Chapter 1

Quality Improvement in the Modern Business Environment

LEARNING OBJECTIVES

After completing this chapter you should be able to:

1. Define and discuss quality and quality improvement
2. Discuss the different dimensions of quality
3. Discuss the evolution of modern quality improvement methods
4. Discuss the role that variability and statistical methods play in controlling and improving quality
5. Describe the quality management philosophies of W. Edwards Deming, Joseph M. Juran, and Armand V. Feigenbaum
6. Discuss total quality management, the Malcolm Baldrige National Quality Award, Six-Sigma, and quality systems and standards
7. Explain the links between quality and productivity and between quality and cost
8. Discuss product liability
9. Discuss the three functions: quality planning, quality assurance, and quality control and improvement

IMPORTANT TERMS AND CONCEPTS

Acceptance sampling
Appraisal costs
Deming's 14 points
Designed experiments
Dimensions of quality
Fitness for use
Internal and External failure costs
ISO 9000:2005
Nonconforming product or service
Prevention costs
Product liability
Quality assurance
Quality characteristics
Quality control and improvement
Quality engineering
Quality of conformance
Quality of design
Quality planning
Quality systems and standards
Six-Sigma
Specifications
Statistical process control (SPC)
The Juran Trilogy
The Malcolm Baldrige National Quality Award
Total quality management (TQM)
Variability

COMMENTS

The modern definition of quality, "Quality is inversely proportional to variability" (text p. 6), implies that product quality increases as variability in important product characteristics decreases. Quality improvement can then be defined as "… the reduction of variability in processes and products" (text p. 7). Since the early 1900's, statistical methods have been used to control and improve quality. In the Introduction to Statistical Quality Control, 7th ed., by Douglas C. Montgomery, methods applicable in the key areas of process control, design of experiments, and acceptance sampling are presented.

To understand the potential for application of statistical methods, it may help to envision the system that creates a product as a "black box" (text Figure 1-3). The output of this black box is a product whose quality is defined by one or more quality characteristics that represent dimensions such as conformance to standards, performance, or reliability. Product quality can be evaluated with acceptance sampling plans. These plans are typically applied to either the output of a process or the input raw materials and components used in manufacturing. Application of process control techniques (such as control charts) or statistically designed experiments can achieve significant reduction in variability.

Black box inputs are categorized as "incoming raw materials and parts," "controllable inputs," and "uncontrollable inputs."

The quality of incoming raw materials and parts is often assessed with acceptance sampling plans. As material is received from suppliers, incoming lots are inspected then dispositioned as either acceptable or unacceptable. Once a history of high quality material is established, a customer may accept the supplier's process control data in lieu of incoming inspection results.

"Controllable" and "uncontrollable" inputs apply to incoming materials, process variables, and environmental factors. For example, it may be difficult to control the temperature in a heat-treating oven in the sense that some areas of the oven may be cooler while some areas may be warmer. Properties of incoming materials may be very difficult to control. For example, the moisture content and proportion of hardwood in trees used for papermaking have a significant impact on the quality characteristics of the finished paper. Environmental variables such as temperature and relative humidity are often hard to control precisely.

Whether or not controllable and uncontrollable inputs are significant can be determined through process characterization. Statistically designed experiments are extremely helpful in characterizing processes and optimizing the relationship between incoming materials, process variables, and product characteristics.

Although the initial tendency is to think of manufacturing processes and products, the statistical methods presented in this text can also be applied to business processes and products, such as financial transactions and services. In some organizations the opportunity to improve quality in three areas is even greater than it is in manufacturing.

Various quality philosophies and management systems are briefly described in the text; a common thread is the necessity for continuous improvement to increase productivity and reduce cost. The technical tools described in the text are essential for successful quality improvement. Quality management systems alone do not reduce variability and improve quality.

Chapter 2

The DMAIC Process

LEARNING OBJECTIVES

After completing this chapter you should be able to:

1. Understand the importance of selecting good projects for improvement activities
2. Explain the five steps of DMAIC: Define, Measure, Analyze, Improve, and Control
3. Explain the purpose of tollgate reviews
4. Understand the decision-making requirements of the tollgate review for each DMAIC step
5. Know when and when not to use DMAIC
6. Understand how DMAIC fits into the framework of the Six Sigma philosophy

IMPORTANT TERMS AND CONCEPTS

Analyze step
Control step
Define step
Design for Six Sigma (DFSS)
DMAIC
Failure modes and effects analysis (FMEA)
Improve step
Key process input variables (KPIV)
Key process output variables (KPOV)
Measure step
Project charter
SIPOC diagram
Six Sigma
Tollgate

EXERCISES

2.7. Explain the importance of tollgates in the DMAIC process.

At a tollgate, a project team presents its work to managers and “owners” of the process. In a six-sigma organization, the tollgate participants also would include the project champion, master black belts, and other black belts not working directly on the project. Tollgates are where the project is reviewed to ensure that it is on track and they provide a continuing opportunity to evaluate whether the team can successfully complete the project on schedule. Tollgates also present an opportunity to provide guidance regarding the use of specific technical tools and other information about the problem. Organization problems and other barriers to success—and strategies for dealing with them—also often are identified during tollgate reviews. Tollgates are critical to the overall problem-solving process; It is important that these reviews be conducted very soon after the team completes each step.

2.11. Suppose that your business is operating at the three-sigma quality level. If projects have an average improvement rate of 50% annually, how many years will it take to achieve Six Sigma quality?

$$3.4 = 66{,}810(1-0.5)^x$$
$$3.4/66{,}810 = 0.5^x$$
$$\ln(3.4/66{,}810) = x \ln 0.5$$
$$x = \frac{\ln(3.4/66{,}810)}{\ln 0.5} = 14.26 \text{ years } \approx 14 \text{ years, 3 months}$$

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2.12. Suppose that your business is operating at the 5-sigma quality level. If projects have an average improvement rate of 50% annually, how many years will it take to achieve Six Sigma quality?

5 sigma quality is approximately 233 ppm defective, assuming the customary 1.5σ shift in mean (Figure 1.2(b)).

$$3.4 = 233(1-0.5)^x$$
$$3.4/233 = 0.5^x$$
$$\ln(3.4/233) = x \ln 0.5$$
$$x = \frac{\ln(3.4/233)}{\ln 0.5} = 6.2 \text{ years } \approx 6 \text{ years, 1 month}$$

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2.13. Explain why it is important to separate sources of variability into special or assignable causes and common or chance causes.

Common or chance causes are due to the inherent variability in the system and cannot generally be controlled. Special or assignable causes can be discovered and removed, thus reducing the variability in the overall system. It is important to distinguish between the two types of variability, because the strategy to reduce variability depends on the source. Chance cause variability can only be removed by changing the system, while assignable cause variability can be addressed by finding and eliminating the assignable causes.

2.15. Suppose that during the analyze phase an obvious solution is discovered. Should that solution be immediately implemented and the remaining steps of DMAIC abandoned? Discuss your answer.

Generally, no. The advantage of completing the rest of the DMAIC process is that the solution will be documented, tested, and it's applicability to other parts of the business will be evaluated. An immediate implementation of an "obvious" solution may not lead to an appropriate control plan. Completing the rest of DMAIC can also lead to further refinements and improvements to the solution.

2.18. It has been estimated that safe aircraft carrier landings operate at about the 5σ level. What level of ppm defective does this imply?

If the operating limits are around the 5σ level, and we assume the 1.5σ shift in the mean customary for Six Sigma applications, then the probability of a safe landing is the area under the normal curve that is within 5σ of the target mean, given that the true mean is 1.5σ off of the target mean. Thus, the probability of a safe landing is 0.999767 and the corresponding ppm defective is $(1 - 0.999767) \times 1{,}000{,}000 = 233$.

Chapter 3

Modeling Process Quality

LEARNING OBJECTIVES

After completing this chapter you should be able to:

1. Construct and interpret visual data displays, including the stem-and-leaf plot, the histogram, and the box plot
2. Compute and interpret the sample mean, the sample variance, the sample standard deviation, and the sample range
3. Explain the concepts of a random variable and a probability distribution
4. Understand and interpret the mean, variance, and standard deviation of a probability distribution
5. Determine probabilities from probability distributions
6. Understand the assumptions for each of the discrete probability distributions presented
7. Understand the assumptions for each of the continuous probability distributions presented
8. Select an appropriate probability distribution
9. Use probability plots
10. Use approximations for some hypergeometric and binomial distributions

IMPORTANT TERMS AND CONCEPTS

Approximations to probability distributions
Binomial distribution
Box plot
Central limit theorem
Continuous distribution
Descriptive statistics
Discrete distribution
Exponential distribution
Gamma distribution
Geometric distribution
Histogram
Hypergeometric probability distribution
Interquartile range
Percentile
Poisson distribution
Population
Probability distribution
Probability plotting
Quartile
Random variable
Run chart
Sample
Sample average
Sample standard deviation
Sample variance
Standard deviation

Lognormal distribution
Mean of a distribution
Median
Negative binomial distribution
Normal distribution
Normal probability plot
Pascal distribution
Standard normal distribution
Statistics
Stem-and-leaf display
Time series plot
Uniform distribution
Variance of a distribution
Weibull distribution

EXERCISES

New exercises are marked with ☺.

3.1.

The content of liquid detergent bottles is being analyzed. Twelve bottles, randomly selected from the process, are measured, and the results are as follows (in fluid ounces): 16.05, 16.03, 16.02, 16.04, 16.05, 16.01, 16.02, 16.02, 16.03, 16.01, 16.00, 16.07.

(a) Calculate the sample average.

$$\bar{x} = \sum_{i=1}^{n} x_i \Big/ n = (16.05 + 16.03 + \cdots + 16.07)/12 = 16.029 \text{ oz}$$

(b) Calculate the sample standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n-1}} = \sqrt{\frac{(16.05^2 + \cdots + 16.07^2) - (16.05 + \cdots + 16.07)^2/12}{12-1}} = 0.0202 \text{ oz}$$

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-1

```
Variable   N  N*    Mean  SE Mean   StDev  Minimum      Q1  Median      Q3
Ex3-1     12   0  16.029  0.00583  0.0202   16.000  16.012  16.025  16.047

Variable  Maximum
Ex3-1      16.070
```

3.2.

The bore diameters of eight randomly selected bearings are shown here (in mm): 50.001, 50.002, 49.998, 49.997, 50.000, 49.996, 50.003, 50.004

(a) Calculate the sample average.

$$\bar{x} = \sum_{i=1}^{n} x_i \Big/ n = \left(50.001 + 49.998 + \cdots + 50.004\right)/8 = 50.000 \text{ mm}$$

(b) Calculate the sample standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n-1}} = \sqrt{\frac{(50.001^2 + \cdots + 50.004^2) - (50.001 + \cdots + 50.004)^2/8}{8-1}} = 0.0029 \text{ mm}$$

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-2

```
Variable  N  N*    Mean  SE Mean    StDev  Minimum      Q1  Median      Q3
Ex3-2     8   0  50.000  0.00103  0.00290   49.996  49.997  50.001  50.003

Variable  Maximum
Ex3-2      50.004
```

3.3. ☺

The service time in minutes from admit to discharge for ten patients seeking care in a hospital emergency department are 21, 136, 185, 156, 3, 16, 48, 28, 100, and 12. Calculate the mean and standard deviation of the service time.

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-3

```
Variable   N  N*  Mean  SE Mean  StDev  Minimum    Q1  Median     Q3  Maximum
Ex3-3     10   0  70.5     21.4   67.7      3.0  15.0    38.0  141.0    185.0
```

3.4. ☺

The Really Cool Clothing Company sells its products through a telephone ordering process. Since business is good, the company is interested in studying the way that sales agents interact with their customers. Calls are randomly selected and recorded, then reviewed with the sales agent to identify ways that better service could possibly be provided or that the customer could be directed to other items similar to those they plan to purchase that they might also find attractive. Call handling time (length) in minutes for 20 randomly selected customer calls handled by the same sales agent are as follows: 5, 26, 8, 2, 5, 3, 11, 14, 4, 5, 2, 17, 9, 8, 9, 5, 3, 28, 22, and 4. Calculate the mean and standard deviation of call handling time.

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-4

```
Variable    N  N*  Mean  SE Mean  StDev  Minimum     Q1  Median     Q3  Maximum
Ex3-4      20   0  9.50     1.77   7.92     2.00   4.00    6.50  13.25    28.00
```

3.5.

The nine measurements that follow are furnace temperatures recorded on successive batches in a semiconductor manufacturing process (units are °F): 953, 955, 948, 951, 957, 949, 954, 950, 959

(a) Calculate the sample average.

$$\bar{x} = \sum_{i=1}^{n} x_i \Big/ n = (953 + 955 + \cdots + 959)/9 = 952.9 \text{ °F}$$

(b) Calculate the sample standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n-1}} = \sqrt{\frac{(953^2 + \cdots + 959^2) - (953 + \cdots + 959)^2/9}{9-1}} = 3.7 \text{ °F}$$

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-5

```
Variable  N  N*    Mean  SE Mean  StDev  Minimum      Q1  Median      Q3
Ex3-5     9   0  952.89     1.24   3.72   948.00  949.50  953.00  956.00

Variable  Maximum
Ex3-5      959.00
```

3.6.

Consider the furnace temperature data in Exercise 3.5.

(a) Find the sample median of these data.

In ranked order, the data are {948, 949, 950, 951, **953**, 954, 955, 957, 959}. The sample median is the middle value.

(b) How much could the largest temperature measurement increase without changing the sample median?

Since the median is the value dividing the ranked sample observations in half, it remains the same regardless of the size of the largest measurement.

3.7.

Yield strengths of circular tubes with end caps are measured. The first yields (in kN) are as follows: 96, 102, 104, 108, 126, 128, 150, 156

(a) Calculate the sample average.

$$\bar{x} = \sum_{i=1}^{n} x_i \Big/ n = (96 + 102 + \cdots + 156)/8 = 121.25 \text{ kN}$$

(b) Calculate the sample standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \Big/ n}{n-1}} = \sqrt{\frac{(96^2 + \cdots + 156^2) - (96 + \cdots + 156)^2 / 8}{8-1}} = 22.63 \text{ kN}$$

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-7

```
Variable  N  N*    Mean  SE Mean  StDev  Minimum     Q1  Median      Q3
Ex3-7     8   0  121.25     8.00  22.63    96.00 102.50  117.00  144.50

Variable  Maximum
Ex3-7      156.00
```

3.8.

The time to failure in hours of an electronic component subjected to an accelerated life test is shown in Table 3E.1. To accelerate the failure test, the units were tested at an elevated temperature (read down, then across).

TABLE 3E.1

Electronic Component Failure Time

127	124	121	117
125	123	136	131
132	120	140	125
124	119	137	133
129	128	125	141
121	133	124	125
142	137	128	140
151	124	129	131
161	143	130	129
125	123	123	126

(a) Calculate the sample average and standard deviation.

(d) Find the sample median and the lower and upper quartiles.

MTB > Stat > Basic Statistics > Display Descriptive Statistics

Descriptive Statistics: Ex3-8_Table 3E.1

```
Variable            N  N*    Mean  SE Mean  StDev  Minimum      Q1  Median
Ex3-8_Table 3E.1   40   0  130.05     1.43   9.06   117.00  124.00  128.00

Variable               Q3  Maximum
Ex3-8_Table 3E.1   135.25   161.00
```

3.8. continued

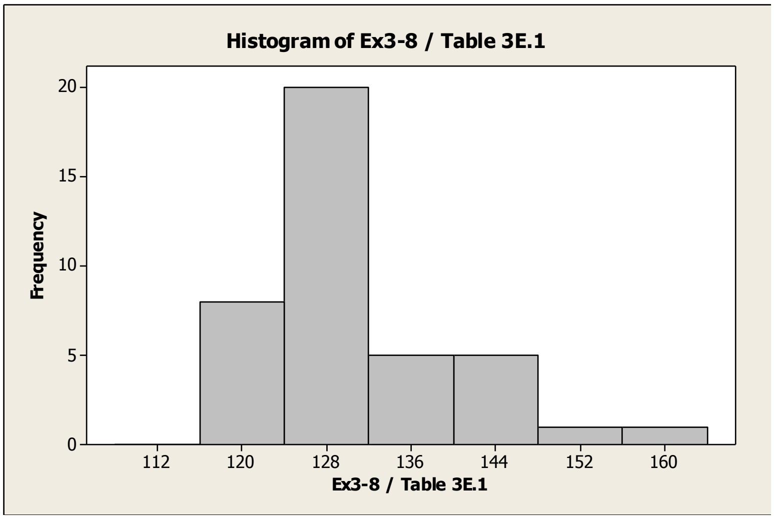
(b) Construct a histogram.

Use $\sqrt{n} = \sqrt{40} \cong 7$ bins

MTB > Graph > Histogram > Simple

(Edit X-axis scale to change binning to 7 intervals)

Histogram of Ex3-8 / Table 3E.1



Note that the histogram has 6 bins. The number of bins can be changed by editing the X scale. However, when 7 bins are specified, Minitab generates a 6-bin histogram. Constructing a 7-bin histogram requires manual specification of the bin cut points. Recall that this formula is an approximation, and therefore either 6 or 8 bins should suffice for assessing the distribution of the data.

3.8. continued

(c) Construct a stem-and-leaf plot.

MTB > Graph > Stem-and-Leaf

Stem-and-Leaf Display: Ex3-8 / Table 3E.1

```
Stem-and-leaf of Ex3-8 / Table 3E.1  N  = 40
Leaf Unit = 1.0


 2    11  89
 12   12  0112334444
(12)  12  555556788999
 16   13  011133
 10   13  677
 7    14  00122
 2    14
 2    15  1
 1    15
 1    16  0
```

3.9.

The data shown in Table 3E.2 are chemical process yield readings on successive days (read down, then across). Construct a histogram for these data. Comment on the shape of the histogram. Does it resemble any of the distributions that we have discussed in this chapter?

TABLE 3E.2

Process Yield

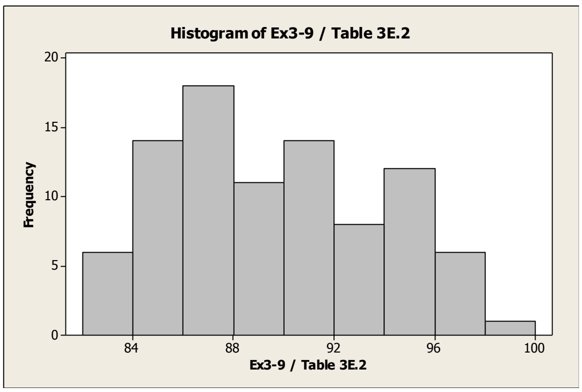
94.1	87.3	94.1	92.4	84.6	85.4
93.2	84.1	92.1	90.6	83.6	86.6
90.6	90.1	96.4	89.1	85.4	91.7
91.4	95.2	88.2	88.8	89.7	87.5
88.2	86.1	86.4	86.4	87.6	84.2
86.1	94.3	85.0	85.1	85.1	85.1
95.1	93.2	84.9	84.0	89.6	90.5
90.0	86.7	87.3	93.7	90.0	95.6
92.4	83.0	89.6	87.7	90.1	88.3
87.3	95.3	90.3	90.6	94.3	84.1
86.6	94.1	93.1	89.4	97.3	83.7
91.2	97.8	94.6	88.6	96.8	82.9
86.1	93.1	96.3	84.1	94.4	87.3
90.4	86.4	94.7	82.6	96.1	86.4
89.1	87.6	91.1	83.1	98.0	84.5

Use $\sqrt{n} = \sqrt{90} \cong 9$ bins

MTB > Graph > Histogram > Simple

(Edit X-axis scale to change binning to 9 intervals)

Histogram of Ex3-9 / Table 3E.2



The distribution appears to have two "peaks" or central tendencies, at about 88 and 94. This is also referred to as a ***bimodal*** distribution. It does not resemble any of the continuous distributions discussed in this chapter (normal, lognormal, exponential, gamma, or Weibull).

3.10.

An article in *Quality Engineering* (Vol. 4, 1992, pp. 487–495) presents viscosity data from a batch chemical process. A sample of these data is presented in Table 3E.3 (read down, then across).

TABLE 3E.3
Viscosity

13.3	14.9	15.8	16.0
14.5	13.7	13.7	14.9
15.3	15.2	15.1	13.6
15.3	14.5	13.4	15.3
14.3	15.3	14.1	14.3
14.8	15.6	14.8	15.6
15.2	15.8	14.3	16.1
14.5	13.3	14.3	13.9
14.6	14.1	16.4	15.2
14.1	15.4	16.9	14.4
14.3	15.2	14.2	14.0
16.1	15.2	16.9	14.4
13.1	15.9	14.9	13.7
15.5	16.5	15.2	13.8
12.6	14.8	14.4	15.6
14.6	15.1	15.2	14.5
14.3	17.0	14.6	12.8
15.4	14.9	16.4	16.1
15.2	14.8	14.2	16.6
16.8	14.0	15.7	15.6

(a) Construct a stem-and-leaf display for the viscosity data.

```
    Stem-and-Leaf Plot (Unordered)
  2    12o|68
  6    13*|3134
 12    13o|776978
 28    14*|3133101332423404
(15)   14o|585669589889695
 37    15*|3324223422112232
 21    15o|568987666
 12    16*|144011
  6    16o|85996
  1    17*|0
Stem  Freq|Leaf
```

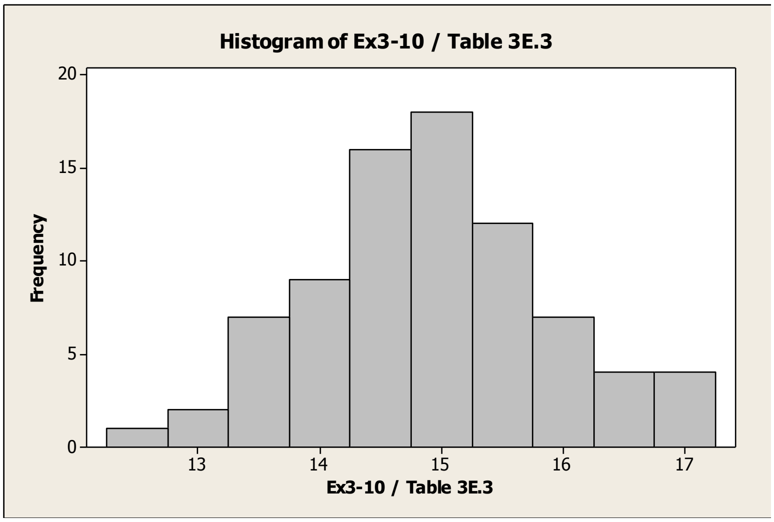
3.10. continued

(b) Construct a frequency distribution and histogram.

Use $\sqrt{n} = \sqrt{80} \cong 9$ bins

MTB > Graph > Histogram > Simple

Histogram of Ex3-10 / Table 3E.3



(c) Convert the stem-and-leaf plot in part (a) into an ordered stem-and-leaf plot. Use this graph to assist in locating the median and the upper and lower quartiles of the viscosity data.

MTB > Graph > Stem-and-Leaf

Stem-and-Leaf Display: Ex3-10 / Table 3E.3

```
Stem-and-leaf of Ex3-10 / Table 3E.3  N  = 80
Leaf Unit = 0.10


 2    12  68
 6    13  1334
 12   13  677789
 28   14  0011122333333444
(15)  14  555566688889999
 37   15  1122222222333344
 21   15  566667889
 12   16  011144
 6    16  56899
 1    17  0
```

3.10.(c) continued

median observation rank is (0.5)(80) + 0.5 = 40.5
$x_{0.50}$ = (14.9 + 14.9)/2 = 14.9

Q1 observation rank is (0.25)(80) + 0.5 = 20.5
Q1 = (14.3 + 14.3)/2 = 14.3

Q3 observation rank is (0.75)(80) + 0.5 = 60.5
Q3 = (15.6 + 15.5)/2 = 15.55

(d) What are the tenth and ninetieth percentiles of viscosity?

10^{th} percentile observation rank = (0.10)(80) + 0.5 = 8.5
$x_{0.10}$ = (13.7 + 13.7)/2 = 13.7

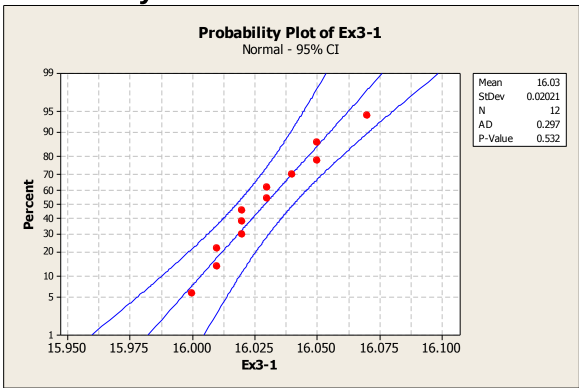
90^{th} percentile observation rank is (0.90)(80) + 0.5 = 72.5
$x_{0.90}$ = (16.4 + 16.1)/2 = 16.25

3.11.

Construct and interpret a normal probability plot of the volumes of the liquid detergent bottles in Exercise 3.1.

MTB > Graph > Probability Plot > Simple and select Normal Distribution

Probability Plot of Ex3-1



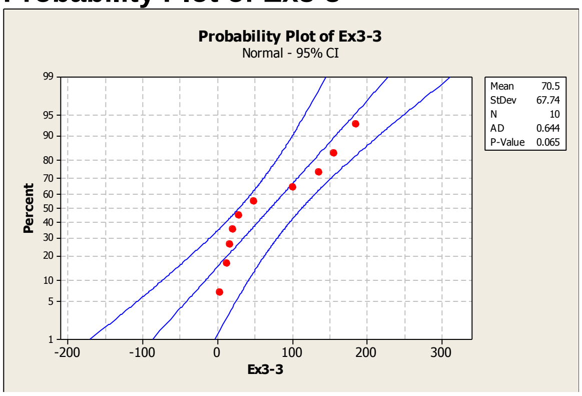
When plotted on a normal probability plot, the data points tend to fall along a straight line, indicating that a normal distribution adequately describes the volume of detergent.

3.12.

Construct and interpret a normal probability plot of the nine furnace temperature measurements in Exercise 3.5.

MTB > Graph > Probability Plot > Simple and select Normal Distribution

Probability Plot of Ex3-3



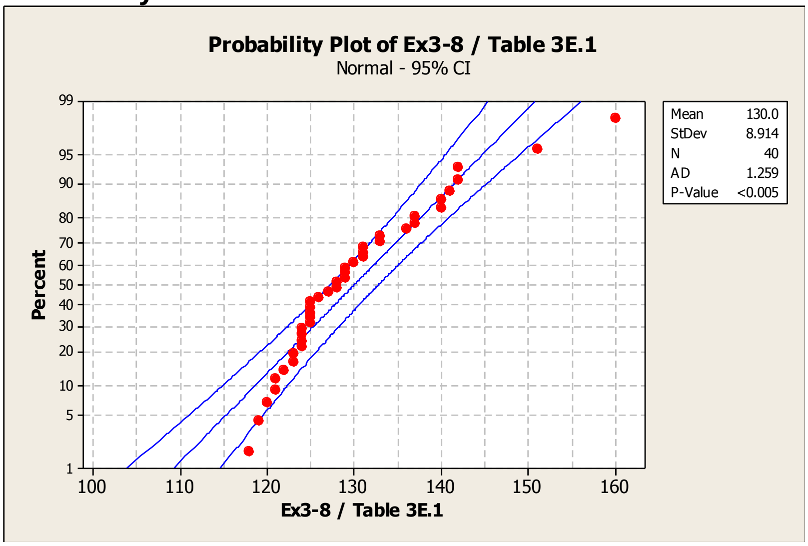
When plotted on a normal probability plot, the data points tend to fall along a straight line, indicating a normal distribution adequately describes the furnace temperatures.

3.13.

Construct a normal probability plot of the failure time data in Exercise 3.8. Does the assumption that failure time for this component is well modeled by a normal distribution seem reasonable?

MTB > Graph > Probability Plot > Simple and select Normal Distribution

Probability Plot of Ex3-8 / Table 3E.1



When plotted on a normal probability plot, the data points do not fall along a straight line, indicating that the normal distribution does not reasonably describe the failure times.