to customer demands by focusing on critical-to-quality (CTQ) characteristics (Harry & Schroeder, 2000).

> Critical-to-quality (CTQ) characteristics "are the items essential for customer satisfaction in a product or service."
>
> (Breyfogle, et al., 2001, 95)

TAGUCHI ROBUSTNESS CONCEPTS

Taguchi advocated designing products and systems that are robust. Robustness is defined as "the condition of a product or process design that remains relatively stable, with a minimum of variation, even though factors that influence operations or usage, such as environment and wear, are constantly changing" (Quality Glossary, 2002). Taguchi referred to these factors as "noise." Within a broader range of activities designed to improve company-wide quality and productivity, Taguchi advocated three steps to achieve robustness that start in product design and continue through production engineering and production operation (Taguchi, Elsayed, & Hsiang, 1989). These steps are:

1. System Design—This step includes development of a prototype design, selection of materials, parts, components, and production system that results in minimum deviation from target performance values.
2. Parameter Design—This step involves determining "the optimal levels for the parameters of each element in the system so that the functional deviations of the product are minimized" (Taguchi, Elsayed, & Hsiang, 1989). Designed experiments are often used in this step.
3. Tolerance Design—This step involves determining the quality loss and cost tradeoffs associated with each parameter. It is designed to "minimize the product cost for a given tolerable deviation from target values" (Taguchi, Elsayed, & Hsiang, 1989).

The result of taking this approach to product design is a more reliable product that can be produced economically.

RELIABILITY

Increasing the reliability of a product or service is a key part of the design process. Reliability is defined as "the probability of a product performing without failure a specified function under given conditions for a specified period of time"

TABLE 3.1. Dimensions of Reliability

1. As a Probability:
   - frequency of successful uses out of certain number of attempts,
   - likelihood of an item lasting a given amount of time.
2. Definition of Failure:
   - a situation in which an item does not perform as intended.
3. Prescribed Operating Conditions:
   - how the product should be used,
   - "normal operating conditions".

(Quality Glossary, 2002). Note that in this definition, probability is used to quantify reliability.

There are three dimensions of reliability: as a probability, as a definition of failure, and as prescribed operating conditions (Stevenson, 2005). These three dimensions are shown in Table 3.1.

Reliability as a probability can be defined in two ways. The first is the probability that a system will perform on a given trial. Another way to state this is the frequency of successful performances of a system in a given number of attempts. An example of this definition would be the probability that a fire extinguisher would perform on a given attempt to use it. This probability could be determined through repeated trials to determine the frequency of successful uses as a percentage of attempts.

The second definition of probability as a reliability is the probability that an item will last for a given length of time in use. This can be illustrated by the example of a light bulb. Most bulbs are rated for a given life. This can be determined by life testing to failure a large number of bulbs and determining the average useful life. These data can be used to determine the probability the light bulb will last for a specified number of hours.

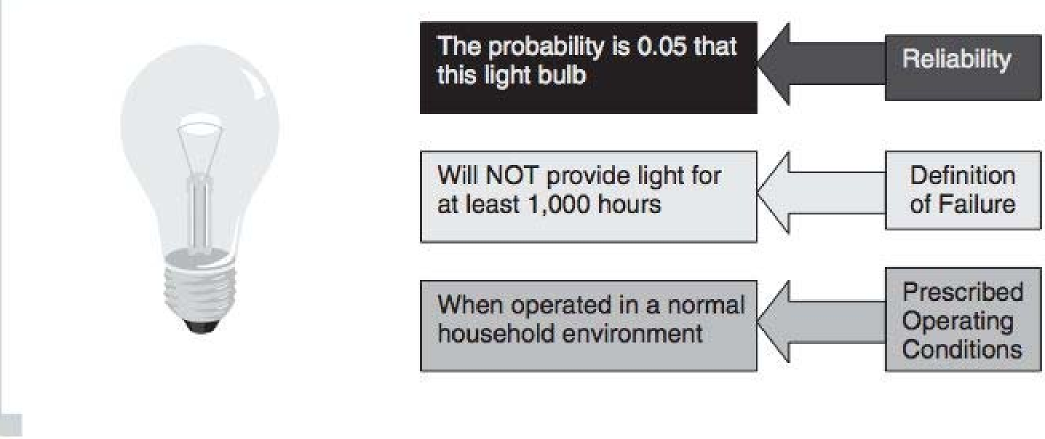
Definition of a failure may seem to be straightforward. In the case of the light bulb, it is—the bulb fails when it no longer produces light. This definition, however, is not so clear in other systems. Consider an automobile tire. Short of catastrophic failure (e.g., blowout), at what point is the tread considered to be depleted—that is, at what point is the tire considered to have failed or used up its useful life?

Prescribed operating conditions must be specified. Only light bulbs specially designed for outdoor use can achieve equivalent useful lives exposed to the weather as indoor bulbs in a more sheltered operating environment. Therefore, when discussing reliability of a system, the standard operating conditions for which the system was designed must be specified.

Types of Reliability Systems

A serial system is one which consists of multiple parts or subassemblies, each of which must function in order for the system to function. System reliability is usually defined

Putting it All Together



as the product of the individual reliabilities of the n parts or subsystems within a system.

$$P_s = P_1 \times P_2 \times P_3 \times \ldots \times P_n \quad (3.1)$$

P_s is the probability of the system working when called upon, and P_n is the probability of component n working when called upon.

Example 3.1a

A manufacturing system consists of 1 subsystem with the following reliability:

$P_1 = 0.970$

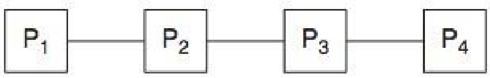
What is the overall reliability of the system?

As the system has only one subsystem or component, the reliability of the subsystem is the reliability of the system = 0.970. This means that the probability of the system performing when called upon is 0.970.

Example 3.1b

A manufacturing system consists of four subsystems with the following reliabilities:

$P_1 = 0.970$
$P_2 = 0.997$
$P_3 = 0.985$
$P_4 = 0.990$



What is the overall reliability of the system?

Recognizing that system reliability is the product of the individual reliabilities of the subsystems, we use Equation 3.1 as follows:

$$P_s = P_1 \times P_2 \times P_3 \times P_4$$
$$P_s = 0.970 \times 0.997 \times 0.985 \times 0.990$$
$$P_s = 0.943$$

Although the assumption of system reliability equaling the product of the reliabilities of the subsystems is only true for serial systems, the formula serves two basic purposes. First, it highlights the effect of increased serial system complexity on overall system reliability. As the number of parts or subsystems increases in a serial system, system reliability decreases dramatically. Second, the formula is often a convenient approximation that can be refined as information becomes available on the interrelationships of parts.

Note that in Example 3.1b the reliability of the system is much lower than the reliabilities of individual components. This is because the components are in *series*, thus requiring that all components work if the system is to work. One way to increase the reliability of serial systems is to increase the reliability of each component.

Example 3.2

As the number of components increases, the reliability of the system decreases, all other things being equal. For critical systems, cost is of little concern when it comes to selecting the most reliable components. Consider a military jet consisting of 1,000,000 critical components. The manufacturer spares no expense to procure components that are 0.999999 reliable (that is, one failure in one million opportunities). What is the reliability of the jet manufactured using these components?

Using Equation 3.1, the reliability of the jet may be calculated as:

$$0.999999 \times 0.999999 \times 0.999999 \times \ldots \text{ one million times.}$$

This may also be calculated as:

$$0.999999^{1,000,000} = 0.368$$

Who would want to go into combat with a jet that will fail almost two thirds of the time?

As Example 3.2 shows, for systems with many components, each of which must function in order for the system to function, there is a limit to how much system reliability can be increased by increasing component reliability alone. To further increase the reliability of the system, we can use *redundancy*. "Redundancy is the existence of more than one element for accomplishing a given task, where all elements must fail before there is an overall failure to the system" (Juran & Gryna, 1980). Parallel redundancy means that we add additional backup components or an additional backup system to the existing system. The extra components or system increase the overall reliability because if the primary system or component fails, the backup or redundant component or system can take over and the overall system will not fail. Redundancy, in addition to the use of extremely reliable components, is the key to making the jet fighter in Example 3.2 sufficiently reliable for use.

When parallel redundancy is used, the overall reliability of a component system consisting of one main component and a backup component is calculated using the following equation:

$$P_C = P_m + P_b(1 - P_m) \tag{3.2}$$

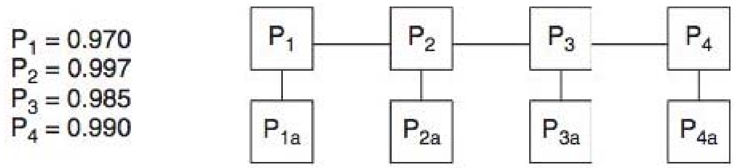
where

P_c = reliability of the component system
P_m = reliability of the main component
P_b = reliability of the backup component
$(1 - P_m)$ = probability that main component will fail

Example 3.3

Management desires to increase the overall reliability of the system in Example 3.1b.

a. Add a parallel *backup component* to each main component of the system with the backup having the same reliability as the *main component*. What does that do to the overall reliability of the system?

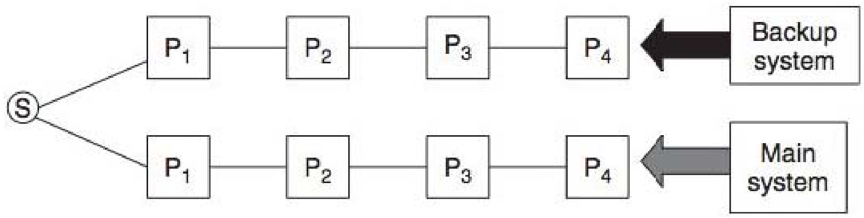


Use Equation 3.2 for each component $P_c = P_m + P_b(1 - P_m)$

$$P_{system} = [0.970 + 0.970(1 - 0.970)] \times [0.997 + 0.997(1 - 0.997)] \times [0.985 + 0.985(1 - 0.985)] \times [0.990 + 0.990(1 - 0.990)]$$

$$P_{system} = 0.9991 \times 0.9999 \times 0.9998 \times 0.9999 = 0.9987$$

b. Add an identical *parallel system* to the *existing system*. What does that do to the overall reliability of the system?



$$P_{existing\ system} = P_1 \times P_2 \times P_3 \times P_4$$
$$P_s = 0.970 \times 0.997 \times 0.985 \times 0.990 = 0.943$$
$$P_{backup\ system} = P_1 \times P_2 \times P_3 \times P_4$$
$$P_b = 0.970 \times 0.997 \times 0.985 \times 0.990 = 0.943$$
$$P_{system} = P_{existing\ system} + P_{backup\ system}\ (1 - P_{existing\ system})$$
$$P_{system} = 0.943 + 0.943(1 - 0.943) = 0.9968$$

When redundant components are incorporated into a system, a switch must be provided to activate the backup component when the primary component fails. Note that in Example 3.3, we assumed the reliability of the switch was 1. In the real world, however, switches can and do fail to work when called upon. In such a case, the redundant component does not have an opportunity to function when the main component fails—therefore the system fails. If we assign a probability to the switch, the reliability of the component with backup component and switch is calculated as follows:

$$P_{component} = P_{main\ component} + [P_{backup\ component} \times (1 - P_{main\ component})] \times P_{switch} \quad (3.3)$$

EXAMPLE 3.4

Using the same reliabilities in Example 3.3-b, calculate the reliability of the system with a switch reliability of 0.99 (99 percent).

$$P_{system} = P_{main\ system} + [P_{backup\ system} \times (1 - P_{main\ system})] \times P_{switch}$$
$$P_{system} = 0.943 + [0.943 \times (1 - 0.943)] \times 0.99 = 0.9962$$

In many cases more than one parallel backup component is used. In the case of the Apollo moon missions, there were several backups in place for critical components such as the guidance computer. The reliability of a component with multiple backups may be calculated as

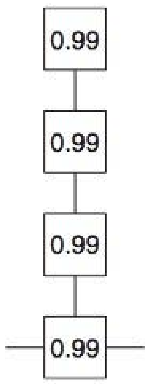
$$P_{system} = 1 - [(1 - P_{primary}) \times (1 - P_{first\ backup}) \times \ldots (1 - P_{nth\ backup}) \qquad (3.4)$$

If the backup components are identical to the primary, this reduces to

$$P_{system} = 1 - (1 - P_{components})^n \qquad (3.5)$$

where n is the number of components in the system.

EXAMPLE 3.5



Calculate the reliability of this system that consists of a main component with a reliability of 0.99 and three identical backup components. Using Equation 3.5

$$P_s = 1 - (1 - 0.99)^4 = 1 - (0.00000001)$$
$$P_s = 0.99999999$$

or one failure in every 100 million opportunities.

Reliability is Also Important in Services

"The Post Office Cancels Business With Two Airlines" blared the headline in the February 21, 2005 edition of *The New York Times*. After many months of unreliable service, the U.S. Postal Service announced it was ceasing to use American Airlines and US Airways for first-class mail delivery. Both airlines are working to improve their on-time performance. In order to win back the mail business, they must develop plans to increase reliability that are acceptable to the Post Office. In an already difficult financial environment for airlines, reliability problems that result in lost business can threaten the very existence of an airline.

Reliability Life Characteristic Concepts (e.g., Bathtub Curve)

If we were to run a piece of equipment to failure, repair it, and repeat the process over and over again, recording the failure time for each run, we would have a set of data that would indicate the failure rate for that piece of equipment. Failure rate is defined as the number of failures per set unit of time. When we plot failure rate against time, we often see a pattern of failure known as a bathtub curve.

EXAMPLE 3.6

The data in the table below were collected for a telephone switch. Plot the failure rate versus time for the switch.

Time of Failure (weeks)			
0.1	1.1	4.0	8.2
0.2	1.2	4.1	8.4
0.2	1.4	4.2	8.5
0.3	1.6	4.6	8.7
0.4	2.0	5.5	8.8
0.5	2.2	5.9	9.0
0.6	2.4	5.9	9.1
0.6	2.6	6.0	9.2
0.7	2.8	6.1	9.2
0.8	2.8	6.2	9.3
0.8	2.9	6.5	9.5
0.8	3.1	7.2	9.7
0.9	3.1	7.5	9.8
0.9	3.1	7.7	9.8
0.9	3.1	7.9	9.9
1.0	3.2	8.0	9.9