Maintenance and Reliability

CHAPTER 17

CHAPTER OUTLINE

Alaska Airlines

10 OM STRATEGY DECISIONS

- Design of Goods and Services
- Managing Quality
- Process Strategy
- Location Strategies
- Layout Strategies
- Human Resources
- Supply-Chain Management
- Inventory Management
- Scheduling
- *Maintenance*

GLOBAL COMPANY PROFILE
Orlando Utilities Commission

Maintenance Provides a Competitive Advantage for the Orlando Utilities Commission

The Orlando Utilities Commission (OUC) owns and operates power plants that supply power to two central Florida counties. Every year, OUC takes each one of its power-generating units off-line for 1 to 3 weeks to perform maintenance work.

In addition, each unit is also taken off-line every 3 years for a complete overhaul and turbine generator inspection. Overhauls are scheduled for spring and fall, when the weather is mildest and demand for power is low. These overhauls last from 6 to 8 weeks.

Units at OUC's Stanton Energy Center require that maintenance personnel perform approximately 12,000 repair and preventive maintenance tasks a year. To accomplish these tasks efficiently, many of these jobs are scheduled daily via a computerized maintenance management program. The computer generates preventive maintenance work orders and lists of required materials.

Every day that a plant is down for maintenance costs OUC about $110,000 extra for the replacement cost of power that must be generated elsewhere. However, these costs pale beside the costs associated with a forced outage. An unexpected outage could cost OUC an additional $350,000 to $600,000 each day!

Scheduled overhauls are not easy; each one has 1,800 distinct tasks and requires 72,000 labor-hours. But the value of preventive maintenance was illustrated by the first overhaul of a new turbine generator. Workers discovered a cracked rotor blade, which could have destroyed a $27 million piece of equipment. To find such cracks, which are invisible to the naked eye, metals are examined using dye tests, X-rays, and ultrasound.

At OUC, preventive maintenance is worth its weight in gold. As a result, OUC's electric distribution system has been ranked number one in the Southeast U.S. by PA Consulting Group—a leading consulting firm. Effective maintenance provides a competitive advantage for the Orlando Utilities Commission.

Orlando Utilities Commission

The Stanton Energy Center in Orlando.

Orlando Utilities Commission

Two employees are on scaffolding near the top of Stanton Energy Center's 23-story high boiler, checking and repairing super heaters.

Orlando Utilities Commission

This inspector is examining a low-pressure section of turbine. The tips of these turbine blades will travel at supersonic speeds of 1,300 miles per hour when the plant is in operation. A crack in one of the blades can cause catastrophic failure.

Monty Rakusen Cultura/Newscom

Maintenance of capital-intensive facilities requires good planning to minimize downtime. Here, turbine overhaul is under way. Organizing the thousands of parts and pieces necessary for a shutdown is a major effort.

LEARNING OBJECTIVES

LO 17.1 ***Describe*** how to improve system reliability 701

LO 17.2 ***Determine*** system reliability 702

LO 17.3 ***Determine*** mean time between failures (MTBF) 703

LO 17.4 ***Distinguish*** between preventive and breakdown maintenance 705

LO 17.5 ***Describe*** how to improve maintenance 706

LO 17.6 ***Compare*** preventive and breakdown maintenance costs 707

LO 17.7 ***Define*** autonomous maintenance 708

The Strategic Importance of Maintenance and Reliability

Managers at Orlando Utilities Commission (OUC), the subject of the chapter-opening *Global Company Profile*, fight for reliability to avoid the undesirable results of equipment failure. At OUC, a generator failure is very expensive for both the company and its customers. Power outages are instantaneous, with potentially devastating consequences. Similarly, managers at Frito-Lay, Walt Disney Company, and United Parcel Service (UPS) are intolerant of failures or breakdowns. Maintenance is critical at Frito-Lay to achieve high plant utilization and excellent sanitation. At Disney, sparkling-clean facilities and safe rides are necessary to retain its standing as one of the most popular vacation destinations in the world. Likewise, UPS's famed maintenance strategy keeps its delivery vehicles operating and looking as good as new for 20 years or more.

VIDEO 17.1
Maintenance Drives Profits at Frito-Lay

STUDENT TIP
If a system is not reliable, the other OM decisions are more difficult.

These companies, like most others, know that poor maintenance can be disruptive, inconvenient, wasteful, and expensive in dollars and even in lives. As Figure 17.1 illustrates, the interdependency of operator, machine, and mechanic is a hallmark of successful maintenance and reliability. Good maintenance and reliability management enhances a firm's performance and protects its investment.

The objective of maintenance and reliability is to maintain the capability of the system. Good maintenance removes variability. Systems must be designed and maintained to reach expected performance and quality standards. **Maintenance** includes all activities involved in keeping a system's equipment in working order. **Reliability** is the probability that a machine part or product will function properly for a specified time under stated conditions.

Maintenance
The activities involved in keeping a system's equipment in working order.

Reliability
The probability that a machine part or product will function properly for a specified time under stated conditions.

In this chapter, we examine four important tactics for improving the reliability and maintenance not only of products and equipment but also of the systems that produce them. The four tactics are organized around reliability and maintenance.

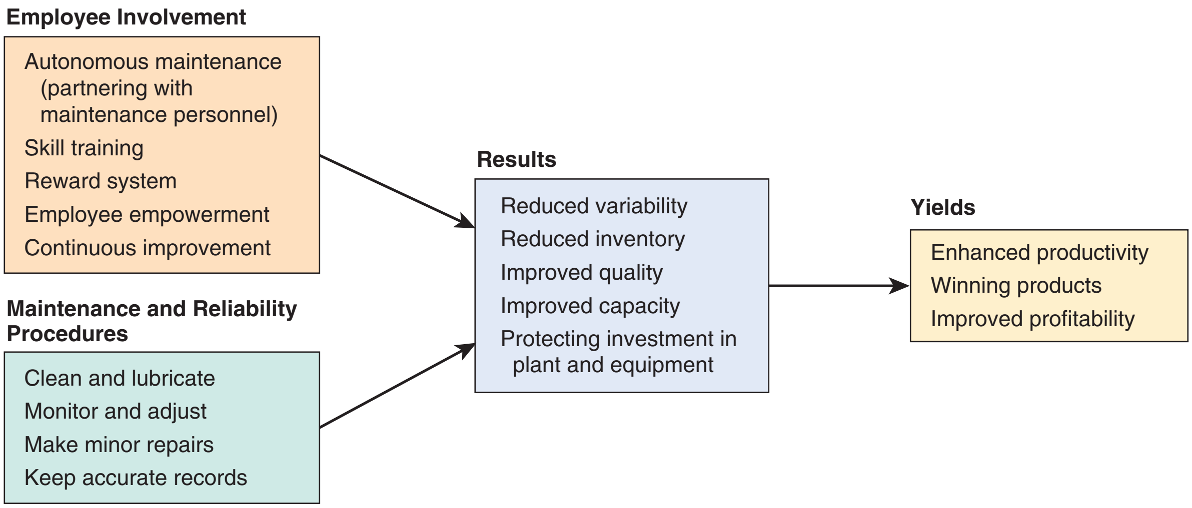


Figure **17.1**

Good Maintenance and Reliability Management Requires Employee Involvement and Good Procedures

The reliability tactics are:

1. Improving individual components
2. Providing redundancy

The maintenance tactics are:

1. Implementing or improving preventive maintenance
2. Increasing repair capabilities or speed

We will now discuss these tactics.

Reliability

Systems are composed of a series of individual interrelated components, each performing a specific job. If any *one* component fails to perform, for whatever reason, the overall system (for example, an airplane or machine) can fail. First, we discuss system reliability and then improvement via redundancy.

System Reliability

STUDENT TIP
Designing for reliability is an excellent place to start reducing variability.

Because failures do occur in the real world, understanding their occurrence is an important reliability concept. We now examine the impact of failure in a series. Figure 17.2 shows that as the number of components in a *series* increases, the reliability of the whole system declines very quickly. A system of $n = 50$ interacting parts, each of which has a 99.5% reliability, has an overall reliability of 78%. If the system or machine has 100 interacting parts, each with an individual reliability of 99.5%, the overall reliability will be only about 60%!

To measure reliability in a system in which each component may have its own unique reliability, we cannot use the reliability curve in Figure 17.2. However, the method of computing system reliability (R_s) is simple. It consists of finding the product of individual reliabilities as follows:

LO 17.1 *Describe* how to improve system reliability

$$R_s = R_1 \times R_2 \times R_3 \times \ldots \times R_n \qquad (17\text{-}1)$$

where R_1 = reliability of component 1
R_2 = reliability of component 2

and so on.

Equation (17-1) assumes that the reliability of an individual component does not depend on the reliability of other components (that is, each component is *independent*). In addition, in this equation, as in most reliability discussions, reliabilities are presented as *probabilities*. Thus, a .90 reliability means that the unit will perform as intended 90% of the time. It also means that

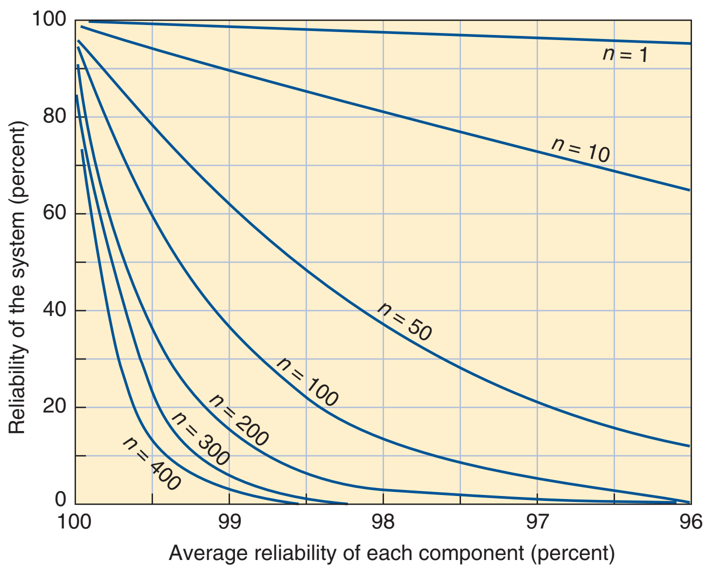


Figure **17.2**

Overall System Reliability as a Function of Number of *n* Components (Each with the Same Reliability) and Component Reliability with Components in a Series

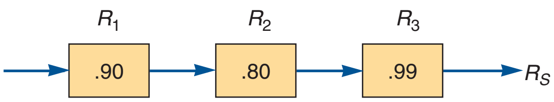
it will fail $1 - .90 = .10 = 10\%$ of the time. We can use this method to evaluate the reliability of a service or a product, such as the one we examine in Example 1.

Example 1

RELIABILITY IN A SERIES

The National Bank of Greeley, Colorado, processes loan applications through three clerks (each checking different sections of the application in series), with reliabilities of .90, .80, and .99. It wants to find the system reliability.

APPROACH ▶ Apply Equation (17-1) to solve for R_s.



SOLUTION ▶ The reliability of the loan process is:

$$R_s = R_1 \times R_2 \times R_3 = (.90)(.80)(.99) = .713, \text{ or } 71.3\%$$

LO 17.2 *Determine* system reliability

INSIGHT ▶ Because each clerk in the series is less than perfect, the error probabilities are cumulative and the resulting reliability for this series is .713, which is less than any one clerk.

LEARNING EXERCISE ▶ If the lowest-performing clerk (.80) is replaced by a clerk performing at .95 reliability, what is the new expected reliability? [Answer: .846.]

RELATED PROBLEMS ▶ 17.1, 17.2, 17.3, 17.9 (17.16 and 17.17 are available in MyOMLab)

ACTIVE MODEL 17.1 This example is further illustrated in Active Model 17.1 in MyOMLab.

EXCEL OM Data File **Ch17Ex1.xls** can be found in MyOMLab.

The basic unit of measure for reliability is the *product failure rate* (FR). Firms producing high-technology equipment often provide failure-rate data on their products. As shown in Equations (17-2) and (17-3), the failure rate measures the percent of failures among the total number of products tested, FR(%), or a number of failures during a period of operating time, FR(N):

$$\text{FR}(\%) = \frac{\text{Number of failures}}{\text{Number of units tested}} \times 100\% \tag{17-2}$$

$$\text{FR}(N) = \frac{\text{Number of failures}}{\text{Number of unit-hours of operating time}} \tag{17-3}$$

Mean time between failures (MTBF)
The expected time between a repair and the next failure of a component, machine, process, or product.

Perhaps the most common term in reliability analysis is the **mean time between failures (MTBF)**, which is the reciprocal of FR(N):

$$\text{MTBF} = \frac{1}{\text{FR}(N)} \tag{17-4}$$

In Example 2, we compute the percentage of failure FR(%), number of failures FR(N), and mean time between failures (MTBF).

Example 2

DETERMINING MEAN TIME BETWEEN FAILURES

Twenty air-conditioning systems designed for use by astronauts in Russia's Soyuz spacecraft were operated for 1,000 hours at a Russian test facility. Two of the systems failed during the test—one after 200 hours and the other after 600 hours.

APPROACH ▶ To determine the percent of failures [FR(%)], the number of failures per unit of time [FR(N)], and the mean time between failures (MTBF), we use Equations (17-2), (17-3), and (17-4), respectively.

SOLUTION ▶ Percentage of failures:

$$\text{FR}(\%) = \frac{\text{Number of failures}}{\text{Number of units tested}} = \frac{2}{20}(100\%) = 10\%$$

Number of failures per operating hour:

$$\text{FR}(N) = \frac{\text{Number of failures}}{\text{Number of unit-hours of operating time}}$$

where

$$\begin{aligned}
\text{Total time} &= (1{,}000 \text{ hr})(20 \text{ units}) \\
&= 20{,}000 \text{ unit-hour} \\
\text{Nonoperating time} &= 800 \text{ hr for 1st failure} + 400 \text{ hr for 2nd failure} \\
&= 1{,}200 \text{ unit-hour} \\
\text{Number of unit-hours of operating time} &= \text{Total time} - \text{Nonoperating time}
\end{aligned}$$

$$\begin{aligned}
\text{FR}(N) &= \frac{2}{20{,}000 - 1{,}200} = \frac{2}{18{,}800} \\
&= .000106 \text{ failure/unit-hour}
\end{aligned}$$

Because $\text{MTBF} = \frac{1}{\text{FR}(N)}$:

LO 17.3 *Determine* mean time between failures (MTBF)

$$\text{MTBF} = \frac{1}{.000106} = 9{,}434 \text{ hr}$$

If the typical Soyuz shuttle trip to the International Space Station lasts 6 days, Russia may note that the failure rate per trip is:

$$\begin{aligned}
\text{Failure rate} &= (\text{Failures/unit-hr})(24 \text{ hr/day})(6 \text{ days/trip}) \\
&= (.000106)(24)(6) \\
&= .0153 \text{ failure/trip}
\end{aligned}$$

INSIGHT ▶ Mean time between failures (MTBF) is the standard means of stating reliability.

LEARNING EXERCISE ▶ If nonoperating time drops to 800, what is the new MTBF? [Answer: 9,606 hr.]

RELATED PROBLEMS ▶ 17.4, 17.5

If the failure rate recorded in Example 2 is too high, Russia will have to increase systems reliability by either increasing the reliability of individual components or by redundancy.

Providing Redundancy

To increase the reliability of systems, **redundancy** is added in the form of *backup* components or *parallel paths*. Redundancy is provided to ensure that if one component or path fails, the system has recourse to another.

Redundancy
The use of backup components or parallel paths to raise reliability.

Backup Redundancy Assume that reliability of a component is .80 and we back it up with another component with reliability of .75. The resulting reliability is the probability of the first component working plus the probability of the backup component working multiplied by the probability of needing the backup component $(1 - .8 = .2)$. Therefore:

$$R_s = \begin{pmatrix}\text{Probability}\\\text{of first}\\\text{component}\\\text{working}\end{pmatrix} + \left[\begin{pmatrix}\text{Probability}\\\text{of second}\\\text{component}\\\text{working}\end{pmatrix} \times \begin{pmatrix}\text{Probability}\\\text{of needing}\\\text{second}\\\text{component}\end{pmatrix}\right] = \tag{17-5}$$

$$(.8) \quad + \quad [(.75) \quad \times \quad (1 - .8)] \quad = .8 + .15 = .95$$

Example 3 shows how redundancy, in the form of backup components, can improve the reliability of the loan process presented in Example 1.

Example 3

RELIABILITY WITH BACKUP

The National Bank is disturbed that its loan-application process has a reliability of only .713 (see Example 1) and would like to improve this situation.

APPROACH ▶ The bank decides to provide redundancy for the two least reliable clerks, with clerks of equal competence.

SOLUTION ▶ This procedure results in the following system:

$$\begin{array}{ccc} R_1 & R_2 & R_3 \\ 0.90 & 0.80 & \\ \downarrow & \downarrow & \\ 0.90 \rightarrow & 0.80 \rightarrow & 0.99 \end{array}$$

$$\begin{aligned} R_s &= [.9 + .9(1 - .9)] \times [.8 + .8(1 - .8)] \times .99 \\ &= [.9 + (.9)(.1)] \times [.8 + (.8)(.2)] \times .99 \\ &= .99 \times .96 \times .99 = .94 \end{aligned}$$

INSIGHT ▶ By providing redundancy for two clerks, National Bank has increased reliability of the loan process from .713 to .94.

LEARNING EXERCISE ▶ What happens when the bank replaces both R_2 clerks with one new clerk who has a reliability of .90? [Answer: $R_s = .88$.]

RELATED PROBLEMS ▶ 17.7, 17.10, 17.12, 17.13, 17.14, 17.15

ACTIVE MODEL 17.2 This example is further illustrated in Active Model 17.2 in MyOMLab.

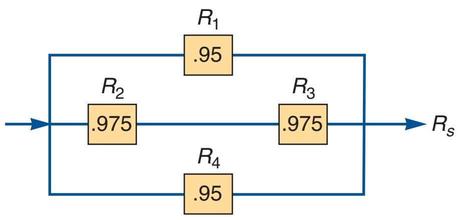
EXCEL OM Data File **Ch17Ex3.xls** can be found in MyOMLab.

Parallel Redundancy Another way to enhance reliability is to provide parallel paths. In a parallel system, the paths are assumed to be independent; therefore, success on any one path allows the system to perform. In Example 4, we determine the reliability of a process with three parallel paths.

Example 4

RELIABILITY WITH PARALLEL REDUNDANCY

A new iPad design that is more reliable because of its parallel circuits is shown below. What is its reliability?



APPROACH ▶ Identify the reliability of each path, then compute the likelihood of needing additional paths (likelihood of failure), and finally subtract the product of those failures from 1.

SOLUTION ▶

Reliability for the middle path $= R_2 \times R_3 = .975 \times .975 = .9506$

Then determine the probability of *failure* for all 3 paths $= (1 - 0.95) \times (1 - .9506) \times (1 - 0.95)$

$= (.05) \times (.0494) \times (.05) = .00012$

Therefore the reliability of the new design is 1 minus the probability of failures, or

$= 1 - .00012 = .99988$

INSIGHT ▶ Even in a system where no component has reliability over .975, the parallel design increases reliability to over .999. Parallel paths can add substantially to reliability.

LEARNING EXERCISE ▶ If reliability of *all* components is only .90, what is the new reliability? [Answer: .9981]

RELATED PROBLEMS ▶ 17.6, 17.8, 17.11

ACTIVE MODEL 17.3 This example is further illustrated in Active Model 17.3 in MyOMLab.

Managers often use a combination of backup components or parallel paths to improve reliability.

Maintenance

There are two types of maintenance: preventive maintenance and breakdown maintenance. **Preventive maintenance** involves monitoring equipment and facilities, performing routine inspections, servicing, and keeping facilities in good repair. These activities are intended to build a system that will reduce variability, find potential failures, and make changes or repairs that will maintain efficient processes. The current generation of sophisticated sensors allows managers to build systems that can detect the slightest unusual vibration, minute changes in temperature or pressure, and slight changes in oil viscosity or chemical components. Preventive maintenance involves designing technical and human systems that will keep the productive process working within tolerance; it allows the system to perform as designed. **Breakdown maintenance** occurs when preventive maintenance fails and equipment/facilities must be repaired on an emergency or priority basis.

Preventive maintenance
A plan that involves monitoring, routine inspections, servicing, and keeping facilities in good repair.

Breakdown maintenance
Remedial maintenance that occurs when preventive maintenance fails and equipment/facilities must be repaired on an emergency or priority basis.

Implementing Preventive Maintenance

Preventive maintenance implies that we can determine when a system needs service or will need repair. Therefore, to perform preventive maintenance, we must know when a system requires service or when it is likely to fail. Failures occur at different rates during the life of a product. A high initial failure rate, known as **infant mortality**, may exist for many products. This is why many electronic firms "burn in" their products prior to shipment: that is to say, they execute a variety of tests (such as a full wash cycle at Whirlpool) to detect "startup" problems prior to shipment. Firms may also provide 90-day warranties. We should note that many infant mortality failures are not product failures per se, but rather failure due to improper use. This fact points up the importance in many industries of operations management's building an after-sales service system that includes installing and training.

Infant mortality
The failure rate early in the life of a product or process.

Once the product, machine, or process "settles in," a study can be made of the MTBF (mean time between failures) distribution. Such distributions often follow a normal curve. When these distributions exhibit small standard deviations, then we know we have a candidate for preventive maintenance, even if the maintenance is expensive.

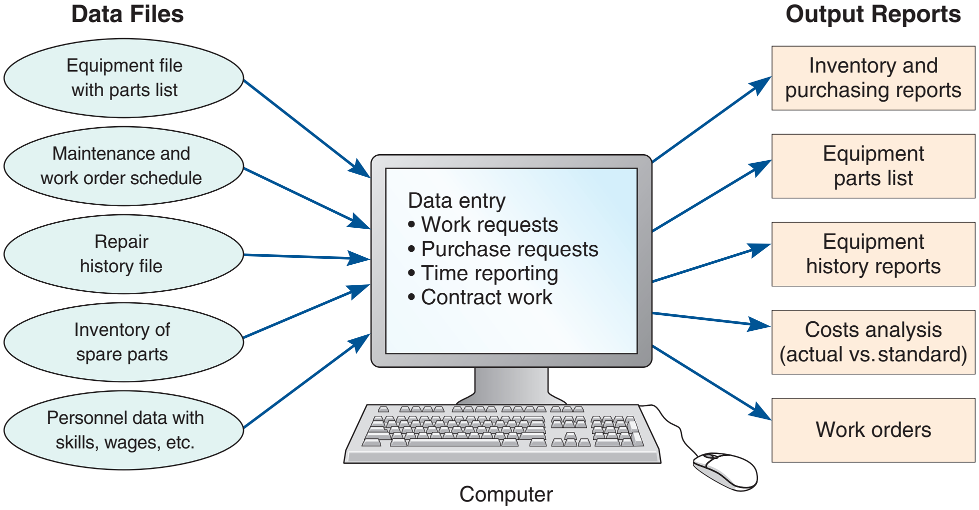
LO 17.4 *Distinguish* between preventive and breakdown maintenance

Once our firm has a candidate for preventive maintenance, we want to determine *when* preventive maintenance is economical. Typically, the more expensive the maintenance, the narrower must be the MTBF distribution (that is, have a small standard deviation). In addition, if the process is no more expensive to repair when it breaks down than the cost of preventive maintenance, perhaps we should let the process break down and then do the repair. However, the consequence of the breakdown must be fully considered. Even some relatively minor breakdowns have catastrophic consequences. At the other extreme, preventive maintenance costs may be so incidental that preventive maintenance is appropriate even if the MTBF distribution is rather flat (that is, it has a large standard deviation).

With good reporting techniques, firms can maintain records of individual processes, machines, or equipment. Such records can provide a profile of both the kinds of maintenance required and the timing of maintenance needed. Maintaining equipment history is an important part of a preventive maintenance system, as is a record of the time and cost to make the repair. Such records can also provide information about the family of equipment and suppliers.

Figure 17.3

A Computerized Maintenance System



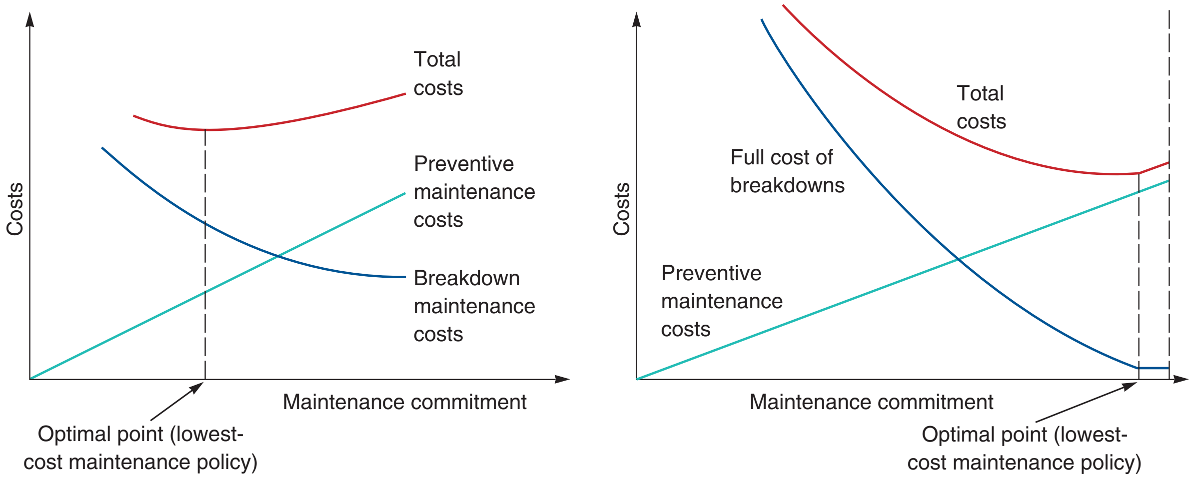
LO 17.5 *Describe* how to improve maintenance

Reliability and maintenance are of such importance that most maintenance management systems are now computerized. Figure 17.3 shows the major components of such a system with files to be maintained on the left and reports generated on the right.

Companies from Boeing to Ford are improving product reliability via their maintenance information systems. Boeing monitors the health of planes in flight by relaying relevant information in real-time to the ground. This provides a head start on reliability and maintenance issues. Similarly, with wireless satellite service, millions of car owners are alerted to thousands of diagnostic issues, from faulty airbag sensors to the need for an oil change. These real-time systems provide immediate data that are used to head off quality issues before customers even notice a problem. The technology enhances reliability and customer satisfaction. And catching problems early saves millions of dollars in warranty costs.

Figure 17.4(a) shows a traditional view of the relationship between preventive maintenance and breakdown maintenance. In this view, operations managers consider a *balance* between the two costs. Allocating more resources to preventive maintenance will reduce the number of breakdowns. At some point, however, the decrease in breakdown maintenance costs may be less than the increase in preventive maintenance costs. At this point, the total cost curve begins to rise. Beyond this optimal point, the firm will be better off waiting for breakdowns to occur and repairing them when they do.

Unfortunately, cost curves such as in Figure 17.4(a) seldom consider the *full costs of a breakdown*. Many costs are ignored because they are not *directly* related to the immediate breakdown. For instance, the cost of inventory maintained to compensate for downtime is not typically



(a) Traditional View of Maintenance **(b) Full Cost View of Maintenance**

Figure 17.4

Maintenance Costs

considered. Moreover, downtime can have a devastating effect on safety and morale. Employees may also begin to believe that "performance to standard" and maintaining equipment are not important. Finally, downtime adversely affects delivery schedules, destroying customer relations and future sales. When the full impact of breakdowns is considered, Figure 17.4(b) may be a better representation of maintenance costs. In Figure 17.4(b), total costs are at a minimum when the system only breaks down due to unanticipated extraordinary events.

STUDENT TIP
When all breakdown costs are considered, much more maintenance may be advantageous.

Assuming that all potential costs associated with downtime have been identified, the operations staff can compute the optimal level of maintenance activity on a theoretical basis. Such analysis, of course, also requires accurate historical data on maintenance costs, breakdown probabilities, and repair times. Example 5 shows how to compare preventive and breakdown maintenance costs to select the least expensive maintenance policy.

Example 5

COMPARING PREVENTIVE AND BREAKDOWN MAINTENANCE COSTS

Farlen & Halikman is a CPA firm specializing in payroll preparation. The firm has been successful in automating much of its work, using high-speed printers for check processing and report preparation. The computerized approach, however, has problems. Over the past 20 months, the printers have broken down at the rate indicated in the following table:

NUMBER OF BREAKDOWNS	NUMBER OF MONTHS THAT BREAKDOWNS OCCURRED
0	2
1	8
2	6
3	4
	Total: 20

Each time the printers break down, Farlen & Halikman estimates that it loses an average of $300 in production time and service expenses. One alternative is to purchase a service contract for preventive maintenance. Even if Farlen & Halikman contracts for preventive maintenance, there will still be breakdowns, *averaging* one breakdown per month. The price for this service is $150 per month.

LO 17.6 *Compare* preventive and breakdown maintenance costs

APPROACH ▶ To determine if the CPA firm should follow a "run until breakdown" policy or contract for preventive maintenance, we follow a 4-step process:

Step 1 Compute the *expected number* of breakdowns (based on past history) if the firm continues as is, without the service contract.

Step 2 Compute the expected breakdown cost per month with no preventive maintenance contract.

Step 3 Compute the cost of preventive maintenance.

Step 4 Compare the two options and select the one that will cost less.

SOLUTION ▶

Step 1

NUMBER OF BREAKDOWNS	FREQUENCY	NUMBER OF BREAKDOWNS	FREQUENCY
0	2/20 = .1	2	6/20 = 0.3
1	8/20 = .4	3	4/20 = 0.2

$$\begin{pmatrix}\text{Expected number}\\ \text{of breakdowns}\end{pmatrix} = \Sigma\left[\begin{pmatrix}\text{Number of}\\ \text{breakdowns}\end{pmatrix} \times \begin{pmatrix}\text{Corresponding}\\ \text{frequency}\end{pmatrix}\right]$$
$$= (0)(.1) + (1)(.4) + (2)(.3) + (3)(.2)$$
$$= 0 + .4 + .6 + .6$$
$$= 1.6 \text{ breakdowns/month}$$

Step 2

$$\text{Expected breakdown cost} = \begin{pmatrix}\text{Expected number}\\\text{of breakdowns}\end{pmatrix} \times \begin{pmatrix}\text{Cost per}\\\text{breakdown}\end{pmatrix}$$
$$= (1.6)(\$300)$$
$$= \$480/\text{month}$$

Step 3

$$\begin{pmatrix}\text{Preventive}\\\text{maintenance cost}\end{pmatrix} = \begin{pmatrix}\text{Cost of expected}\\\text{breakdowns if service}\\\text{contract signed}\end{pmatrix} + \begin{pmatrix}\text{Cost of}\\\text{service contract}\end{pmatrix}$$
$$= (1\ \text{breakdown/month})(\$300) + \$150/\text{month}$$
$$= \$450/\text{month}$$

Step 4 Because it is less expensive overall to hire a maintenance service firm ($450) than to not do so ($480), Farlen & Halikman should hire the service firm.

INSIGHT ▶ Determining the expected number of breakdowns for each option is crucial to making a good decision. This typically requires good maintenance records.

LEARNING EXERCISE ▶ What is the best decision if the preventive maintenance contract cost increases to $195 per month? [Answer: At $495 (= $300 + $195) per month, "run until breakdown" becomes less expensive (assuming that all costs are included in the $300 per breakdown cost).]

RELATED PROBLEMS ▶ 17.18–17.21 (17.22–17.24 are available in MyOMLab)

Using variations of the technique shown in Example 5, operations managers can examine maintenance policies.

Increasing Repair Capabilities

Because reliability and preventive maintenance are seldom perfect, most firms opt for some level of repair capability. Enlarging repair facilities or improving maintenance management may be an excellent way to get the system back in operation faster.

However, not all repairs can be done in the firm's facility. Managers must, therefore, decide where repairs are to be performed. Figure 17.5 provides a continuum of options and how they rate in terms of speed, cost, and competence. Moving to the right in Figure 17.5 may improve the competence of the repair work, but at the same time it increases costs and replacement time.

LO 17.7 *Define* autonomous maintenance

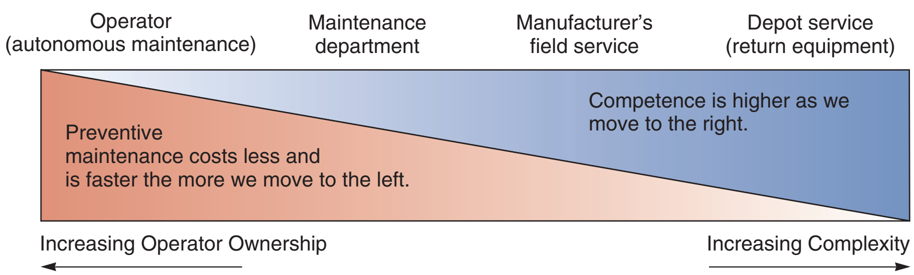
Autonomous Maintenance

Autonomous maintenance
Operators partner with maintenance personnel to observe, check, adjust, clean, and notify.

Preventive maintenance policies and techniques must include an emphasis on employees accepting responsibility for the "observe, check, adjust, clean, and notify" type of equipment maintenance. Such policies are consistent with the advantages of employee empowerment. This approach is known as **autonomous maintenance**. Employees can predict failures, prevent breakdowns, and prolong equipment life. With autonomous maintenance, the manager is making a step toward both employee empowerment and maintaining system performance.

Figure **17.5**

The Operations Manager Determines How Maintenance Will Be Performed



Total Productive Maintenance

Many firms have moved to bring total quality management concepts to the practice of preventive maintenance with an approach known as **total productive maintenance (TPM)**. It involves the concept of reducing variability through autonomous maintenance and excellent maintenance practices. Total productive maintenance includes:

- Designing machines that are reliable, easy to operate, and easy to maintain
- Emphasizing total cost of ownership when purchasing machines, so that service and maintenance are included in the cost
- Developing preventive maintenance plans that utilize the best practices of operators, maintenance departments, and depot service
- Training for autonomous maintenance so operators maintain their own machines and partner with maintenance personnel

Total productive maintenance (TPM)

Combines total quality management with a strategic view of maintenance from process and equipment design to preventive maintenance.

High utilization of facilities, tight scheduling, low inventory, and consistent quality demand reliability. Total productive maintenance, which continues to improve with recent advances in the use of simulation, expert systems, and sensors, is the key to reducing variability and improving reliability.

STUDENT TIP

Maintenance improves productivity.

Summary

Operations managers focus on design improvements, backup components, and parallel paths to improve reliability. Reliability improvements also can be obtained through the use of preventive maintenance and excellent repair facilities.

Firms give employees "ownership" of their equipment. When workers repair or do preventive maintenance on their own machines, breakdowns are less common. Well-trained and empowered employees ensure reliable systems through preventive maintenance. In turn, reliable, well-maintained equipment not only provides higher utilization but also improves quality and performance to schedule. Top firms build and maintain systems that drive out variability so that customers can rely on products and services to be produced to specifications and on time.

Key Terms

Maintenance (p. 700)
Reliability (p. 700)
Mean time between failures (MTBF) (p. 702)
Redundancy (p. 703)
Preventive maintenance (p. 705)
Breakdown maintenance (p. 705)
Infant mortality (p. 705)
Autonomous maintenance (p. 708)
Total productive maintenance (TPM) (p. 709)

Ethical Dilemma

The space shuttle *Columbia* disintegrated over Texas on its 2003 return to Earth. The *Challenger* exploded shortly after launch in 1986. And the *Apollo 1* spacecraft imploded in fire on the launch pad in 1967. In each case, the lives of all crew members were lost. The hugely complex shuttle may have looked a bit like an airplane but was very different. In reality, its overall statistical reliability is such that about 1 out of every 50 flights had a major malfunction. As one aerospace manager stated, "Of course, you can be perfectly safe and never get off the ground."

Given the huge reliability and maintenance issues NASA faced (seals cracking in cold weather, heat shielding tiles falling off, tools left in the capsule), should astronauts have been allowed to fly? (In earlier *Atlas* rockets, men were inserted not out of necessity but because test pilots and politicians thought they should be there.) What are the pros and cons of staffed space exploration from an ethical perspective? Should the U.S. spend billions of dollars to return an astronaut to the moon or send one to Mars?

Discussion Questions

1. What is the objective of maintenance and reliability?
2. How does one identify a candidate for preventive maintenance?
3. Explain the notion of "infant mortality" in the context of product reliability.
4. How could simulation be a useful technique for maintenance problems?
5. What is the trade-off between operator-performed maintenance versus supplier-performed maintenance?
6. How can a manager evaluate the effectiveness of the maintenance function?
7. How does machine design contribute to either increasing or alleviating the maintenance problem?

8. What roles can computerized maintenance management systems play in the maintenance function?

9. During an argument as to the merits of preventive maintenance at Windsor Printers, the company owner asked, "Why fix it before it breaks?" How would you, as the director of maintenance, respond?

10. Will preventive maintenance eliminate *all* breakdowns?

Using Software to Solve Reliability Problems

Excel OM and POM for Windows may be used to solve reliability problems. The reliability module allows us to enter (1) number of systems (components) in the series (1 through 10); (2) number of backup, or parallel, components (1 through 12); and (3) component reliability for both series and parallel data.

Solved Problems

Virtual Office Hours help is available at MyOMLab.

SOLVED PROBLEM 17.1

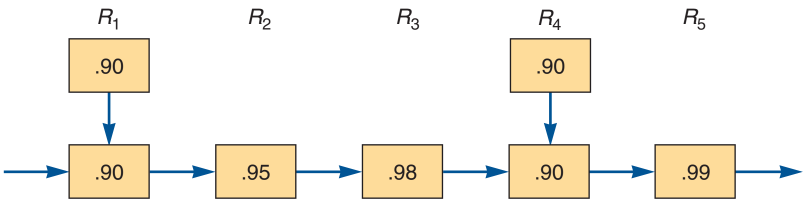
The semiconductor used in the Sullivan Wrist Calculator has five circuits, each of which has its own reliability rate. Component 1 has a reliability of .90; component 2, .95; component 3, .98; component 4, .90; and component 5, .99. What is the reliability of one semiconductor?

SOLUTION

$$\begin{aligned}\text{Semiconductor reliability, } R_s &= R_1 \times R_2 \times R_3 \times R_4 \times R_5\\ &= (.90)(.95)(.98)(.90)(.99)\\ &= .7466\end{aligned}$$

SOLVED PROBLEM 17.2

A recent engineering change at Sullivan Wrist Calculator places a backup component in each of the two least reliable transistor circuits. The new circuits will look like the following:



What is the reliability of the new system?

SOLUTION

$$\begin{aligned}\text{Reliability} &= [.9 + (1 - .9) \times .9] \times .95 \times .98 \times [.9 + (1 - .9) \times .9] \times .99\\ &= [.9 + .09] \times .95 \times .98 \times [.9 + .09] \times .99\\ &= .99 \times .95 \times .98 \times .99 \times .99\\ &= .903\end{aligned}$$

Problems

Note: PX means the problem may be solved with POM for Windows and/or Excel OM.

Problems 17.1–17.17 relate to Reliability

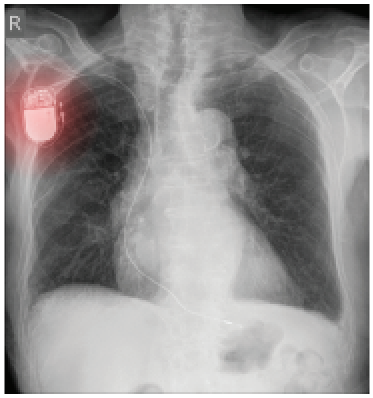
• **17.1** The Beta II computer's electronic processing unit contains 50 components in series. The average reliability of each component is 99.0%. Using Figure 17.2, determine the overall reliability of the processing unit.

• **17.2.** A testing process at Boeing Aircraft has 400 components in series. The average reliability of each component is 99.5%. Use Figure 17.2 to find the overall reliability of the whole testing process.

•• **17.3** A new aircraft control system is being designed that must be 98% reliable. This system consists of three components in series. If all three of the components are to have the same level of reliability, what level of reliability is required? PX

•• **17.4** Robert Klassan Manufacturing, a medical equipment manufacturer, subjected 100 heart pacemakers to 5,000 hours of testing. Halfway through the testing, 5 pacemakers failed. What was the failure rate in terms of the following:

a) Percentage of failures?
b) Number of failures per unit-hour?
c) Number of failures per unit-year?
d) If 1,100 people receive pacemaker implants, how many units can we expect to fail during the following year?

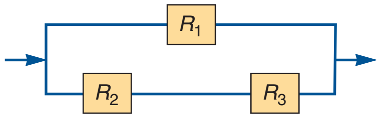


Skyhawk x/Shutterstock

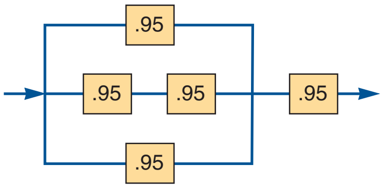
•• **17.5** A manufacturer of disk drives for notebook computers wants an MTBF of at least 50,000 hours. Recent test results for 10 units were one failure at 10,000 hours, another at 25,000 hours, and two more at 45,000 hours. The remaining units were still running at 60,000 hours. Determine the following:

a) Percent of failures
b) Number of failures per unit-hour
c) MTBF at this point in the testing

• • 17.6 What is the reliability of the following parallel production process? $R_1 = 0.95$, $R_2 = 0.90$, $R_3 = 0.98$.



• • 17.7 What is the overall reliability that bank loans will be processed accurately if each of the 5 clerks shown in the chart has the reliability shown?



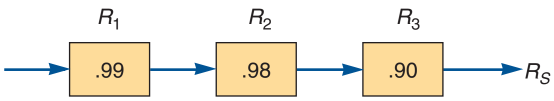
Hint: The three paths are done in parallel, followed by an additional independent step.

• • 17.8 Merrill Kim Sharp has a system composed of three components in parallel. The components have the following reliabilities:

$$R_1 = 0.90, \quad R_2 = 0.95, \quad R_3 = 0.85$$

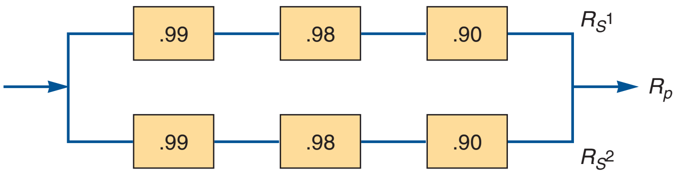
What is the reliability of the system? (*Hint:* See Example 4.)

• 17.9 A medical control system has three components in series with individual reliabilities (R_1, R_2, R_3) as shown:



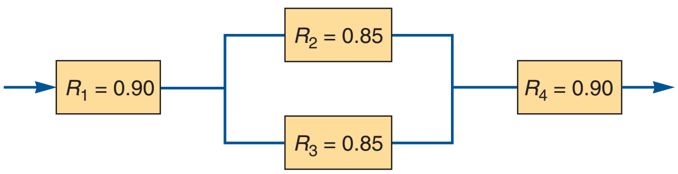
What is the reliability of the system?

• • 17.10 What is the reliability of the system shown?



• 17.11 How much would reliability improve if the medical control system shown in Problem 17.9 changed to the redundant parallel system shown in Problem 17.10?

• • 17.12 Elizabeth Irwin's design team has proposed the following system with component reliabilities as indicated:



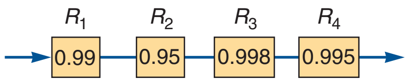
What is the reliability of the system?
Hint: The system functions if either R_2 or R_3 work.

• • 17.13 Rick Wing, salesperson for Wave Soldering Systems, Inc. (WSSI), has provided you with a proposal for improving the temperature control on your present machine. The machine uses a hot-air knife to cleanly remove excess solder from printed circuit boards; this is a great concept, but the hot-air temperature control lacks reliability. According to Wing, engineers at WSSI have improved the reliability of the critical temperature controls. The new system still has the four sensitive integrated circuits controlling the temperature, but the new machine has a backup for each. The four integrated circuits have reliabilities of .90, .92, .94, and .96. The four backup circuits all have a reliability of .90.

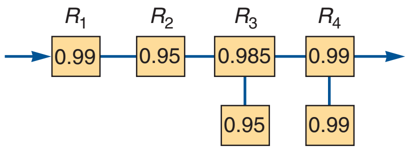
a) What is the reliability of the new temperature controller?
b) If you pay a premium, Wing says he can improve all four of the backup units to .93. What is the reliability of this option?

• • • • 17.14 As VP for operations at Méndez-Piñero Engineering, you must decide which product design, A or B, has the higher reliability. B is designed with backup units for components R_3 and R_4. What is the reliability of each design?

Product Design A



Product Design B



• • • • 17.15 A typical retail transaction consists of several smaller steps, which can be considered components subject to failure. A list of such components might include:

COMPONENT	DESCRIPTION	DEFINITION OF FAILURE
1	Find product in proper size, color, etc.	Can't find product
2	Enter cashier line	No lines open; lines too long; line experiencing difficulty
3	Scan product UPC for name, price, etc.	Won't scan; item not on file; scans incorrect name or price
4	Calculate purchase total	Wrong weight; wrong extension; wrong data entry; wrong tax
5	Make payment	Customer lacks cash; check not acceptable; credit card refused
6	Make change	Makes change incorrectly
7	Bag merchandise	Damages merchandise while bagging; bag splits
8	Conclude transaction and exit	No receipt; unfriendly, rude, or aloof clerk

Let the eight probabilities of success be .92, .94, .99, .99, .98, .97, .95, and .96. What is the reliability of the system; that is, the probability that there will be a satisfied customer? If you were the store manager, what do you think should be an acceptable value for this probability? Which components would be good candidates for backup, which for redesign?

Additional problems **17.16–17.17** *are available in* MyOMLab.

Problems 17.18–17.24 relate to Maintenance

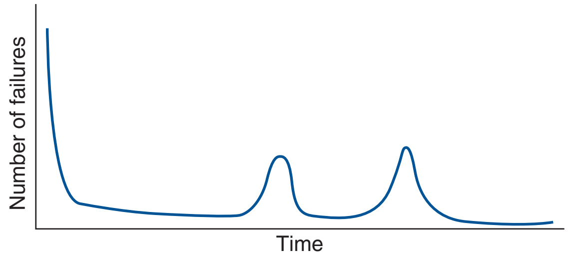
• 17.18 What are the *expected* number of yearly breakdowns for the power generator at Orlando Utilities that has exhibited the following data over the past 20 years?

Number of breakdowns	0	1	2	3	4	5	6
Number of years in which breakdown occurred	2	2	5	4	5	2	0

• **17.19** Each breakdown of a graphic plotter table at Airbus Industries costs $50. Find the expected daily breakdown cost, given the following data: Px

Number of breakdowns	0	1	2	3	4
Daily breakdown probability	.1	.2	.4	.2	.1

• • **17.20** David Hall, chief of the maintenance department at Mechanical Dynamics, has presented you with the following failure curve. What does it suggest?



• • • **17.21** The fire department has a number of failures with its oxygen masks and is evaluating the possibility of outsourcing preventive maintenance to the manufacturer. Because of the risk associated with a failure, the cost of each failure is estimated at $2,000. The current maintenance policy (with station employees performing maintenance) has yielded the following history:

Number of breakdowns	0	1	2	3	4	5
Number of years in which breakdowns occurred	4	3	1	5	5	0

This manufacturer will guarantee repairs on any and all failures as part of a service contract. The cost of this service is $5,000 per year.

a) What is the expected number of breakdowns per year with station employees performing maintenance?
b) What is the cost of the current maintenance policy?
c) What is the more economical policy?

Additional problems **17.22–17.24** *are available in* MyOMLab.

CASE STUDY

Maintenance Drives Profits at Frito-Lay

Video Case

Frito-Lay, the multi-billion-dollar subsidiary of food and beverage giant PepsiCo, maintains 36 plants in the U.S. and Canada. These facilities produce dozen of snacks, including the well-known Lay's, Fritos, Cheetos, Doritos, Ruffles, and Tostitos brands, each of which sells over $1 billion per year.

Frito-Lay plants produce in the high-volume, low-variety process model common to commercial baked goods, steel, glass, and beer industries. In this environment, preventive maintenance of equipment takes a major role by avoiding costly downtime. Tom Rao, vice president for Florida operations, estimates that each 1% of downtime has a negative annual profit impact of $200,000. He is proud of the $1\frac{1}{2}$% unscheduled downtime his plant is able to reach—well below the 2% that is considered the "world-class" benchmark. This excellent performance is possible because the maintenance department takes an active role in setting the parameters for preventive maintenance. This is done with weekly input to the production schedule.

Maintenance policy impacts energy use as well. The Florida plant's technical manager, Jim Wentzel, states, "By reducing production interruptions, we create an opportunity to bring energy and utility use under control. Equipment maintenance and a solid production schedule are keys to utility efficiency. With every production interruption, there is substantial waste."

As a part of its total productive maintenance (TPM) program,* Frito-Lay empowers employees with what it calls the "Run Right" system. Run Right teaches employees to "identify and do." This means each shift is responsible for identifying problems and making the necessary corrections, when possible. This is accomplished through (1) a "power walk" at the beginning of the shift to ensure that equipment and process settings are performing to standard, (2) mid-shift and post-shift reviews of standards and performance, and (3) posting of any issues on a large whiteboard in the shift office. Items remain on the whiteboard until corrected, which is seldom more than a shift or two.

With good manpower scheduling and tight labor control to hold down variable costs, making time for training is challenging. But supervisors, including the plant manager, are available to fill in on the production line when that is necessary to free an employee for training.

The 30 maintenance personnel hired to cover 24/7 operations at the Florida plant all come with multi-craft skills (e.g., welding, electrical, plumbing). "Multi-craft maintenance personnel are harder to find and cost more," says Wentzel, "but they more than pay for themselves."

Discussion Questions**

1. What might be done to help take Frito-Lay to the next level of outstanding maintenance? Consider factors such as sophisticated software.
2. What are the advantages and disadvantages of giving more responsibility for machine maintenance to the operator?
3. Discuss the pros and cons of hiring multi-craft maintenance personnel.

*At Frito-Lay, preventive maintenance, autonomous maintenance, and total productive maintenance are part of a Frito-Lay program known as total productive manufacturing.

**You may wish to view the video that accompanies this case before answering these questions.

• **Additional Case Studies:** Visit MyOMLab for these free case studies:
Cartak's Department Store: Requires the evaluation of the impact of an additional invoice verifier.
Worldwide Chemical Company: The maintenance department in this company is in turmoil.

Chapter 17 *Rapid* Review

Main Heading	Review Material	MyOMLab
THE STRATEGIC IMPORTANCE OF MAINTENANCE AND RELIABILITY (pp. 662–663)	Poor maintenance can be disruptive, inconvenient, wasteful, and expensive in dollars and even in lives. The interdependency of operator, machine, and mechanic is a hallmark of successful maintenance and reliability. Good maintenance and reliability management requires employee involvement and good procedures; it enhances a firm's performance and protects its investment. *The objective of maintenance and reliability is to maintain the capability of the system.* ■ **Maintenance**—All activities involved in keeping a system's equipment in working order. ■ **Reliability**—The probability that a machine part or product will function properly for a specified time under stated conditions. The two main tactics for improving reliability are: 1. Improving individual components 2. Providing redundancy The two main tactics for improving maintenance are: 1. Implementing or improving preventive maintenance 2. Increasing repair capabilities or speed	Concept Questions: 1.1–1.4 **VIDEO 17.1** Maintenance Drives Profits at Frito-Lay
RELIABILITY (pp. 663–667)	A system is composed of a series of individual interrelated components, each performing a specific job. If any *one* component fails to perform, the overall system can fail. As the number of components in a *series* increases, the reliability of the whole system declines very quickly: $R_s = R_1 \times R_2 \times R_3 \times \ldots \times R_n$ (17-1) where R_1 = reliability of component 1, R_2 = reliability of component 2, and so on. Equation (17-1) assumes that the reliability of an individual component does not depend on the reliability of other components. A .90 reliability means that the unit will perform as intended 90% of the time, and it will fail 10% of the time. The basic unit of measure for reliability is the *product failure rate* (FR). FR(%) is the percent of failures among the total number of products tested, and FR(*N*) is the number of failures during a period of time: $\text{FR}(\%) = \dfrac{\text{Number of failures}}{\text{Number of units tested}} \times 100\%$ (17-2) $\text{FR}(N) = \dfrac{\text{Number of failures}}{\text{Number of unit-hours of operating time}}$ (17-3) ■ **Mean time between failures (MTBF)**—The expected time between a repair and the next failure of a component, machine, process, or product. $\text{MTBF} = \dfrac{1}{\text{FR}(N)}$ (17-4) ■ **Redundancy**—The use of components in parallel to raise reliability. The reliability of a component along with its backup equals: (Probability that 1st component works) + [(Prob. that backup works) × (Prob. that 1st fails)] (17-5)	Concept Questions: 2.1–2.4 Problems: 17.1–17.17 Virtual Office Hours for Solved Problems: 17.1, 17.2 **ACTIVE MODELS 17.1, 17.2, 17.3**
MAINTENANCE (pp. 667–670)	■ **Preventive maintenance**—Involves routine inspections, monitoring, servicing, and keeping facilities in good repair. ■ **Breakdown maintenance**—Remedial maintenance that occurs when preventive maintenance fails and equipment/facilities must be repaired on an emergency or priority basis. ■ **Infant mortality**—The failure rate early in the life of a product or process. Consistent with job enrichment practices, machine operators must be held responsible for preventive maintenance of their own equipment and tools. Reliability and maintenance are of such importance that most maintenance systems are now computerized.	Concept Questions: 3.1–3.4 Problems: 17.18–17.24

Chapter 17 *Rapid Review* continued

Main Heading	Review Material	MyOMLab
	Costs of a breakdown that may get ignored include: 1. The cost of inventory maintained to compensate for downtime 2. Downtime, which can have a devastating effect on safety and morale and which adversely affects delivery schedules, destroying customer relations and future sales ■ **Autonomous maintenance**—Operators partner with maintenance personnel to observe, check, adjust, clean, and notify. Employees can predict failures, prevent breakdowns, and prolong equipment life. With autonomous maintenance, the manager is making a step toward both employee empowerment and maintaining system performance.	
TOTAL PRODUCTIVE MAINTENANCE (p. 671)	■ **Total productive maintenance (TPM)**—Combines total quality management with a strategic view of maintenance from process and equipment design to preventive maintenance. Total productive maintenance includes: 1. Designing machines that are reliable, easy to operate, and easy to maintain 2. Emphasizing total cost of ownership when purchasing machines, so that service and maintenance are included in the cost 3. Developing preventive maintenance plans that utilize the best practices of operators, maintenance departments, and depot service 4. Training for autonomous maintenance so operators maintain their own machines and partner with maintenance personnel Three techniques that have proven beneficial to effective maintenance are simulation, expert systems, and sensors.	Concept Questions: 4.1–4.4

Self Test

■ **Before taking the self-test,** refer to the learning objectives listed at the beginning of the chapter and the key terms listed at the end of the chapter.

LO 17.1 The two main tactics for improving reliability are _______ and _______.

LO 17.2 The reliability of a system with n independent components equals:
- **a)** the sum of the individual reliabilities.
- **b)** the minimum reliability among all components.
- **c)** the maximum reliability among all components.
- **d)** the product of the individual reliabilities.
- **e)** the average of the individual reliabilities.

LO 17.3 What is the formula for the mean time between failures?
- **a)** Number of failures ÷ Number of unit-hours of operating time
- **b)** Number of unit-hours of operating time ÷ Number of failures
- **c)** (Number of failures ÷ Number of units tested) × 100%
- **d)** (Number of units tested ÷ Number of failures) × 100%
- **e)** 1 ÷ FR(%)

LO 17.4 The process that is intended to find potential failures and make changes or repairs is known as:
- **a)** breakdown maintenance.
- **b)** failure maintenance.
- **c)** preventive maintenance.
- **d)** all of the above.

LO 17.5 The two main tactics for improving maintenance are _______ and _______.

LO 17.6 The appropriate maintenance policy is developed by balancing preventive maintenance costs with breakdown maintenance costs. The problem is that:
- **a)** preventive maintenance costs are very difficult to identify.
- **b)** full breakdown costs are seldom considered.
- **c)** preventive maintenance should be performed, regardless of the cost.
- **d)** breakdown maintenance must be performed, regardless of the cost.

LO 17.7 _______ maintenance partners operators with maintenance personnel to observe, check, adjust, clean, and notify.
- **a)** Partnering
- **b)** Operator
- **c)** Breakdown
- **d)** Six Sigma
- **e)** Autonomous

Answers: LO 17.1. improving individual components, providing redundancy; LO 17.2. d; LO 17.3. b; LO 17.4. c; LO 17.5. implementing or improving preventive maintenance, increasing repair capabilities or speed; LO 17.6. b; LO 17.7. e.