) \times [$15(20/60) + $1.35] = 89.54$</td>
<td>7,139.54</td>
<td>2,379.85</td>
</tr>
<tr>
<td>4 years</td>
<td>16,000 hours</td>
<td>7,050</td>
<td>$\text{Prob } [z &lt; (16 – 25)/5] = .0359$</td>
<td>$3,000(.0359)($6.35) = 683.90$</td>
<td>7,733.90</td>
<td>1,933.48*</td>
</tr>
<tr>
<td>5 years</td>
<td>20,000 hours</td>
<td>7,050</td>
<td>$\text{Prob } [z &lt; (20 – 25)/5] = .1587$</td>
<td>$3,000(.1587)($6.35) = 3,023.24$</td>
<td>10,073.24</td>
<td>2,014.65</td>
</tr>
</tbody>
</table>

The lowest annual cost is for replacement after four years. Note: For simplicity, we have assumed that if a light bulb failed before group replacement time and was replaced, it would not fail again before the group replacement time.

**Solution**

**OM in ACTION**

**Dofasco’s Maintenance System**

When in the early 1990s competition in the steel industry increased, Dofasco’s equipment maintenance activities were mainly reactive to breakdowns. Dofasco had a Computerized Maintenance Management System (CMMS) software, but this was used only for issuing work orders. Because relevant information could not be input into the CMMS, planning for maintenance could not be performed effectively. Given the absence of a decision support software, Dofasco wrote its own software called Intelligent Condition Monitoring System (ICMS). ICMS, a predictive or condition-based maintenance software, is now being marketed by the consulting firm Ivara under the name EXP.

ICMS analyzes the data on temperature, pressure, vibration, etc., of a piece of equipment (collected by various types of inspection and test equipment) using “expert” rules to provide equipment condition indicators that will provide warnings and alarms under abnormal conditions. For example, a rule is “if pressure is raised to between 5.1 and 6 units, indicate a warning.” The system also provides root causes. For example, “if pressure warning is indicated, the cause is most likely a dirty filter.” ICMS also prescribes preventive inspection/maintenance for each piece of equipment. For example, “operator check sheet every 12 hours, lube every week, vibration analysis every 3 years.”

As a result of using ICMS, most maintenance work now is proactive and equipment uptime has increased by 10 percent, while maintenance workforce and parts inventory have been reduced by half.

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Summary

Maintaining the productive capability of an organization is an important function. Maintenance includes all of the activities related to keeping facilities and equipment in good operating order. The goal of maintenance management is to minimize the total cost of keeping the facilities and equipment in good working order. Maintenance decisions typically reflect a trade-off between preventive maintenance (regular cleaning, lubricating, tightening bolts, replacing worn parts, etc.), which seeks to reduce breakdowns, and breakdown (emergency) maintenance (repair or replacement only after failure). Reliability-centred maintenance tries to reduce the effect of each major cause of failure for equipment functions. Most preventive maintenance is performed periodically. However, predictive or condition-based maintenance also uses symptoms to detect impending failure. Total productive maintenance involves the operators to perform basic preventive maintenance themselves. Despite performing preventive maintenance, failures/breakdowns do occur and one needs to be prepared (e.g., have spare equipment/parts on site). Replacement is unavoidable. Its timing depends on the increasing cost of repair vs. cost of a new machine (minus salvage value of old machine). Group replacement of components may be economical when there are labour cost savings for replacing all units together.

Key Terms

- breakdown (emergency) maintenance, 2
- preventive maintenance, 2
- maintenance, 2
- predictive or condition-based maintenance, 5
- reliability-centred maintenance (RCM), 3
- total productive maintenance, 6

Discussion and Review Questions

1. What is maintenance and what is the goal of maintenance management? (LO1)
2. What are the costs associated with equipment breakdown? (LO1)
3. What advantages does preventive maintenance have over breakdown (emergency) maintenance? (LO1)
4. Explain the term reliability-centred maintenance. How is it different from preventive maintenance? (LO1 & 2)
5. What are three different ways preventive maintenance is scheduled? (LO2)
6. Explain the term predictive or condition-based maintenance. Give an example. (LO2)
7. Explain the term total productive maintenance. Give an example. (LO2)
8. List the major approaches organizations use to deal with breakdowns. (LO3)
9. Give an example of group replacement, other than replacing light bulbs in a factory. (LO4)
10. Discuss the key points of this supplement as they relate to maintenance of an automobile. (LO1–4)

Internet Exercises

1. Visit http://iom.invensys.com/EN/Pages/Avantis_EnterpriseAssetManagement.aspx, pick a case study of Avantis software, and determine how it has helped the customer. (LO1–4)
2. Visit http://www.pmworx.com/windmill.php?category=case_studies& page=case_study_1, pick a case study, and determine how Windmill Software has helped the customer. (LO1–4)
3. Visit http://www.desmaint.com/company/clientprofiles.htm, pick a case study, and determine how MAINTelligence software has helped the customer. (LO1–4)
4. Visit http://www.ivara.com/index.php/customer-success/case-studies, pick a case study, and determine how EXP software has helped the customer. (LO1–4)
5. Visit http://www.genesissolutions.com/resource-center/project-profiles/, pick a project, and summarize how GenesisSolutions has helped the client with maintenance management. (LO1–4)
6. Visit http://www.pemac.org/job.html, pick a maintenance management job announcement, and summarize the duties involved. (LO1–4)
7. Visit www.impomag.com/scripts/PRArchive.asp?RPTID=ARCHIVE&RELTYPE=CS&DISPTYPEPE=FULLARCH, choose a Cover Story article, and summarize its important points. (LO1–4)
1. The probability that a piece of equipment used in a hospital lab will need a number of repairs per year is given below. A service firm is willing to provide any number of necessary repairs for a fixed fee of $650 per year. Without this plan, a repair costs $500 on average. Which approach would be most economical, repair as needed or the fixed-fee service contract? (LO1)

<table>
<thead>
<tr>
<th>Number of repairs per year</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of occurrence</td>
<td>.15</td>
<td>.25</td>
<td>.30</td>
<td>.20</td>
<td>.10</td>
</tr>
</tbody>
</table>

2. The frequency of breakdown of a machine that issues lottery tickets is given below. Repairs cost an average of $240 per repair. A service firm is willing to provide annual service contracts under either of two options. #1 is $500 and covers all necessary repairs, and #2 is $350 and covers any repairs after the first one. Which option would have the lowest expected cost: pay for all repairs as they arise, service option #1, or service option #2? (LO1)

<table>
<thead>
<tr>
<th>Number of breakdowns/year</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of occurrence</td>
<td>.10</td>
<td>.30</td>
<td>.30</td>
<td>.20</td>
<td>.10</td>
</tr>
</tbody>
</table>

3. Determine the optimum preventive maintenance frequency for each of the pieces of equipment below if time between breakdowns is Normally distributed: (LO2)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Average Time (weeks) between Breakdowns</th>
<th>Standard Deviation (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A201</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>B400</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>C850</td>
<td>40</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Preventive Maintenance Cost</th>
<th>Breakdown Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A201</td>
<td>$300</td>
<td>$2,300</td>
</tr>
<tr>
<td>B400</td>
<td>$200</td>
<td>$3,500</td>
</tr>
<tr>
<td>C850</td>
<td>$530</td>
<td>$4,800</td>
</tr>
</tbody>
</table>

4. A grocery chain has 50 refrigerated trailers. Each trailer is used for approximately 2,500 hours per year. A critical part of the refrigerator is a belt that fails after an average of 575 hours with standard deviation of 175 hours (time between failures is Normally distributed). If the belt is replaced during a scheduled maintenance, the cost is $85, whereas a non-scheduled replacement costs $285. What is the optimal scheduled replacement interval? (LO2)

5. A centrifugal pump has a mean time between breakdowns of 3,000 hours and a standard deviation of 400 hours (time between failures is Normally distributed). The value of its service (uptime) is $100 per hour. Repair of the pump requires an overhaul. It will cost $1,500 of parts and labour to overhaul the pump. If overhaul is planned, it will cause 8 hours of downtime, whereas if it is unplanned, it will cause 24 hours of downtime. What is the optimal scheduled overhaul interval? (LO2)

6. You just bought a new car for $20,000 and would like to know how many years you should keep it before selling it. You estimate the maintenance cost to be $200 in the first year and increase 20 percent per year. Also, the resale value of the car will decrease 10 percent per year (i.e., it will be worth $18,000 after 1 year, $18,000(.9) = $16,200 after 2 years, and so on). Assume that the price of a new car remains at $20,000. What is the optimal replacement year? (LO4)

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Problems

7. A trucking company keeps detailed records on the life of its tires. A statistical analysis of the data showed that the lifetime of a tire is closely approximated by the Weibull distribution with parameters $k = 2.3$ and $\lambda = 13,900$ miles. If the tire fails during use, it will cost $450 (including lost time and potential liability of an accident), whereas if it is replaced before failure it will cost only $220. What is the optimal tire replacement interval? Hint: If the life of a tire in miles $(X)$ has a Weibull distribution, then $\text{prob}(X < x; \lambda, k) = 1 - e^{\left(-\frac{x}{\lambda}\right)^k}$. We can use this formula in reverse to obtain $x$ so that $\text{prob}(X < x; \lambda, k) = p$. We get $x = \lambda \cdot \left(\frac{1}{\ln(1-p)}\right)^{1/k}$. (LO4)

8. A large sign consists of 8,000 bulbs. A bulb costs $2 to replace as it fails but it can be replaced for $0.30 if all the bulbs are replaced together. Based on past experience, bulbs fail according to the following probability distribution: (LO4)

<table>
<thead>
<tr>
<th>Month in Service</th>
<th>Prob. of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>0.08</td>
</tr>
<tr>
<td>6</td>
<td>0.09</td>
</tr>
<tr>
<td>7</td>
<td>0.07</td>
</tr>
<tr>
<td>8</td>
<td>0.10</td>
</tr>
<tr>
<td>9</td>
<td>0.11</td>
</tr>
<tr>
<td>10</td>
<td>0.13</td>
</tr>
<tr>
<td>11</td>
<td>0.15</td>
</tr>
<tr>
<td>12</td>
<td>0.14</td>
</tr>
</tbody>
</table>

For simplicity, assume that if a light bulb failed before the group replacement time and was replaced, it will not fail again before the group replacement time. What is the optimal time to replace all the bulbs as a group?

9. The purchase price of an air filter for a specific car is $30. The car is driven 1,000 km per month. Gasoline costs $1 per litre. When the air filter is new, during the first quarter of operation the car's mileage is 15 km/litre. As the filter is used, it starts to slowly get clogged with dirt and dust, and the mileage drops as follows: (LO4)

<table>
<thead>
<tr>
<th>Age (quarters)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>km/litre</td>
<td>15</td>
<td>14.5</td>
<td>14</td>
<td>13.5</td>
<td>13</td>
</tr>
</tbody>
</table>

What is the economic replacement time for the air filter?

10. In an open-pit mining operation the current policy is to replace the clutch on a piece of mobile equipment only when it fails. Based on collected data, the time to failure of a clutch has a Weibull distribution with $k = 1.79$ and $\lambda = 7,307$ hours. A preventive replacement of a clutch involves 16 hours of labour (2 mechanics each working 8 hours) and 8 hours of equipment downtime. A breakdown replacement involves 24 hours of labour (2 mechanics each working 12 hours) and 12 hours of equipment downtime. If mechanics cost $20 per hour and cost of

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equipment downtime is $100 per hour, determine the optimal interval for preventive replacement of clutch. Note: The formula for $x$ so that \[ \text{prob}(X < x; \lambda, k) = p \] is \[ x = \lambda \left( \frac{-\ln(1 - p)}{k} \right). \] (L04)

11. A critical bearing in a shaker machine in a foundry was replaced only after breakdown. The cost of a breakdown replacement was approximately twice the cost of replacing the bearing under preventive maintenance. The data on most recent failure ages (in weeks) were 12, 23, 9, 13, and 19. Weibull distribution was fit to this data. Best estimates for its parameters are $k = 2.97$ and $\lambda = 17.55$ weeks. Determine the optimal preventive replacement age. (L04)

12. A group of 40 valves in a compressor in a gas plant are replaced every 9,000 hours. Occasionally a valve fails before the group replacement time and it is replaced. From the small number of failures, the failure distribution was estimated to be Weibull with $k = 2$ and $\lambda = 138,118$ hours. The cost associated with compressor failure due to a valve problem is $94,000 whereas the preventive replacement cost for all 40 valves is only $24,000. Should the company change its preventive maintenance schedule? (L04)

**MINI-CASE**

**Cover-Shield Failure and Falling Incident at R. H. Saunders Hydroelectric Generating Station**

(Abridged)

Marc A. Rosen, UOIT

Ontario Power Generation’s R. H. Saunders Station, located on a dam on the St. Lawrence River near Cornwall, Ontario, is the second-largest hydro power station in Ontario. It contains typical hydroelectric equipment such as turbines, generators, a repair shop (called the erection bay), and a 300-ton gantry crane (a moving, four-legged overhead structure). R. H. Saunders is an outdoor type of generating station, where the 16 generators are located across the dam, side by side, and are easily accessible by the gantry crane. The crane is used to handle generators in need of repair. It moves on rails and can be moved into the erection bay. The erection bay is a closed structure near shore on the dam, with a huge door that can be opened to let the crane in.

The door opening measures 20 metres by 20 metres. The door is powered by a motor. A drive shaft runs across the top of the door opening. The drive shaft has sections joined by three chain-type couplings (see Exhibit 1). The cast-aluminum covers that are mounted over the couplings (see Exhibit 2) rotate with the couplings as the drive shaft turns to operate the door.

The coupling covers are made up of two sections. Each section weighs approximately 3 kg. The two mating surfaces of the coupling cover sections are joined by two bolts. There are no nuts used.

At approximately 11:00 a.m. on Saturday, October 30, 1999, a maintenance technician started to open the erection bay door from the inside push-button station on the south side of the door. The door had raised approximately 2 metres when he heard a noise at the north side of the door and saw something fall to the erection bay floor. He stopped the door and went to investigate. The technician found two halves of a drive-shaft coupling cover and two bolts for securing the coupling cover on the floor. The coupling cover was from the north drive-shaft coupling.

After the incident, the door was isolated. The coupling cover was bolted back on the coupling. Also, the covers on the two other drive shaft couplings were inspected. Two bolts on the south coupling cover had to be tightened 1/8 turn each. One bolt on the centre coupling cover was tight and the other bolt had to be tightened 1/8 turn. The door was returned to service.

The incident was reported to the station manager, who rated the incident as “potentially high risk.” The level of investigation is more detailed for the high-risk incidents. The erection bay door is original to the station and maintenance responsibilities were turned over to the station in January 1960. The 1960 document includes manufacturer servicing instructions. Inspections of door components should be scheduled on a monthly to six-month basis. The inspections should include checks of oil levels, chains, brakes, cables, and gear cases.

The maintenance file on the bay door was not complete. It showed that mechanical maintenance was done on the door in 1983, 1984, 1989, and 1996. The work in 1989 was described as “emergency inspection and repair” and was performed by an

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external service provider. The work in 1996 was conducted with technical assistance from an external service provider.

This door is categorized as non-production equipment. According to Ontario Power Generation, “[Non-production equipment] are the lowest-priority systems and work on these systems often gets deferred. However, maintenance on these structures/systems cannot be forgotten as eventually this will lead to failures which will have an overall impact on the facility.”

Questions

1. The erection bay door has been relegated to breakdown (emergency) maintenance status during the last 20 years or so (as opposed to periodic inspection and preventive maintenance recommended by the manufacturer). Give arguments for and against this change in maintenance policy.

2. Is there a design problem in the cover shield assembly? Is there a simple fix?

3. Were there adequate breakdown (emergency) maintenance plans in place on the day of the incident?

4. What do you think OPG should do?