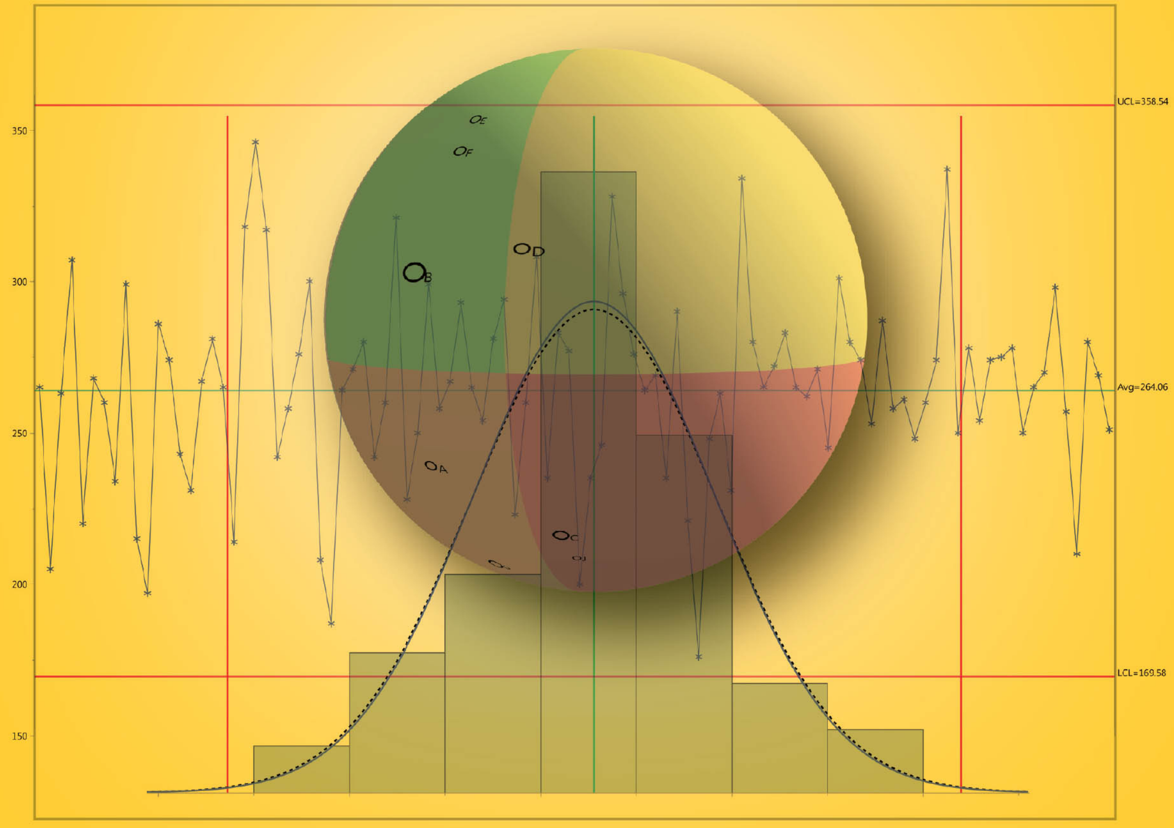
jmp

Douglas Montgomery's Introduction to Statistical Quality Control

A JMP® Companion



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Douglas Montgomery's Introduction to Statistical Quality Control: A JMP® Companion

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About This Book

Why Statistical Quality Control?

What comes to mind when you think of statistical quality control (SQC)? The Encyclopedia Britannica defines this phrase as “the use of statistical methods in the monitoring and maintaining of the quality of products and services.” This definition is in line with our initial exposure to SQC during our college years, in classes like Statistical Process Control. These ideas continued to take shape when we studied for the American Society for Quality Certified Quality Engineering exam, which had us memorize numerous facts about different statistical quality tools. But it was not until we started using these tools and techniques in a real-world manufacturing environment that we truly understood their impact on improving products and processes.

Thirty years and several industries later, we have become great stewards of SQC techniques, and their use and application have become second nature. Therefore, when we were asked to author a companion book to Prof. Montgomery’s *Introduction to Statistical Quality Control* (ISQC), we enthusiastically agreed. Like many, we were introduced to his work through his many books. They are among our favorites because they are very readable, practical, and relevant, not only to the industries that we have worked in but also to the engineers and scientists with whom we often interact. This is no coincidence since Professor Montgomery holds BS, MS, and PhD degrees, all in engineering, and has spent many years both as a professor of Industrial Engineering and Statistics at Arizona State University and as a practitioner collaborating with people in industry.

The synergy between engineering, science, and statistics is always found in Prof. Montgomery’s teachings. Take ISQC, for example. This book provides applications for many of the common SPC techniques using data sources from well-known manufacturing and business processes. For example, the book educates the reader about XBar and Range charts using dimensional measurements from a Hard-Bake process, C charts are applied to nonconformities on a printed circuit board, and we interpret the results of an attribute gauge capability analysis to understand the consistency of a manual underwriting process for mortgage loan applications. ISQC Chapter 10, “Other Univariate Statistical Process-Monitoring and Control Techniques,” contains many useful monitoring techniques that are very effective in practice but may be overlooked or misunderstood. We encourage you to check out his discussions for how to adapt SPC charts for the following scenarios: short production runs, nonstationary and autocorrelated output, change-point models, profile monitoring, and multistream processes.

Following in Prof. Montgomery’s footsteps, we have written a companion book that is geared toward the practitioner of SQC, one who is using these techniques to monitor and improve products and processes. One of our goals in writing this book is to share valuable lessons that we have learned from applying SQC techniques to solve problems in a variety of industries, including semiconductors, electronics, chemical, and biotechnology.

Finally, to fully answer the question of why SQC, we must turn our attention to JMP software. We have been avid JMP users for almost as long as we have been industrial statisticians and know the software well. JMP not only has powerful SQC tools that are easy to use, but it also has plenty of state-of-the-art analysis and visualization tools if the need arises. We have included more than 20 JMP SQC platforms in our book, with step-by-step instructions and tips and tricks

What Does This Book Cover?

As the title suggests, this book is a JMP companion to *Introduction to Statistical Quality Control, Seventh Edition* by Douglas C. Montgomery, which we refer to as ISQC throughout this book. However, the main emphasis of this book is on statistical process control and capability analysis. Therefore, we focus on the techniques provided in ISQC Part 3, "Basic Methods of Statistical Process Control and Capability Analysis," and ISQC Part 4, "Other Statistical Process Monitoring and Control Techniques." These include topics such as Statistical Process Control (SPC), Process Capability Analysis (PCA), Measurement System Analysis (MSA), and Advanced Statistical Process Control (SPC).

For ISQC Chapters 6, 7, 8, 9, 10, and 11, we systematically reproduce the examples and relevant output using JMP. We provide the reader with easy step-by-step instructions, screen captures, and tips and tricks to follow along with. This book is useful for the practitioner because we emphasize the interpretation of the output and provide practical advice for how to navigate common challenges when using these techniques, based on our many years of experience using SPC.

Some recent advances in JMP related to these topics are highlighted in this book. This includes a thorough review of the **Control Chart Builder** and **CUSUM Control Chart**, which are relatively new additions to the **Quality and Process** menu. We are also excited to include a chapter on the **Process Screening** platform, new to JMP version 13, which includes the Stability Ratio in B. Ramírez and G. Runger (2006), and JMP Process Performance Graph, based on the process performance dashboard of J. Ramírez. This information is used to identify the overall health of a process through a Process Health Assessment (PHA).

Is This Book for You?

The main audience for this book is you, the practitioner, who uses these valuable quality and productivity statistical techniques and for which JMP provides a state-of-the-art implementation of them. This book provides the reader with an overview of concepts and tools used to statistically monitor process output, determine the ability of a process to meet specification limits, understand measurement system variability, and assess and prioritize the overall health of many processes. These techniques are used to aid development and manufacturing activities in a variety of industries, including, but not limited to, the automotive, biotechnology, electronics, pharmaceutical, medical devices, chemical, military, and aerospace industries.

This book is also suitable for anyone using Prof. Montgomery's *Introduction to Statistical Quality Control* book to increase your knowledge of these techniques. This includes students taking a SQC course with ISQC as the textbook. In addition to emphasizing the key topic-related content of ISQC, we also provide additional analyses that offer insight to effectively implementing these important tools. Finally, for those who want to learn how to use JMP to more easily explore your data using tools associated with SPC, PCA, MSA, and Advanced SPC, this book is a must.

What Are the Prerequisites for This Book?

Although we provide an overview of each statistical quality tool introduced in this book, we refer the reader to Prof. Montgomery's *Introduction to Statistical Quality Control* for detailed discussions on theory and concepts. We also assume a familiarity with the basic functions of JMP, such as importing and manipulating data, navigating around the JMP menus and windows, and using the basic JMP tools. A summary of related JMP help and resources is provided in the subsequent section called JMP Software.

What Should You Know about the Examples?

For most of the examples presented in ISQC Parts 3 and 4, step-by-step instructions are provided for the reader to follow along, with lots of JMP screen captures. A discussion of the analysis results is also included, and the output is interpreted in the context of the analysis goals. Supplementary examples are provided in the Statistical Insights section in each chapter to illustrate additional JMP functionality not previously covered or to elaborate on important points. A summary of the examples used in this book is provided in Chapter 1.

Software Used to Develop the Book's Content

This book was written using JMP version 14. We have included more than 20 JMP SQC platforms in our book, which are primarily part of the **Quality and Process** menu. As mentioned previously, we are aware of two platforms discussed in this book that were added in the last several versions, Process Screening (version 13) and CUSUM Control Chart (version 14). A summary of the JMP platforms used in this book is shown in Chapter 1.

Example Data

The data used in this book is available at http://support.sas.com/jramirez or http://support.sas.com/bramirez. Users can download the JMP tables and follow along.

About the Authors

Brenda S. Ramírez, MS, is an industrial statistician with many years of experience working in the semiconductor, chemical, and biotechnology industries. In this role, Brenda partners with engineers and scientists to bring new products to market, sustain manufacturing operations, and guide process improvements through the union of science and statistics. She has spent her career using and promoting Statistical Quality Control techniques, such as SPC and Process Stability metrics. Brenda received an MS in applied statistics from Worcester Polytechnic Institute and an MS in industrial and management engineering from Rensselaer Polytechnic Institute. She is an avid user of SAS and JMP statistical software from SAS. Her book, *Analyzing and Interpreting Continuous Data Using JMP: A Step-by-Step Guide*, written with her husband José Ramírez, won the 2010 Award of Excellence in the Society for Technical Communications International Technical Publications Competition.

José G. Ramírez, PhD, is a statistical engineer with years of experience in the semiconductor, electronics and biotech industries. A JMP user for more than 25 years, he works closely with engineers and scientists to help them make sense of data, and through collaborative education, helps promote statistical thinking and JMP usage. He received a degree in mathematics from Universidad Simón Bolívar in Caracas, Venezuela, and both an MS in applied statistics and a PhD in statistics from the University of Wisconsin-Madison. He was one of the founding members of the Center for Quality and Productivity Improvement at the University of Wisconsin-Madison. At the 1998 international SAS users conference, Ramírez won the best contributed statistics paper, and in 2002 he received the SAS User Feedback Award. His book, *Analyzing and Interpreting Continuous Data Using JMP: A Step-by-Step Guide*, written with his wife Brenda Ramírez, won the 2010 Award of Excellence in the Society for Technical Communications International Technical Publications Competition.

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Overview

This chapter illustrates how to generate control charts using examples from Chapter 6, "Control Charts for Variables," of *Introduction to Statistical Quality Control* (ISQC), as well as some of the fundamental ideas behind statistical process control (SPC).

These control chart techniques are presented for data measured on a quantitative scale and are referred to as *variable control charts*. They include the $\overline{X}$ and Range, $\overline{X}$ and Standard Deviation, and Individual Measurement and Moving Range control charts.

Two JMP platforms are highlighted in this chapter: the **Control Chart Builder** and the **Control Chart**.

Variables Control Chart Review

Most books on control charts are partitioned into two buckets: control charts for *variable* data and control charts for *attribute* data. This distinction is important to select the most effective control chart to adequately represent the data of interest. In general, variable data is a measurement that is obtained on a continuous scale, such as temperature, pressure, or thickness. For a thorough discussion of measurement scales, see Chapter 2 in Ramírez and Ramírez (2009).

The most common control charts for *variable* data include the $\overline{X}$ and Range, the $\overline{X}$ and Standard Deviation, and the Individual Measurement and Moving Range (XmR). The first Shewhart control chart, the $\overline{X}$ and Range, is the landmark chart of SPC as we have come to know it today. This chart is appropriate when the natural grouping of the measurements taken in a process is greater than one, also referred to as the subgroup size, *n*. The $\bar{X}$ chart plots the subgroup averages and is used to understand the homogeneity of a process by determining if the subgroup-to-subgroup averages are consistent, as compared to the within-subgroup variation. The Range chart plots the subgroup ranges (maximum value – minimum value) and looks for consistent within-subgroup variation from subgroup to subgroup.

The $\bar{X}$ and Standard Deviation chart is also used to monitor subgroup averages and within-subgroup variation. However, instead of using the subgroup ranges, the chart displays the sample standard deviation to monitor the variation within each subgroup. It is a more appropriate choice when the number of measurements in a subgroup is larger (for example, n>=5). The control limits for the $\bar{X}$ chart are calculated using an estimate of the within-subgroup variation (ranges or standard deviations).

The third chart that is covered in this chapter is the one for individual measurements, referred to as *XmR*. This chart is appropriate when the natural subgroup size is one, and the data are continuous in nature. For example, if one thickness measurement is taken per hour or per equipment run, then an XmR chart is appropriate. The control limits for this chart are constructed from an estimate of the variation from consecutive moving ranges.

The control charts described here are built on statistical assumptions, including the basic model for the observations $y_i = \mu + \varepsilon_i$, where $\varepsilon_i \sim$ i.i.d. $N(\mu, \sigma)$. Although these charts are robust to moderate departures in these assumptions, we emphasize several examples from ISQC to understand the impact of certain departures on the performance of the chart. For example, a 3-way control chart is used to widen inappropriately tight limits on an $\bar{X}$ chart due to a lack of independence among the subgroup measurements, and probability limits from a lognormal distribution are used to accommodate a skewed distribution.

JMP Variables Control Chart Platforms

Two platforms are used to create variables control charts such as $\bar{X}$ and Range, $\bar{X}$ and Standard Deviation, and XmR charts. One is the legacy **Control Chart** platform and the other one is the **Control Chart Builder**. The **Control Chart Builder** is part of the new generation of JMP quality tools, which makes it easier to design, create, and evaluate control charts. These platforms were introduced in Chapter 2. In this chapter, we focus on the use of these platforms for variables data. Table 3.1 provides a summary of the features we find most useful from both platforms.

Table 3.1 Comparison of Features for JMP Variables Control Chart Platforms

Feature	Control Chart Builder	Control Chart
Control chart types	$\bar{X}$ and Range $\bar{X}$ and Standard Deviation XmR	$\bar{X}$ and Range $\bar{X}$ and Standard Deviation XmR
Save limits	In Column and in new Table	In Column and in new Table
Save summaries	Yes	Yes

Feature	Control Chart Builder	Control Chart
Save sigma	No	Yes
Annotation features	Using the Annotate tool	Using the Annotate tool
Interactivity	Yes	Yes

Note that throughout the remainder of this chapter the term *XBar* is used for $\bar{X}$.

Examples from ISQC Chapter 6

The examples presented here from Chapter 6 of ISQC, and their emphasis, are shown in Table 3.2. The examples are reproduced using JMP as are shown in ISQC. For some examples, additional output not provided in ISQC is shown to illustrate JMP functionality or elaborate on important points considered by the authors.

Table 3.2 Summary of Examples from Chapter 6 of ISQC

ISQC Example Number	JMP Table Name	JMP Platform Control Chart Types	Key Points
6.1 Flow Width	Chapter 3 – ISQC Table 6.1, 6.2	Control Chart XBar and Range and Phase Chart	Apply runs tests and save limits to new data. Add box plots to graphs. Produce an OC curve for an XBar chart and create a Phase Chart.
6.3, 6.4 Piston Ring Diameter	Chapter 3 – ISQC Table 6.3, 6.4	Control Chart Builder XBar and Standard Deviation	Save control limits. Use variable subgroup sizes for control limits.
6.5 Loan Processing Cost	Chapter 3 – ISQC Table 6.6	Control Chart IR (XmR)	Create an XmR chart and apply runs tests.
6.6 Resistivity of Silicon Wafers	Chapter 3 – ISQC Table 6.8	Control Chart IR (XmR) and JMP Script	Fit normal and lognormal distributions to data and generate lognormal probability limits.
6.11 Vane Height of Aerospace Casting	Chapter 3 – ISQC Table 6.11	Control Chart Builder 3-way chart and Variability/ Attribute Gage	Create control limits for hierarchical data and perform variance components analysis.

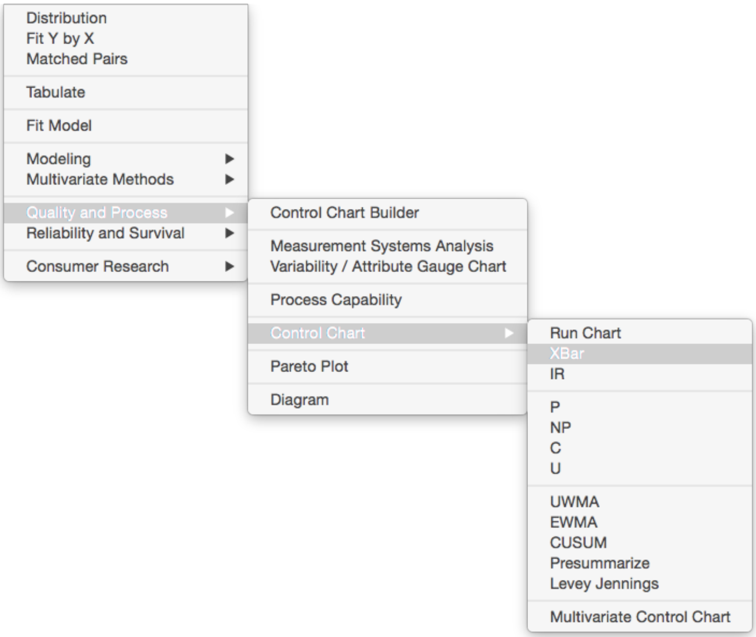
ISQC Example 6.1 Flow Width

In this example, we show how to construct an XBar and Range chart using the legacy **Control Chart** platform in JMP because this platform has the ability to add box plots to the control chart. The data in Table 6.1 of ISQC consists of Flow Width measurements for a hard-bake process used with photolithography in semiconductor manufacturing. For each of 25 runs, a single measurement is taken on five wafers. Therefore, the natural subgroup is one run of the process equipment, and the subgroup size is five wafers or $n = 5$.

The following steps illustrate how to construct the control chart using the **Control Chart** platform:

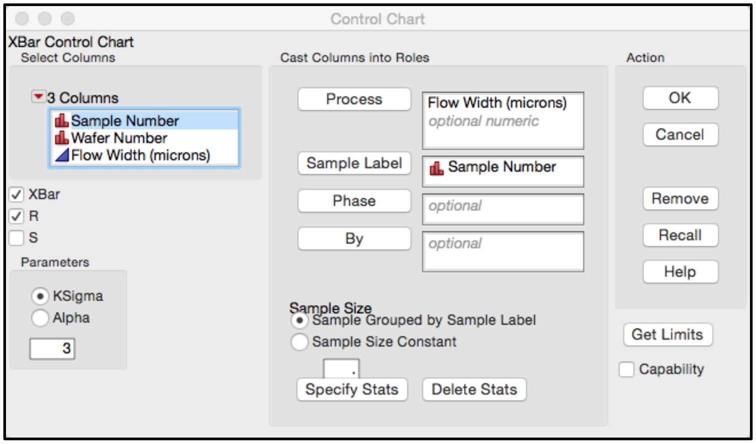
1. Open the JMP table Chapter 3 - ISQC Table 6.1.jmp, which has variables called *Sample Number, Wafer Number,* and *Flow Width (microns)*. Sample Number is the subgroup variable and Flow Width (microns) is the measurement.
2. Select **Analyze ► Quality and Process ► Control Chart ► XBar** (Figure 3.1).

Figure 3.1 JMP Menu Selections for XBar and Range Chart



3. When the XBar control chart launch window appears (Figure 3.2), select **Flow Width (microns)** as the **Process** variable. Then select **Sample Number** and click **Sample Label** to identify the subgroup variable.

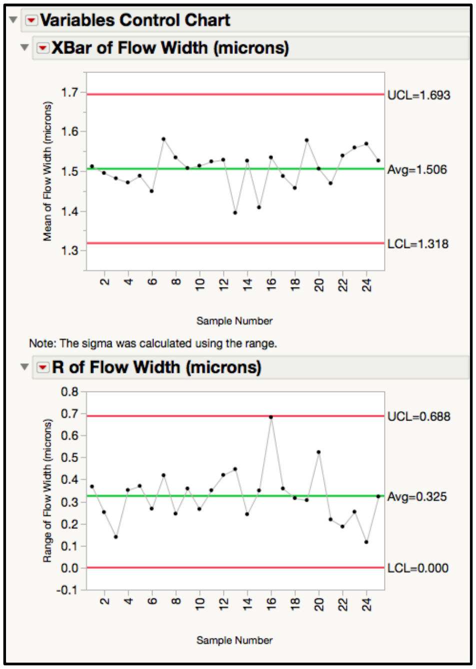
Figure 3.2 Column Selections for XBar and Range Chart



Process: Flow Width (microns)
Sample Label: Sample Number
☑ XBar
☑ R
☐ S
● KSigma
○ Alpha
3
● Sample Grouped by Sample Label
○ Sample Size Constant

4. Click **OK** to create the control chart.

Figure 3.3 XBar and Range Control Chart for Flow Width



Note: The sigma was calculated using the range.

The chart in Figure 3.3 corresponds to Figure 6.2 in ISQC. The Range chart is interpreted first, and because there are no points beyond the control limits, the within-subgroup variation appears to be consistent. Similarly, there are no points outside of the limits for the XBar chart, and we can say that the process is in a state of control. Note that the process capability analysis for this data, which is discussed in ISQC Chapter 6, is presented in Chapter 5 in this book.

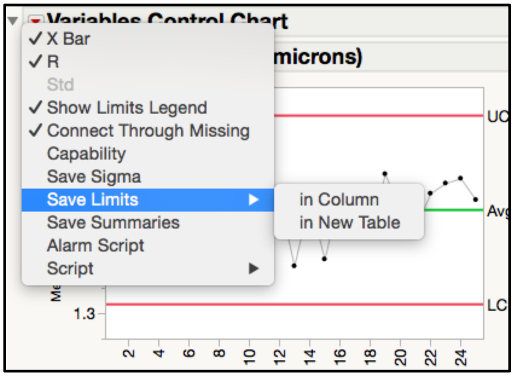
New Data Added

ISQC Table 6.2 shows 20 additional runs of the process with five wafers each, for a total of 100 observations. We want to see if the process is still in control using the control limits established from the first 25 runs. To apply the limits to the new data, we have to save the control limits that were established for the previous chart.

The following steps illustrate how to save the control limits in JMP for the control chart in Figure 3.3 and apply them to new data:

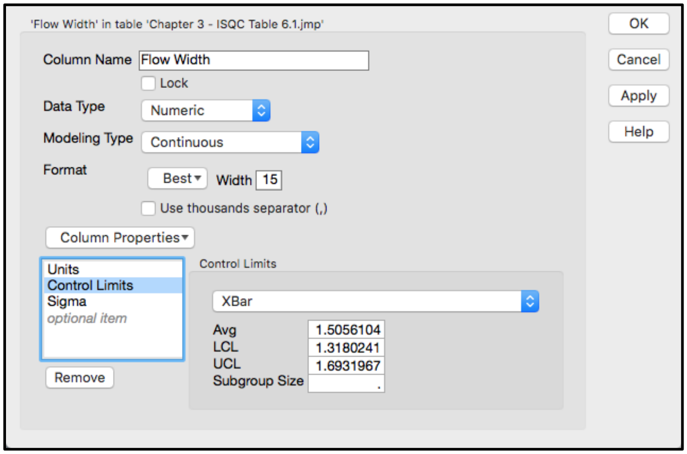
1. Click on the red trianno, bogle next to the **Variables Control Chart** title at the top of the window. This brings up a menu (Figure 3.4). There are two options available to save the limits: **in Column** saves them to a column property in the JMP table containing the original data, while **in New Table** saves them to a new JMP table.

Figure 3.4 Saving Control Limits for Variables Charts



2. To save the limits to a column, select **Save Limits ▶ in Column**. To view the limits, just right-click on the column heading name Flow Width (microns) in the JMP table and select **Control Limits** from the **Column Properties** drop-down menu. In addition, the value of the estimated standard deviation used to compute the limits is also saved as a Sigma column property. The saved column properties are shown in Figure 3.5.

Figure 3.5 Control Limits Saved in Column Properties


'Flow Width' in table 'Chapter 3 - ISQC Table 6.1.jmp'

Column Name: Flow Width

☐ Lock

Data Type: Numeric

Modeling Type: Continuous

Format: Best Width 15

☐ Use thousands separator (,)

Column Properties: Units, Control Limits, Sigma, *optional item*

Control Limits: XBar

Avg 1.5056104

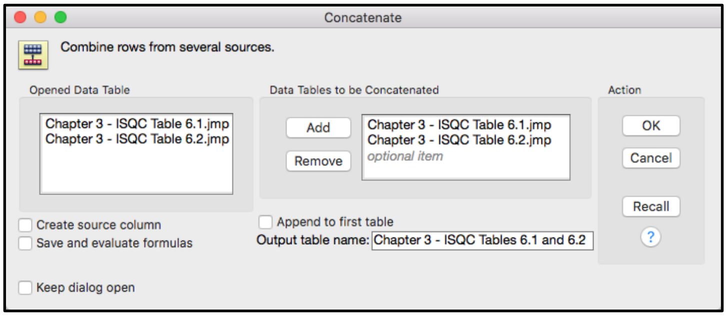
LCL 1.3180241

UCL 1.6931967

Subgroup Size .

3. To update the control chart with new data, open a new JMP table and paste the new data to it. Save the table as Chapter 3 - ISQC Table 6.2.jmp. The new table has 100 (20 subgroups of size, $n = 5$) rows of data.
4. Make sure Chapter 3 - ISQC Table 6.1.jmp is open and selected. From the main menu bar, select **Tables ► Concatenate**. The Concatenate dialog box appears with the Chapter 3 - ISQC Table 6.1.jmp added to the window on the right (Figure 3.6a). To add the new data, select Chapter 3 - ISQC Table 6.2.jmp from the selection list and click **Add**. Enter the output table name as Chapter 3 - ISQC Tables 6.1 and 6.2 and click **OK.** A portion of the resulting table is shown in Figure 3.6b.

Figure 3.6a Concatenating Two JMP Tables


Concatenate

Combine rows from several sources.

Opened Data Table: Chapter 3 - ISQC Table 6.1.jmp, Chapter 3 - ISQC Table 6.2.jmp

Data Tables to be Concatenated: Chapter 3 - ISQC Table 6.1.jmp, Chapter 3 - ISQC Table 6.2.jmp, *optional item*

☐ Create source column

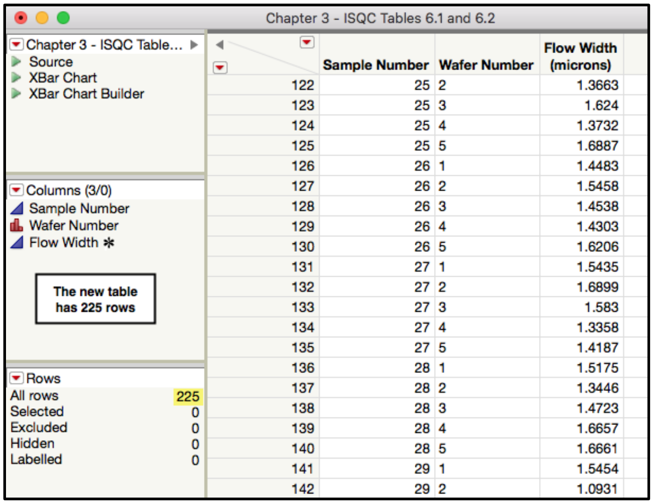
☐ Save and evaluate formulas

☐ Append to first table

Output table name: Chapter 3 - ISQC Tables 6.1 and 6.2

☐ Keep dialog open

Figure 3.6b Concatenated JMP Tables 6.1 and 6.2



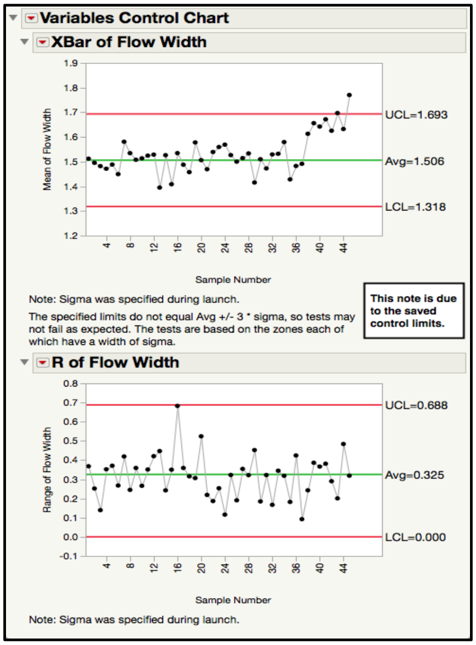
The new table has 225 rows

Rows	
All rows	225
Selected	0
Excluded	0
Hidden	0
Labelled	0

	Sample Number	Wafer Number	Flow Width (microns)
122	25	2	1.3663
123	25	3	1.624
124	25	4	1.3732
125	25	5	1.6887
126	26	1	1.4483
127	26	2	1.5458
128	26	3	1.4538
129	26	4	1.4303
130	26	5	1.6206
131	27	1	1.5435
132	27	2	1.6899
133	27	3	1.583
134	27	4	1.3358
135	27	5	1.4187
136	28	1	1.5175
137	28	2	1.3446
138	28	3	1.4723
139	28	4	1.6657
140	28	5	1.6661
141	29	1	1.5454
142	29	2	1.0931

5. *Optional*: Alternatively, to add new data to the chart, click the JMP table Chapter 3 - ISQC Table 6.1 and select **Rows ▶ Add Rows** from the main JMP menu bar. A window appears and you can enter the number of rows we want to add (100) to the table and then click **OK**. Now select all the new rows that were added, rows 126 to 225, and copy and paste new rows of data from a data source, such as Excel, or another JMP table.
6. To view the control chart with the new data, repeat steps 2 through 3 from the previous example. The limits on the control chart should be the same limits shown in Figure 3.3.

Figure 3.7 Updated XBar and Range Control Chart for Flow Width



Note: Sigma was specified during launch.

The specified limits do not equal Avg +/- 3 * sigma, so tests may not fail as expected. The tests are based on the zones each of which have a width of sigma.

This note is due to the saved control limits.

Note: Sigma was specified during launch.

The chart in Figure 3.7 corresponds to Figure 6.4 of ISQC. The Range chart implies that the within-subgroup variation is consistent because no points are above the upper control limit (UCL). However, there are two points above the UCL for the XBar chart and there appears to be a run of points above the centerline. To aid in the visual assessment for patterns among the subgroup averages, a variety of runs tests can be turned on in the chart. The commonly used Western Electric rules are listed as Test 1, Test 2, Test 5, and Test 6. Refer to the online documentation for a complete description of the different runs tests.

> **JMP Note 3.1:** Click on the point above the UCL in the XBar chart to identify it in the JMP table.

7. To turn on runs tests, click on the red triangle next to the **XBar of Flow Width (microns)** title bar and select **Show Zones.** Then go back and select **Tests ▶ All Tests** (Figure 3.8). This applies the eight Nelson runs tests, as it is shown in Figure 3.9.

Figure 3.8 Turn on Runs Tests for XBar Chart

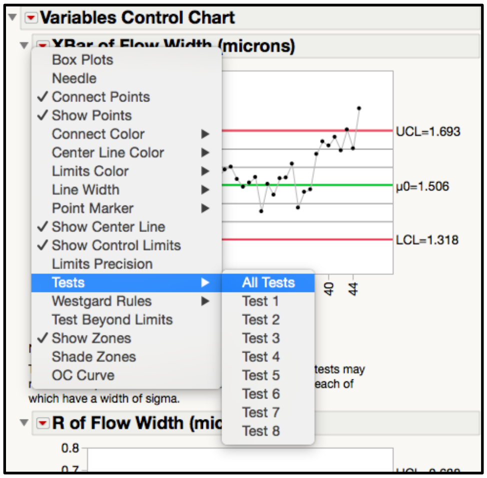
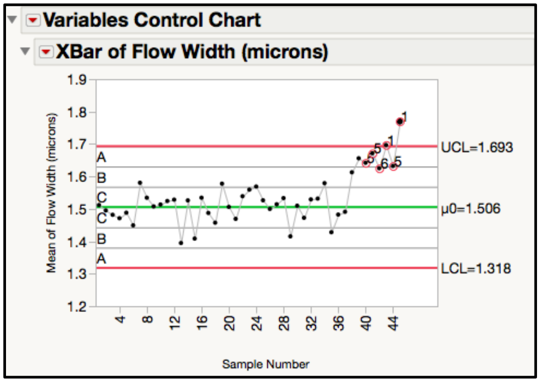
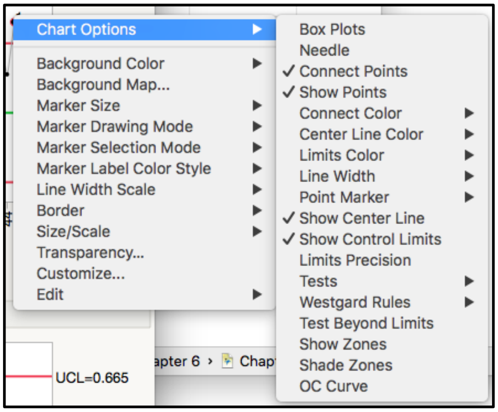


Figure 3.9 XBar Chart for Flow Width with Runs Tests



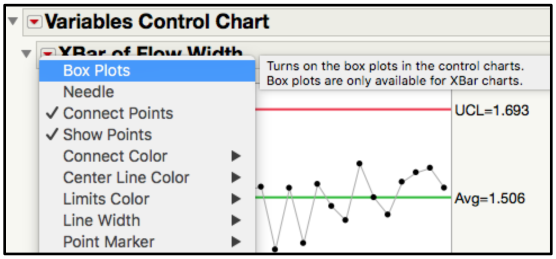
The visual assessment is confirmed, with two points labeled above the UCL and violations for Test 5 and Test 6 (Figure 3.9). It might be helpful to look at the distribution for each subgroup to further evaluate the new data. This is accomplished by adding box plots for each subgroup, which shows the range of the five measurements.

JMP Note 3.2: Select a point in the chart and right-click to see the Chart Options menu. This menu allows you to apply Tests, Test Beyond Limits, Show Zones, and so on.



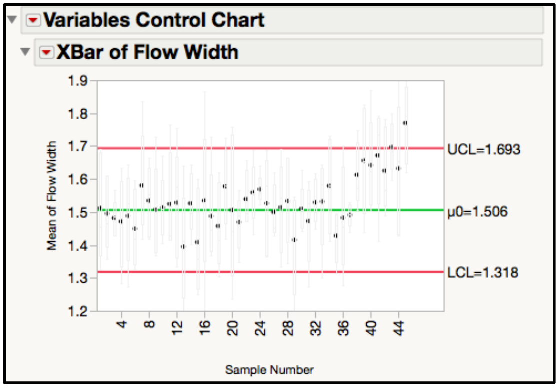
8. To add box plots to the XBar chart, click on the red triangle next to the **XBar of Flow Width (microns)** title bar and select **Box plots**, as shown in Figure 3.10a. The control chart with box plots is shown in Figure 3.10b.

Figure 3.10a Adding Box Plots to Control Chart



Turns on the box plots in the control charts. Box plots are only available for XBar charts.

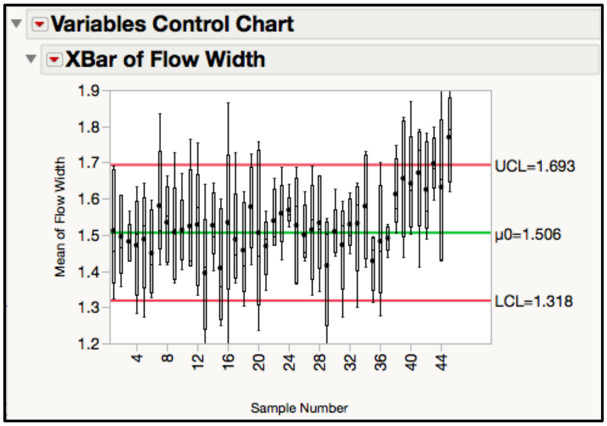
Figure 3.10b XBar Chart for Flow Width with Box Plots



9. The default box plots in Figure 3.10b are light gray. To change the color of the box plots to black, use the script Box Plot Line Color Black.jsl. With the control chart window active, open the script Box Plot Line Color Black.jsl, and run it by pressing CTRL-R (Command-R on a Mac).
10. The script changes the color of the boxes to black as shown in Figure 3.10c, which corresponds to Figure 6.5 of ISQC Chapter 6.

> **JMP Note 3.3**: The default color of the boxes can be changed to black with the JMP script, Box Plot Line Color Black.jsl

Figure 3.10c Updated XBar Chart for Flow Width with Black Box Plots



Note that with the exception of the box plots, the XBar and Range chart in this example can be generated using the **Control Chart Builder**. The next example showcases the **Control Chart Builder**.

ISQC Example 6.3 Piston Ring Diameter

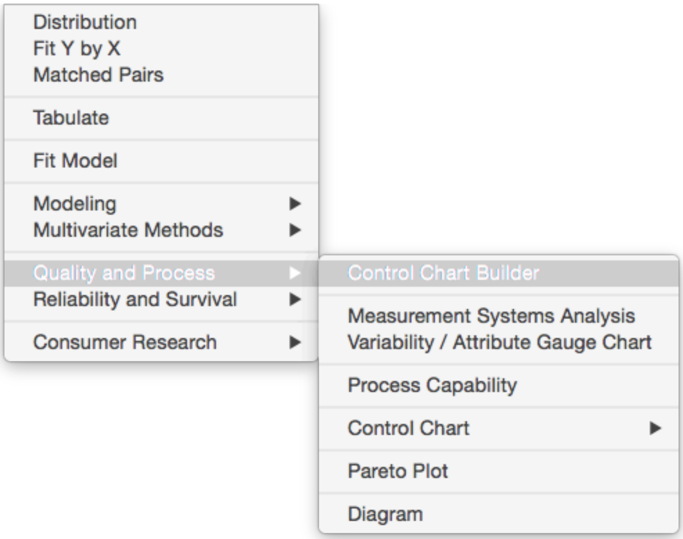
In this example, we show how to construct an XBar and Standard Deviation chart using the **Control Chart Builder** in JMP. As mentioned earlier, the **Control Chart Builder**, part of the new generation of JMP quality tools, makes it easier to design and evaluate control charts. The **Control Chart Builder** has a similar drag-and-drop interface to the **Graph Builder**, which allows the user to quickly visualize charts and change the limits calculations, for example, on the fly.

The data set consists of inside diameter measurements for forged automobile engine piston rings (ISQC Table 6.3). For each of 25 runs, a single measurement is taken on five piston rings. Therefore, the natural subgroup is one run of the process equipment, and the subgroup size is n = 5. Later in this example, we show what happens when the subgroup sizes are unequal.

The following steps illustrate how to construct the control chart using the **Control Chart Builder** platform:

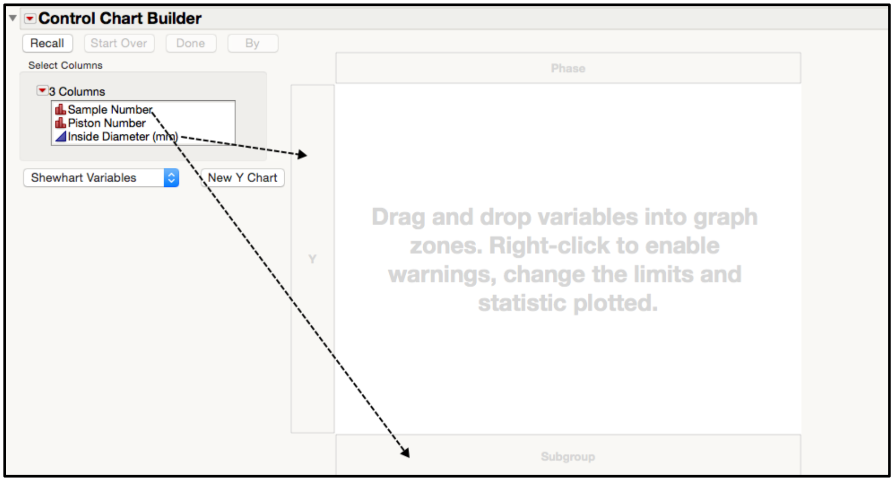
1. Open Chapter 3 – ISQC Table 6.3.jmp, which has variables called *Sample Number*, *Piston Ring Number*, and *Inside Diameter (mm)*. Sample Number is the subgroup variable and Inside Diameter (mm) is the measurement.
2. Select **Analyze ► Quality and Process ► Control Chart Builder** (Figure 3.11). The **Control Chart Builder** launch window appears.

Figure 3.11 Launching Control Chart Builder



3. Drag **Sample Number** from the left-hand window to the **Subgroup** zone (X axis). Similarly, drag **Inside Diameter (mm)** from the left-hand window to the **Y zone** (Y axis) (Figure 3.12).

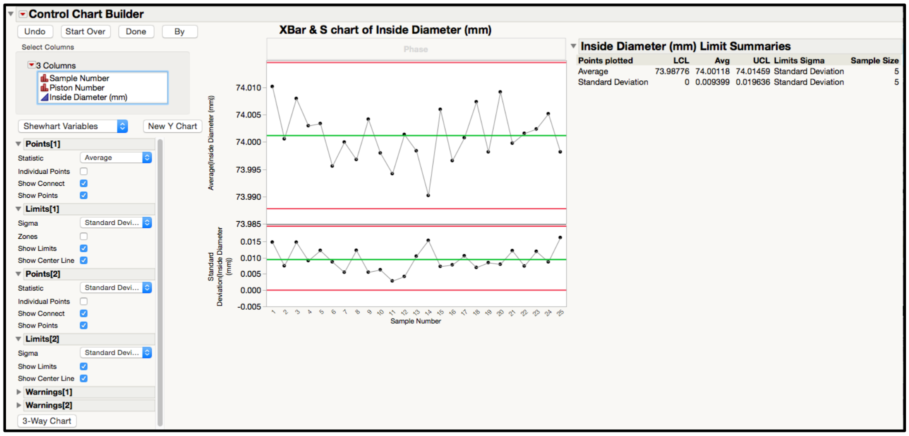
Figure 3.12 Launch Window for Control Chart Builder



Drag and drop variables into graph zones. Right-click to enable warnings, change the limits and statistic plotted.

4. The XBar and Range chart appears first in the window. To change it to an XBar and standard deviation chart, select **Standard Deviation** from the drop-down list next to **Sigma** and under **Limits[1]**. Then select **Standard Deviation** from the drop-down list next to **Statistic** and under **Points[2]**. Finally, when the chart has all the required features, click **Done** in the upper left corner of the window (Figure 3.13).

Figure 3.13 XBar and S Chart for Piston Data



Points[1]
Statistic: Average
Individual Points ☐
Show Connect ☑
Show Points ☑

Limits[1]
Sigma: Standard Devi...
Zones ☐
Show Limits ☑
Show Center Line ☑

Points[2]
Statistic: Standard Devi...
Individual Points ☐
Show Connect ☑
Show Points ☑

Limits[2]
Sigma: Standard Devi...
Show Limits ☑
Show Center Line ☑

Warnings[1]

Warnings[2]

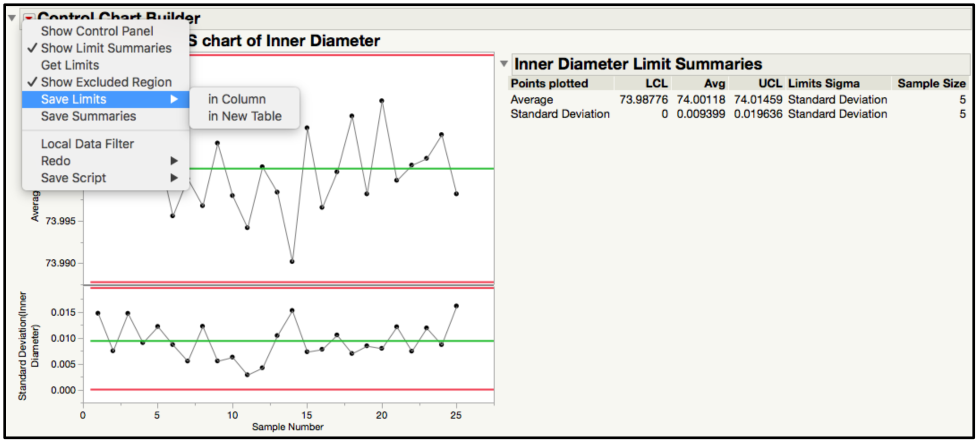
Inside Diameter (mm) Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Average	73.98776	74.00118	74.01459	Standard Deviation	5
Standard Deviation	0	0.009399	0.019636	Standard Deviation	5

Figure 3.13 corresponds to ISQC Figure 6.17. In this figure, the standard deviation chart is plotting the sample standard deviation for each subgroup and shows that the within-subgroup variation is consistent, with no points outside of the control limits. The XBar chart is plotting the subgroup averages and does not show any points outside of the control limits. If these limits are appropriate to apply to future subgroups, then they can be saved to the column properties in the JMP table using the **Control Chart Builder**.

5. The control limits can be saved to the column properties of the JMP table by clicking on the small red triangle at the top of the window and selecting **Save Limits ▶ in Column** (Figure 3.14).

Figure 3.14 Saving Control Limits for Piston Data XBar and S Chart



Inner Diameter Limit Summaries

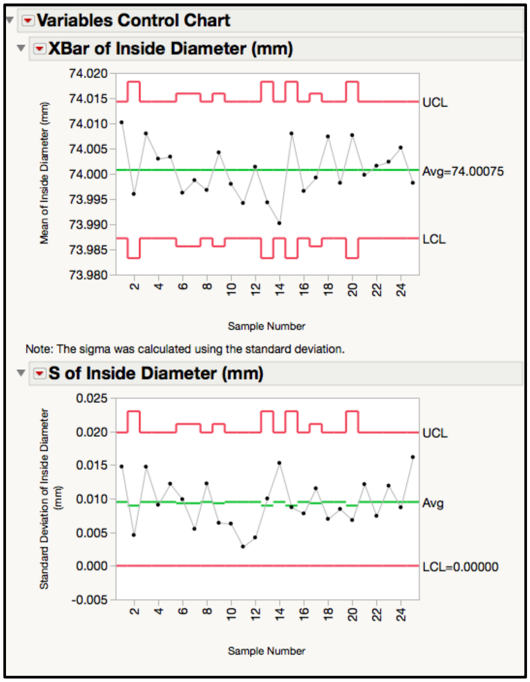
Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Average	73.98776	74.00118	74.01459	Standard Deviation	5
Standard Deviation	0	0.009399	0.019636	Standard Deviation	5

ISQC Example 6.4 Piston Ring Diameter

Sometimes the subgroup size is not constant in the data that we want to plot on a control chart. This could occur for a variety of reasons; for example, perhaps data could not be obtained for all samples in a subgroup or the sampling scheme might depend on a dynamic production schedule. In any event, the control limits for both charts will be impacted since they depend on the subgroup size, *n*. The **Control Chart** platform will automatically adjust the control limits for variable subgroup size.

1. Open Chapter 3 – ISQC Table 6.4.jmp, which has variables called *Sample Number*, *Piston Ring Number*, and *Inside Diameter (mm)*. This data is similar to Chapter 3 – ISQC Table 6.3.jmp; however, some of the subgroup results have been removed to create variable subgroup sizes.
2. Select **Analyze ▶ Quality and Process ▶ Control Chart ▶ XBar**. When the XBar Control Chart launch window appears, select **Inside Diameter (mm)** as the **Process** variable. Then select **Sample Number** and click **Sample Label** to identify the subgroup variable.
3. Click **OK** to create the control chart. Figure 3.15 corresponds to ISQC Figure 6.18.

Figure 3.15 XBar and S Chart for Piston Data with Variable Subgroup Sizes



Note: The sigma was calculated using the standard deviation.

Statistics Note 3.1: The reason the control limits vary is because they are a function of the sample size, and in Figure 3.15 the number of samples in each subgroup varies.

ISQC Example 6.5 Loan Processing Costs

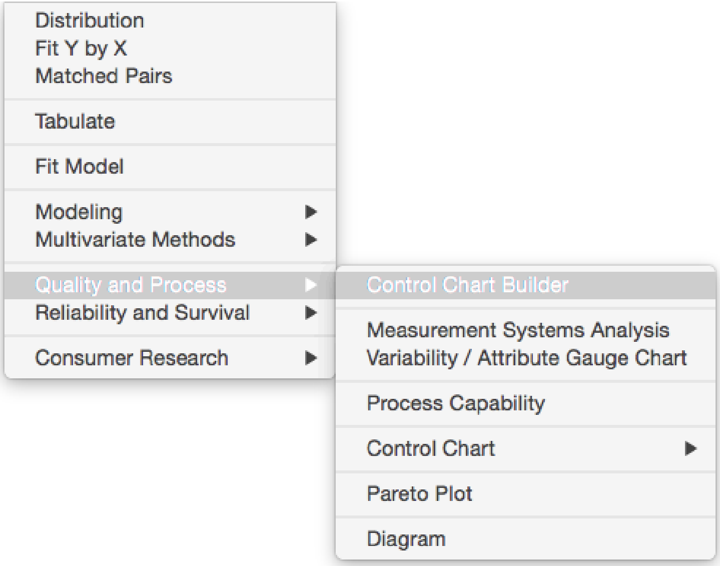
In this example, we show how to construct an Individual Measurement and Moving Range (XmR) chart using the **Control Chart Builder** platform in JMP. The data set consists of the cost of processing loan applications at a bank. The quantity tracked is the average weekly processing costs, which represents the ratio of the total weekly cost and the number of loans processed during the week. Because the bank is interested in the average weekly cost, the natural subgroup is one week of data and the subgroup size is $n = 1$. When the subgroup size $n = 1$, an XmR control chart is an appropriate choice.

The following steps illustrate how to construct the control chart using the **Control Chart Builder**:

1. Open Chapter 3 – ISQC Table 6.6.jmp, which has variables called *Weeks* and *Cost x*. Weeks is the subgroup variable and Cost x is the measurement.

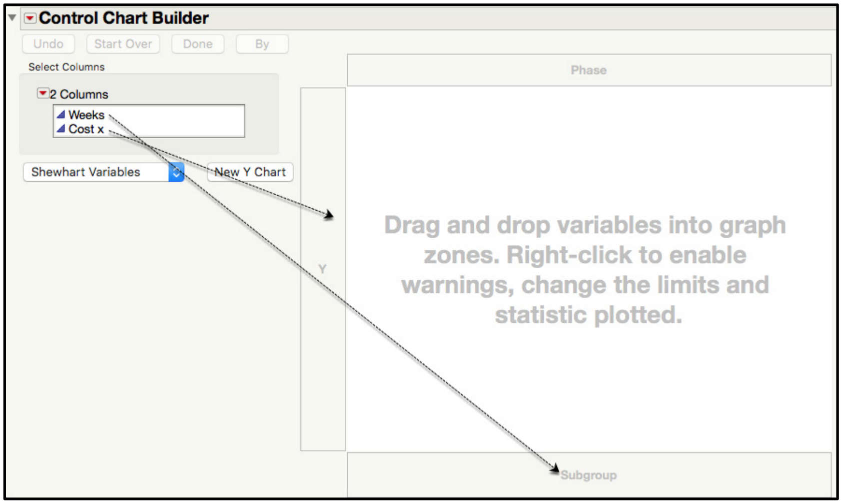
2. Select **Analyze ▶ Quality and Process ▶ Control Chart Builder** (Figure 3.16).

Figure 3.16 Launching Control Chart Builder



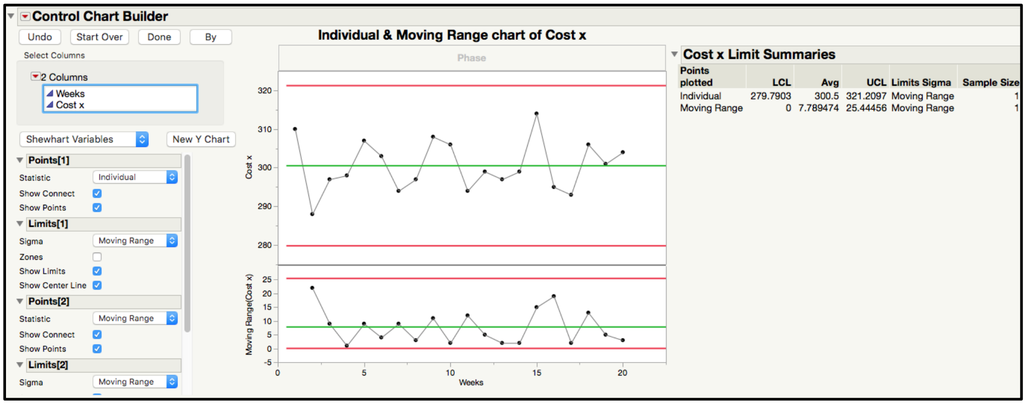
3. Drag **Cost x** from the left-hand window to the **Y** zone (Y axis). Similarly, drag **Weeks** from the left-hand window to the **Subgroup** zone (X axis) (Figure 3.17).

Figure 3.17 Launch Window for Control Chart Builder



The Individual and Moving Range chart appears in the window, reflecting how quickly charts can be generated with the **Control Chart Builder**. The **Points[1]** menu shows **Individual** under **Statistic**, while the **Limits[1]** menu shows **Moving Range** under **Sigma**. The control limits appear under the **Cost x Limit Summaries** report.

Figure 3.18 Individual & Moving Range Chart for Cost x Data



Points[1]
Statistic Individual
Show Connect ☑
Show Points ☑
Limits[1]
Sigma Moving Range
Zones ☐
Show Limits ☑
Show Center Line ☑
Points[2]
Statistic Moving Range
Show Connect ☑
Show Points ☑
Limits[2]
Sigma Moving Range

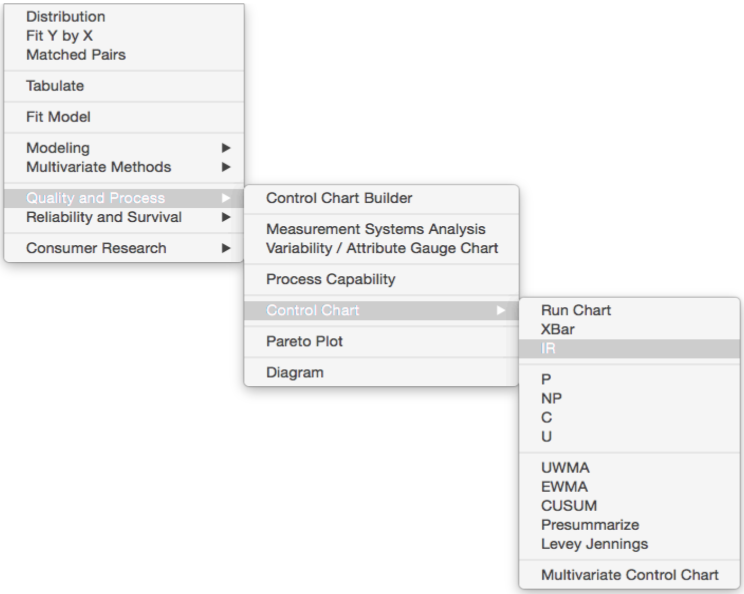
Cost x Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Individual	279.7903	300.5	321.2097	Moving Range	1
Moving Range	0	7.789474	25.44456	Moving Range	1

Figure 3.18 corresponds to ISQC Figure 6.19. This chart can also be generated using the **Control Chart** platform.

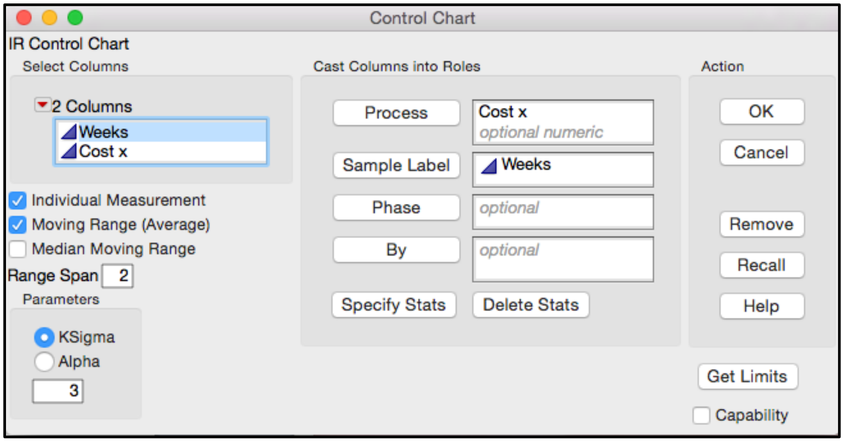
1. Select **Analyze ▶ Quality and Process ▶ Control Chart ▶ IR** (Figure 3.19).

Figure 3.19 Launching Control Chart for XmR



2. When the IR Control Chart launch window appears, select **Cost x** as the **Process** variable. Then select **Weeks** and click **Sample Label** to identify the subgroup variable.

Figure 3.20 Launch Window for XmR for Cost x



Process: Cost x (optional numeric)
Sample Label: Weeks
Phase: optional
By: optional

☑ Individual Measurement
☑ Moving Range (Average)
☐ Median Moving Range
Range Span 2

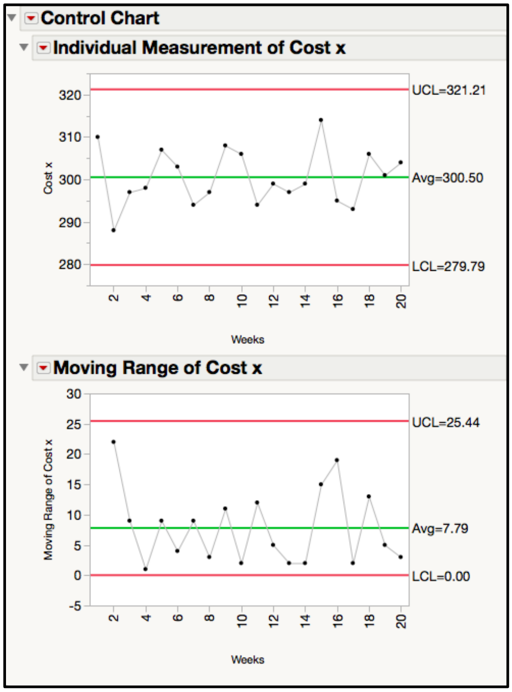
● KSigma
○ Alpha
3

☐ Capability

In this launch window, there are several options available for determining how the standard deviation is calculated, which is used to calculate the control limits for the individuals chart. The default settings (that is, **Moving Range (Average)** and a **Range Span** = 2) are selected by default when the launch window appears. The standard deviation can be derived using the average moving range or the median moving range, as shown by the options located in the left-hand side of the window. Although the average moving range is typically used, the median moving range might be more robust to outliers. The span of the moving ranges can also be specified. Once again, while a span of 2 is the most common choice, a larger span might be used to incorporate more variation into the estimate.

3. To produce the control chart, click **OK**.

Figure 3.21 XmR Control Chart for Cost x Data



In Figure 3.21, the Moving Range chart monitors the short-term variation by plotting the consecutive differences in two adjacent results. For this parameter, there are no points that exceed the upper control limit. The Individual Measurement control chart monitors the process mean and, because there are no points outside of the control limits, the process output is stable.

Statistics Note 3.2: Some people do not find value in evaluating the Moving Range chart because it is thought to provide redundant information that can be obtained from the Individuals control chart. However, there is a subtle difference in the monitoring objectives for the two charts. It is possible to have a moving range that exceeds the upper control limit, but it does not produce a signal on the Individual Measurement control chart and vice versa. For example, in the chart in Figure 3.21, it is possible that the difference between two consecutive costs can exceed 25.44, with both costs falling within 279.79 and 321.21 (for example, (315 – 285) = 30). Conversely, two consecutive points might exceed the UCL but be in control in the Moving Range chart with a UCL of 25.44 (for example, (324 – 323) = 1).

---

4. More subtle shifts in the mean can be examined by turning on the runs tests. This is accomplished by clicking on the red triangle next to the **Individual Measurement of Cost x** title bar and selecting **Show Zones** and then going back and selecting **Tests ► All Tests**.

This applies the eight Nelson runs tests. Because there are no violations, the control chart is not reproduced here.

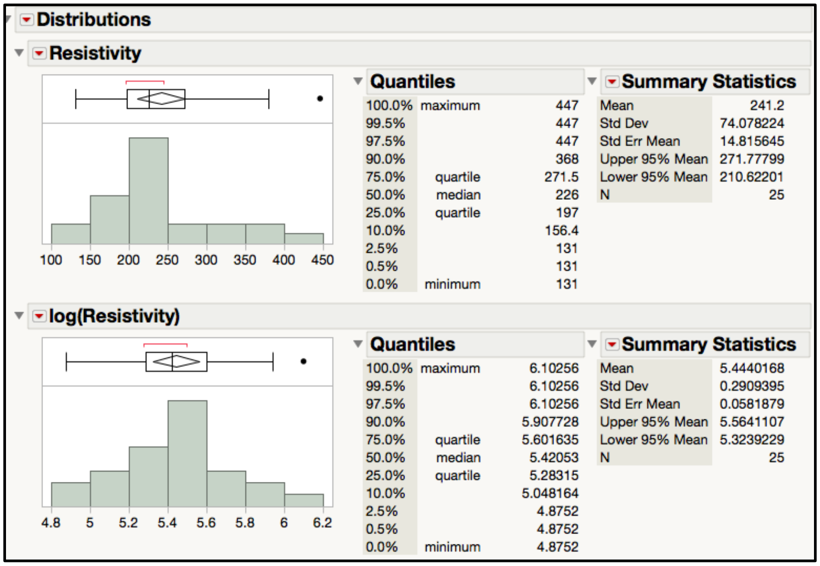
ISQC Example 6.6 Resistivity of Silicon Wafers

In this example, we show how to construct an Individual Measurement and Moving Range (XmR) chart using the **Control Chart** platform in JMP. The data set consists of resistivity measurements of 25 silicon wafers after an epitaxial layer is deposited in a single-wafer deposition process. Because a resistivity measurement is taken on a single wafer per run, the natural subgroup size is $n = 1$. The assumption of normality is explored, and a lognormal transformation of the data is used for process monitoring using an XmR chart. Note that in JMP the XmR chart is called the IR chart.

The following steps illustrate how to evaluate the distributional assumptions and construct the control chart using the **Control Chart** platform:

1. Open Chapter 3 – ISQC Table 6.8.jmp, which has variables called *Sample Number*, *Resistivity*, and *log(Resistivity)*. Sample Number is the subgroup variable, Resistivity is the measurement, and log(Resistivity) is the natural log transformation of the Resistivity measurements.
2. Select **Analyze ► Distribution**. A launch window appears. Select **Resistivity** and **log(Resistivity)** and select **Y, Columns** to add them to the window. Click **OK** when you are done. The histograms are shown in Figure 3.22.

Figure 3.22 Distributions for Wafer Resistivity Data



Distributions

Resistivity

Quantiles

100.0%	maximum	447
99.5%		447
97.5%		447
90.0%		368
75.0%	quartile	271.5
50.0%	median	226
25.0%	quartile	197
10.0%		156.4
2.5%		131
0.5%		131
0.0%	minimum	131

Summary Statistics

Mean	241.2
Std Dev	74.078224
Std Err Mean	14.815645
Upper 95% Mean	271.77799
Lower 95% Mean	210.62201
N	25

log(Resistivity)

Quantiles

100.0%	maximum	6.10256
99.5%		6.10256
97.5%		6.10256
90.0%		5.907728
75.0%	quartile	5.601635
50.0%	median	5.42053
25.0%	quartile	5.28315
10.0%		5.048164
2.5%		4.8752
0.5%		4.8752
0.0%	minimum	4.8752

Summary Statistics

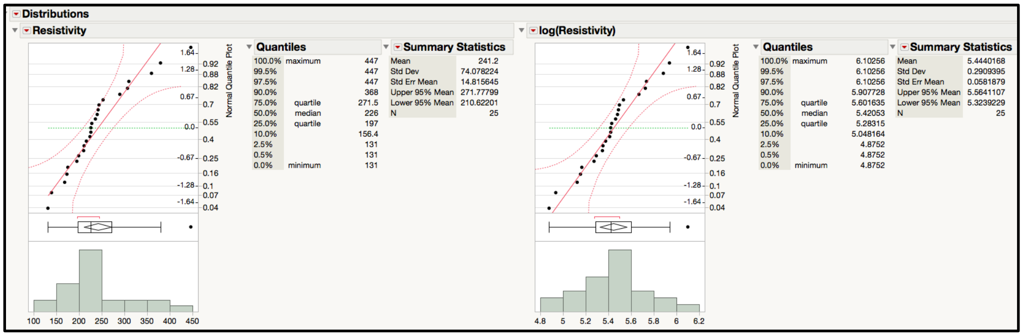
Mean	5.4440168
Std Dev	0.2909395
Std Err Mean	0.0581879
Upper 95% Mean	5.5641107
Lower 95% Mean	5.3239229
N	25

3. To add normal probability plots to Figure 3.22, click on the red triangle at the top of the window next to the **Resistivity** label while holding down the Ctrl key and select **Normal**

Quantile Plot from the drop-down menu. Normal quantile plots are added above each histogram.

4. To rearrange the graphs, click on the red triangle next to **Distributions** at the top of the window, select **Arrange in Rows,** enter **2** in the dialog box that appears, and click **OK**.

Figure 3.23 Normal Probability Plots for Resistivity and log(Resistivity)



Resistivity

Quantiles

100.0%	maximum	447
99.5%		447
97.5%		447
90.0%		368
75.0%	quartile	271.5
50.0%	median	226
25.0%	quartile	197
10.0%		156.4
2.5%		131
0.5%		131
0.0%	minimum	131

Summary Statistics

Mean	241.2
Std Dev	74.078224
Std Err Mean	14.815645
Upper 95% Mean	271.77799
Lower 95% Mean	210.62201
N	25

log(Resistivity)

Quantiles

100.0%	maximum	6.10256
99.5%		6.10256
97.5%		6.10256
90.0%		5.907728
75.0%	quartile	5.601635
50.0%	median	5.42053
25.0%	quartile	5.28315
10.0%		5.048164
2.5%		4.8752
0.5%		4.8752
0.0%	minimum	4.8752

Summary Statistics

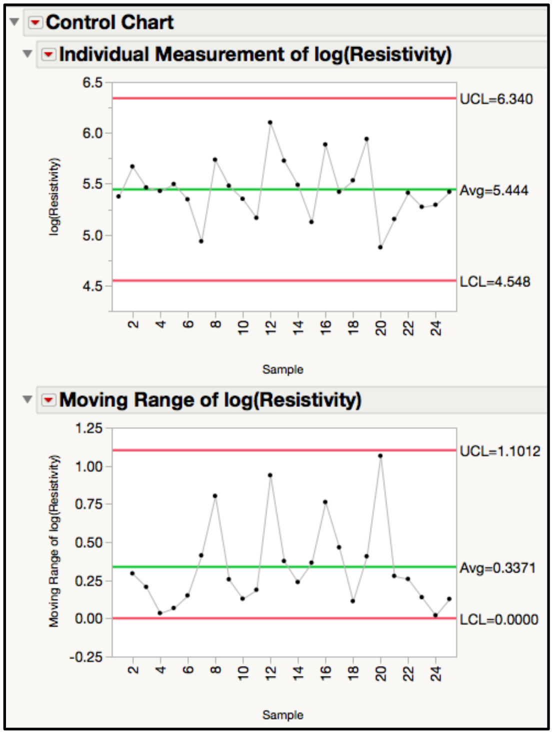
Mean	5.4440168
Std Dev	0.2909395
Std Err Mean	0.0581879
Upper 95% Mean	5.5641107
Lower 95% Mean	5.3239229
N	25

The normal probability plots are displayed above the histograms for each response (Figure 3.23). These displays can be evaluated to determine the best fit for the data at hand. If the data in the probability plot falls along the straight line and within the provided bands, then the distribution is a good approximation to the data set. For wafer resistivity, the normal plot for the log-transformed data appears to provide a slightly better fit than that for the untransformed data. In addition, the histogram and the box plot are more symmetrical around the mean for the log-transformed data, suggesting a departure from the normal distribution. In Figure 3.23 the normal probability plot for Resistivity corresponds to ISQC Figure 6.22, while the one for log(Resistivity) corresponds to ISQC Figure 6.23.

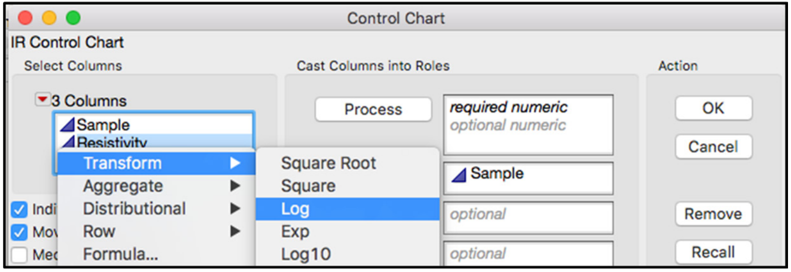
There are two ways to control chart wafer resistivity using the lognormal distribution. The first way involves charting the log, base *e*, transformed data using an XmR control chart, which is shown here. A second approach, using lognormal probability limits, is discussed in the Statistical Insights section in this chapter.

5. From the main menu, select **Analyze ► Quality and Process ► Control Chart ►IR**.
6. A launch window appears. Select **log(Resistivity)** as the **Process** variable. Then select **Sample** and click **Sample Label** to identify the subgroup variable. Click **OK** when you are done. The chart is shown in Figure 3.24.

Figure 3.24 XmR Chart for log(Resistivity)



JMP Note 3.4: You can transform the response right from the control chart by right-clicking on the response Resistivity and selecting **Transform ► Log**.

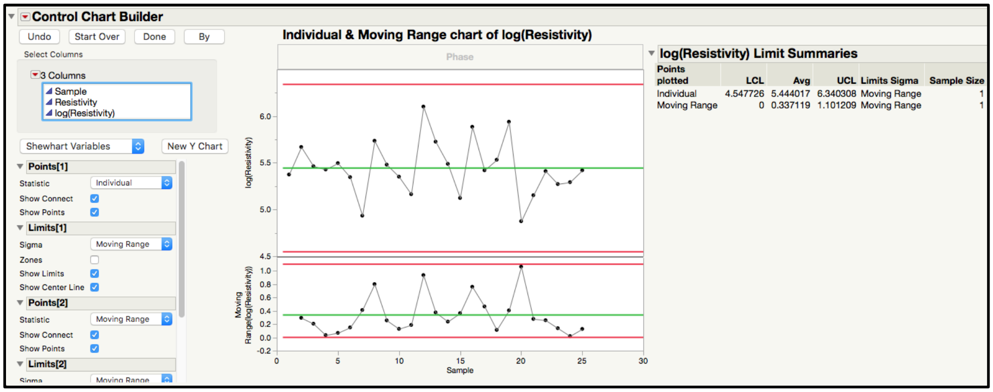


The Moving Range chart of the transformed data, shown in Figure 3.24 (ISQC Figure 6.24), no longer has any points above the upper control limit and the Individual chart shows no violations of runs tests.

We can also use the **Control Chart Builder** to generate the control chart in Figure 3.24, as follows:

1. From the main menu, select **Analyze ▶ Quality and Process ▶ Control Chart Builder**.
2. Drag **log(Resistivity)** from the left-hand window to the **Y** zone (Y axis). Similarly, drag **Sample** from the left-hand window to the **Subgroup** zone (X axis). Figure 3.25 shows the XmR chart.

Figure 3.25 Control Chart Builder XmR Chart for log(Resistivity)



Points[1]

Statistic: Individual

Show Connect ☑

Show Points ☑

Limits[1]

Sigma: Moving Range

Zones ☐

Show Limits ☑

Show Center Line ☑

Points[2]

Statistic: Moving Range

Show Connect ☑

Show Points ☑

Limits[2]

Sigma: Moving Range

log(Resistivity) Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Individual	4.547726	5.444017	6.340308	Moving Range	1
Moving Range	0	0.337119	1.101209	Moving Range	1

ISQC Example 6.11 Vane Height of an Aerospace Casting

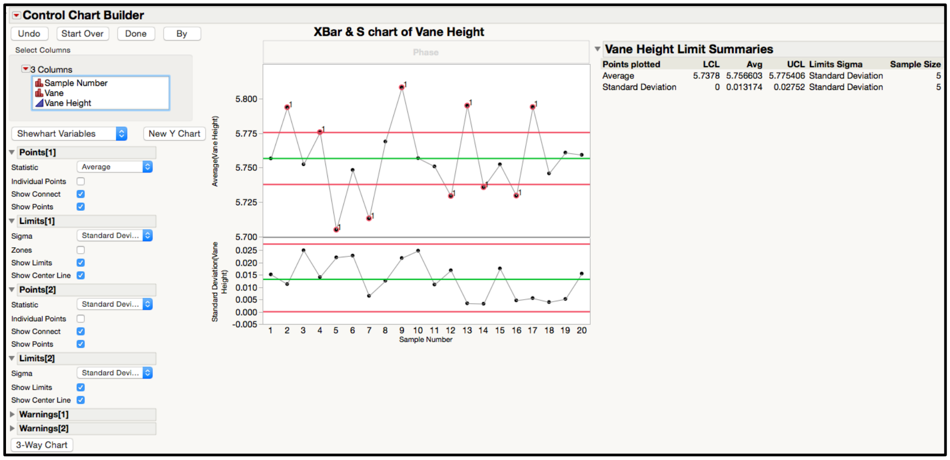
In this example, we show how easy it is to construct a 3-way chart using the **Control Chart Builder** platform in JMP. The data set consists of vane height measurements on 20 aerospace castings, which are used in a gas turbine jet aircraft engine. Data on vane heights are collected by randomly selecting five vanes on each casting produced. Since five measurements are taken per casting, the natural subgroup size is $n = 5$. An XBar and Standard Deviation control chart is adapted for this sampling scheme using a 3-way chart.

The following steps illustrate how to create a 3-way chart using the **Control Chart Builder** platform:

1. Open Chapter 3 – ISQC Table 6.11.jmp, which has variables called *Sample Number*, *Vane*, and *Vane Height*. Sample Number is the subgroup variable and Vane Height is the measurement.
2. Select **Analyze ▶ Quality and Process ▶ Control Chart Builder**. A launch window appears. Drag **Sample Number** from the left-hand window to the **Subgroup** zone (X axis). Similarly, drag **Vane Height** from the left-hand window to the **Y** zone (Y axis).

   The XBar and Range charts appear first in the window. To change it to an XBar and standard deviation chart, select **Standard Deviation** from the drop-down list next to **Sigma** and under **Limits[1]**. Then select **Standard Deviation** from the drop-down list next to **Statistic** and under **Points[2]**. Finally, select **Standard Deviation** from the drop-down list next to **Sigma** and under **Limits[2]**. To turn on the runs tests, right-click in the control chart and select **Warnings ▶ Tests ▶ Test 1**.

Figure 3.26 XBar and Standard Deviation Chart for Vane Height Data



Points[1]
Statistic: Average
Individual Points ☐
Show Connect ☑
Show Points ☑

Limits[1]
Sigma: Standard Devi...
Zones ☐
Show Limits ☑
Show Center Line ☑

Points[2]
Statistic: Standard Devi...
Individual Points ☐
Show Connect ☑
Show Points ☑

Limits[2]
Sigma: Standard Devi...
Show Limits ☑
Show Center Line ☑

Warnings[1]
Warnings[2]

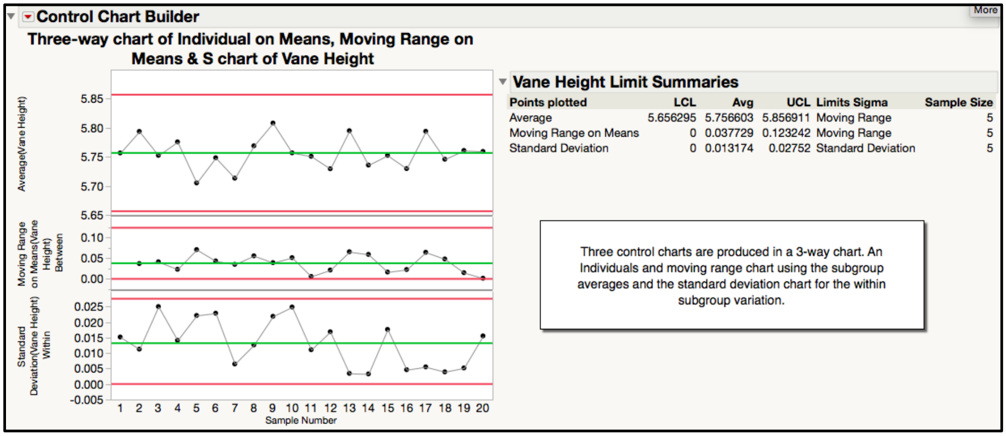
Vane Height Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Average	5.7378	5.756603	5.775406	Standard Deviation	5
Standard Deviation	0	0.013174	0.02752	Standard Deviation	5

In Figure 3.26, the standard deviation chart displays the sample standard deviation for each subgroup and shows that the within-subgroup variation is consistent, with no points outside of the control limits. The XBar chart is plotting the subgroup averages and shows many points outside of the control limits. The control limits for the XBar chart must be adjusted to include the subgroup-to-subgroup variation, using a 3-way control chart.

3. Click **3-Way Chart** at the lower left-hand side of the window. Select **Moving Range on Means** from the drop-down list next to **Statistic** and under **Points[2]**. Then select **Moving Range** from the drop-down list next to **Sigma** and under **Limits[2]**. Finally, select **Standard Deviation** from the drop-down list next to **Statistic** and under **Points[3]** and click **Done** when you are finished.

Figure 3.27 3-Way Control Chart for Vane Height Data



Vane Height Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Average	5.656295	5.756603	5.856911	Moving Range	5
Moving Range on Means	0	0.037729	0.123242	Moving Range	5
Standard Deviation	0	0.013174	0.02752	Standard Deviation	5

Three control charts are produced in a 3-way chart. An Individuals and moving range chart using the subgroup averages and the standard deviation chart for the within subgroup variation.

The 3-way chart in Figure 3.27 (ISQC Figure 6.27) gets its name because three control charts are displayed. The first two charts are Individual Measurement and Moving Range charts for the subgroup averages, which display the short-term Casting-to-Casting variation, and the third chart is the standard deviation chart for the within-casting variation. The control limits for the subgroup averages are much wider than the ones previously calculated, and there are no longer any out-of-control points. The control limits for the standard deviation chart remain unchanged from the ones presented previously.

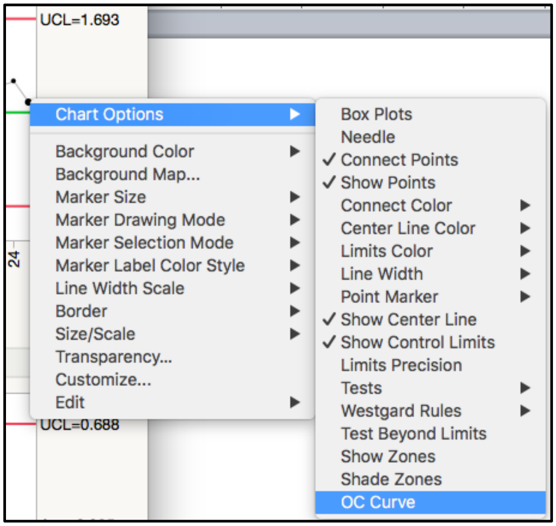
Statistical Insights

In this section, we elaborate on some of the examples provided in ISQC Chapter 6. The examples highlighted in this section include several important concepts we have encountered over our many years of applying SPC successfully to a variety of industries. For most of these examples, additional output not provided in ISQC is included to illustrate JMP functionality or further elaborate on important points.

Operating Characteristic Curve

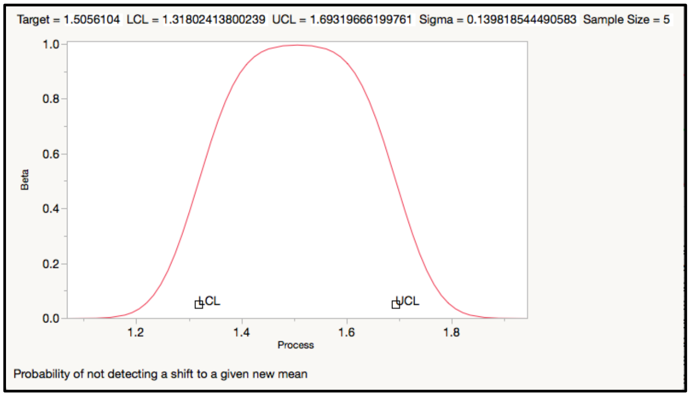
The operating characteristic (OC) curve (see ISQC Section 6.2.6) shows the probability, β, of not detecting a mean shift (ISQC equation 6.19) with the next subgroup when three sigma limits are used. The curve is usually shown with β on the Y axis and the mean shift, k, on the X axis. For the control chart shown in Figure 3.3 (ISQC Figure 6.2), the OC curve is easily obtained by right-clicking on any chart point and selecting **OC Curve** from the resulting menu or by clicking on the red triangle next to **XBar of Flow Width** and choosing **OC Curve** from the menu (Figure 3.28).

Figure 3.28 Control Chart Options for Flow Width



JMP produces a 2-sided OC curve, corresponding to the lower and upper control limits (Figure 3.29). At the top of the OC curve, we see the control chart parameters: target or CL = 1.51, LCL = 1.31, UCL = 1.69, sigma = 0.14, and subgroup size *n* = 5. At the target value of 1.51, the probability of not detecting a shift is 1, but as we move away from the target in either direction, the probability decreases to 0 at around 1.2 for the lower side and 1.8 for the upper side. The value of 1.8 corresponds to a shift of about 0.3 microns, which is equivalent to 2 standard deviations.

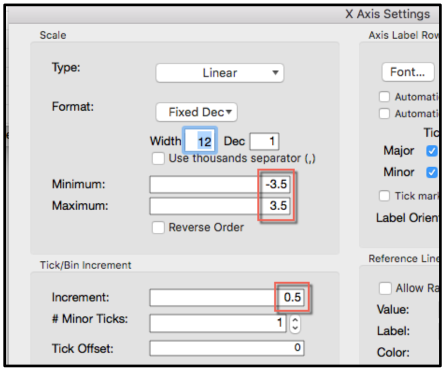
Figure 3.29 OC Curve for the Flow Width XBar Chart.



The OC curve can be presented in a more generic fashion, with a target = 0 and standard deviation = 1, by clicking on the **Target** value and entering 0 and on the **Sigma** value and entering 1. The control limits can be calculated as LCL = 0 –k/√n = 0 –3/√5 = -1.34; UCL = 0 + 3/√5= 1.34. We also need to scale the X axis in units of sigma by double-clicking the X axis and setting the **Minimum** =-3.5, the **Maximum** =3.5, and the **Increment** =0.5 in the **X Axis Settings** window, as shown in Figure 3.30a.

Statistics Note 3.3: So why look at the OC curve at all? The OC curve is used to evaluate the sensitivity of the control chart in the units of the data. For example, shifts of 0.3 microns or more will be detected with a high probability (β < 0.044). However, the probability of not detecting a shift of 0.1 microns is about 93% (β = 0.933) or the probability of detecting the shift is only 7%.

Figure 3.30a X Axis Setting for OC Curve


X Axis Settings

Scale

Type: Linear

Format: Fixed Dec

Width 12 Dec 1

☐ Use thousands separator (,)

Minimum: -3.5

Maximum: 3.5

☐ Reverse Order

Tick/Bin Increment

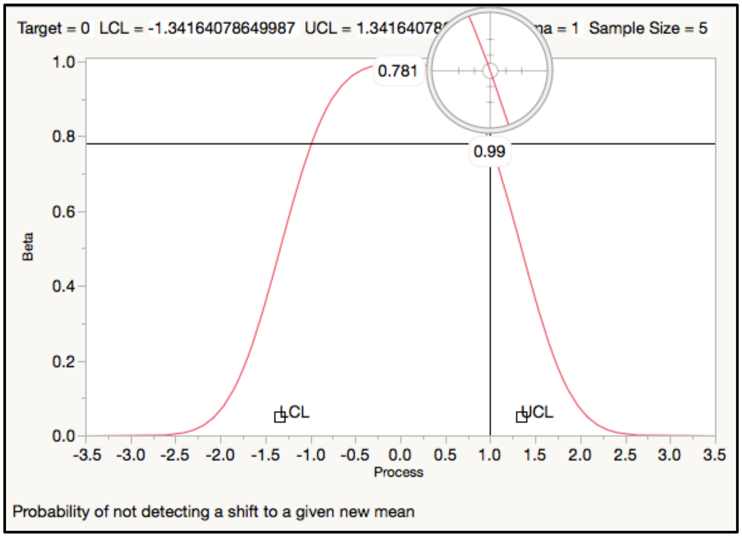
Increment: 0.5

Minor Ticks: 1

Tick Offset: 0

The crosshair tool can be used to read the value of β for a given σ shift. If the shift is 1σ, then for *n* = 5 the probability of not detecting a mean shift is β=0.781 (Figure 3.30b**)** or the probability of detecting a 1σ shift is only 1-β=0.219. The curve to the right of 0 is the same as the *n* = 5 curve of Figure 6.13 in ISQC Section 6.2.6, from which, for a 1σ shift, as Montgomery points out, “we have β=0.75, approximately.”

Figure 3.30b OC Curve for Standardized ±3 Control Limits for *n* = 5

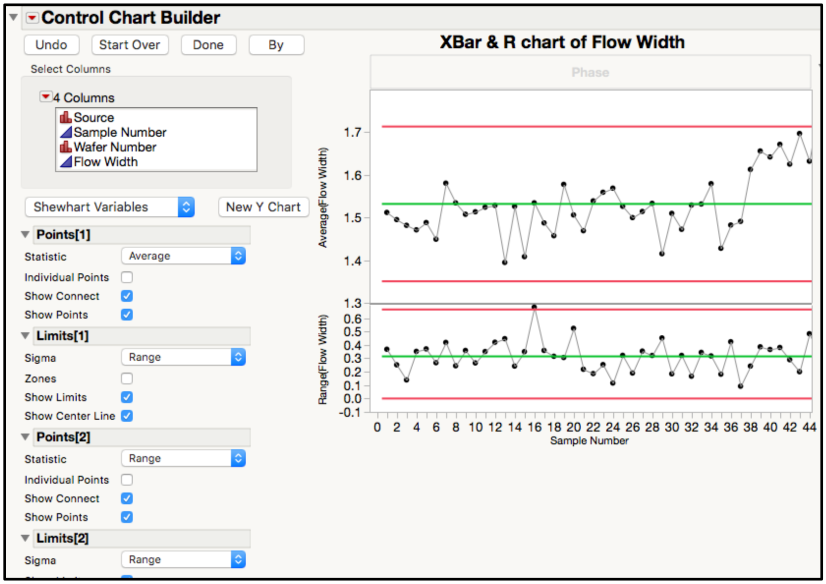


Phase Chart

The additional data in ISQC Example 6.1 showed a shift in the process from an average of 1.506 microns to about 1.56 microns. What if we want to construct a chart that displays two sets of limits, one for the original data and one for the additional data? This can be accomplished using a phase chart, where each phase represents a section of the data. The JMP data set Chapter 3 - ISQC Example 1 Phase Chart.jmp contains the combined data of ISQC Tables 6.1 and 6.2 with an additional column, Source, to denote the source of the data: Original (ISQC Table 6.1) or Additional (ISQC Table 6.2). The following steps illustrate how to create a phase chart using the **Control Chart Builder** platform:

1. Open Chapter 3 - ISQC Example 1 Phase Chart.jmp, which has variables called *Source*, *Sample Number*, *Wafer Number*, and *Flow Width*. Sample Number is the subgroup variable and Flow Width is the measurement.
2. Select **Analyze ► Quality and Process ► Control Chart Builder**. A launch window appears. Drag **Sample Number** from the left-hand window to the **Subgroup** zone (X axis). Similarly, drag **Flow Width** from the left-hand window to the **Y** zone (Y axis). The XBar and Range chart appears first in the window (Figure 3.31).

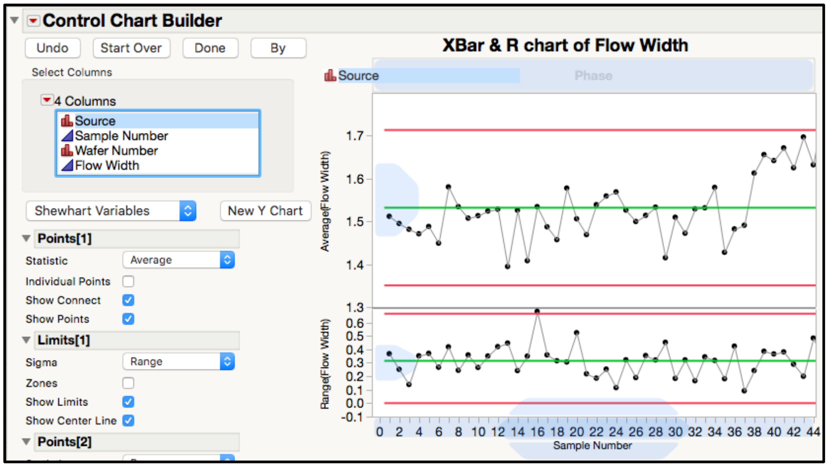
Figure 3.31 XBar and R Chart for Combined Flow Width Data



Points[1]
Statistic: Average
Individual Points ☐
Show Connect ☑
Show Points ☑
Limits[1]
Sigma: Range
Zones ☐
Show Limits ☑
Show Center Line ☑
Points[2]
Statistic: Range
Individual Points ☐
Show Connect ☑
Show Points ☑
Limits[2]
Sigma: Range

3. To change the chart to a XBar and Range Phase chart, drag **Source** from the left-hand window to the **Phase** zone at the top of the XBar chart, as shown in Figure 3.32.

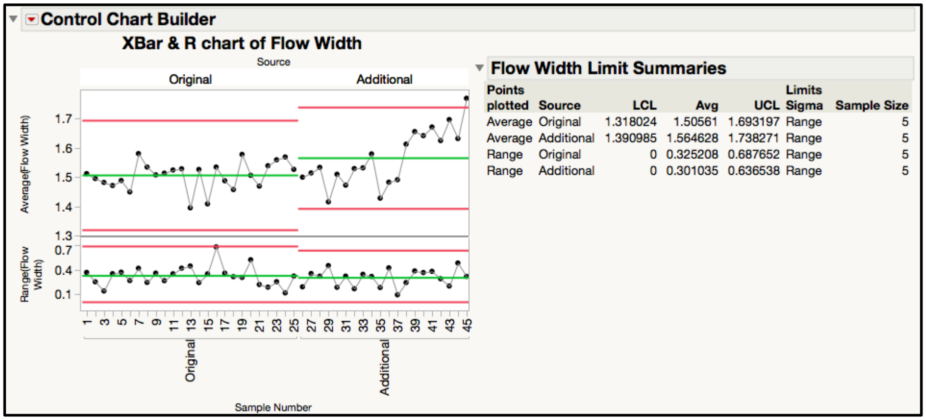
Figure 3.32 Drag Source to the Phase Area



Points[1]
Statistic: Average
Individual Points ☐
Show Connect ☑
Show Points ☑
Limits[1]
Sigma: Range
Zones ☐
Show Limits ☑
Show Center Line ☑
Points[2]

This calculates limits for both the original data and the additional data, as shown in Figure 3.33.

Figure 3.33 Phase Control Chart for Combined Flow Width Data



Flow Width Limit Summaries

Points plotted	Source	LCL	Avg	UCL	Limits Sigma	Sample Size
Average	Original	1.318024	1.50561	1.693197	Range	5
Average	Additional	1.390985	1.564628	1.738271	Range	5
Range	Original	0	0.325208	0.687652	Range	5
Range	Additional	0	0.301035	0.636538	Range	5

The two Range charts show that the two groups of data have similar average ranges, as shown by the green lines. The XBar charts show that the average of the additional data is larger than the average of the original data, and there is a similar spread between the LCL and UCL. From the Limits Summaries table, we can calculate the average difference between the additional and original data as is 1.565- 1.506 = 0.059 microns.

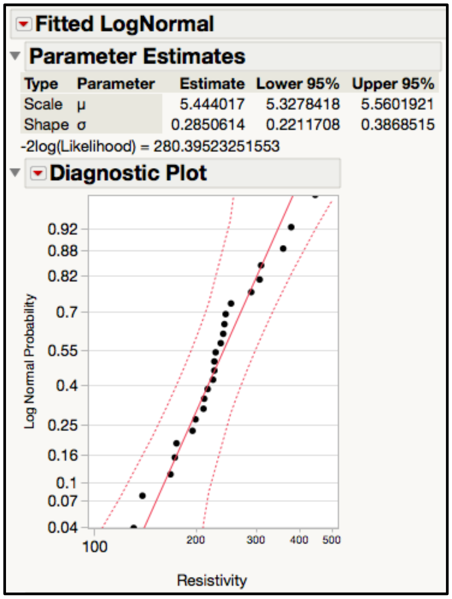
Lognormal Probability Limits

Even though the process behavior chart is robust to departures from normality (see ISQC Section 6.2.5 or Wheeler and Chambers (1992) Section 4.3), there are situations where the normality assumption should be examined more closely. In ISQC Example 6.6, we demonstrated how to create an XmR control chart using the log-transformed wafer resistivity results (see Figure 3.24). Although the limits might be more appropriate to monitor wafer resistivity, it is more difficult to visually interpret the results in the natural log scale. To alleviate this problem, wafer resistivity might also be charted in the original units using the lognormal distribution. It does require several extra steps to set up the control chart, but interpretation of trends and unusual points is easier.

The following steps show how to evaluate the distribution of the data using the lognormal distribution directly and how to generate a limits table using a script for the Individual Measurement and Moving Range control chart. Note that the limits for the Moving Range chart do not need to be altered to accommodate the skew in the data.

1. Open Chapter 3 – ISQC Table 6.8.jmp.
2. Select **Analyze ► Distribution**. A launch window appears. Select **Resistivity** and select **Y, Columns** to add it to the window. Click **OK** when you are done.
3. Click on the red triangle next to **Resistivity** and select **Continuous Fit ► Lognormal** from the drop-down menu. The parameters for the fitted distribution appear in the window, with a drop-down menu labeled **Fitted LogNormal**. To add a lognormal probability plot, select **Diagnostic Plot** from the drop-down menu. The parameter estimates, and diagnostic plot are shown in Figure 3.34.

Figure 3.34 Lognormal Probability Plot for Wafer Resistivity



Fitted LogNormal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Scale	μ	5.444017	5.3278418	5.5601921
Shape	σ	0.2850614	0.2211708	0.3868515

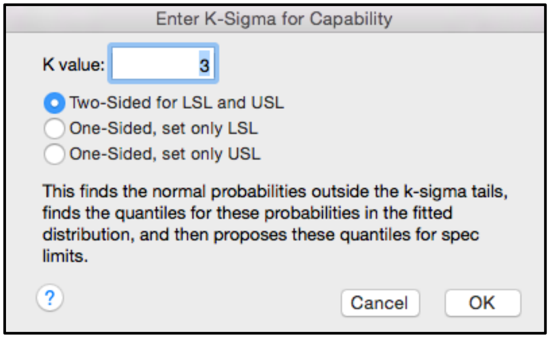
-2log(Likelihood) = 280.39523251553

Diagnostic Plot

The lognormal probability plot is used to evaluate the appropriateness of the distribution for the data in a similar manner as the normal probability plot. The points should fall along the straight line and be mostly contained within the bands. The control limits are obtained using the parameter estimates for the lognormal distribution and the lognormal quantiles associated with "3σ" probabilities for a normal distribution, 0.135% (LCL) and 99.865% (UCL). These quantiles are easily obtained from JMP.

4. Click on the red triangle next to **Fitted LogNormal** and select **Set Spec Limits for K Sigma**. A dialog box appears (Figure 3.35), which prompts you for the **K value** and the desired limits (one- or two-sided). Tail probabilities corresponding to K standard deviations are computed and the probabilities are converted to quantiles from the lognormal distribution. To calculate 3σ control limits, enter 3 in the **K Value** box, select **Two-Sided for LSL and USL**.

Figure 3.35 Dialog Box for Lognormal Probability Limits



Enter K-Sigma for Capability

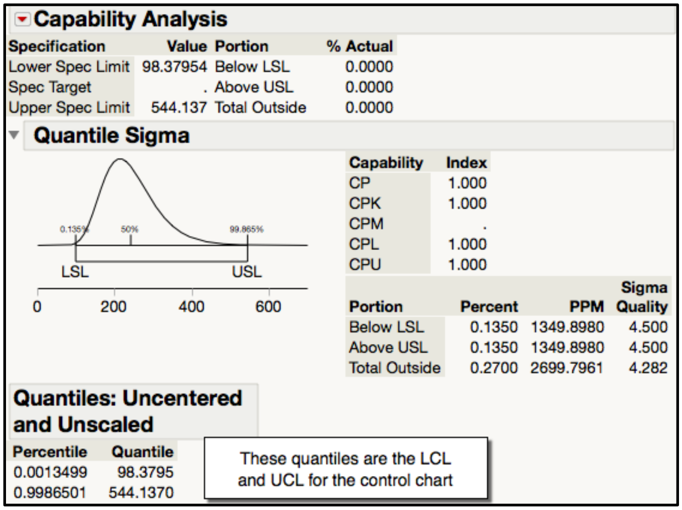
K value: 3

● Two-Sided for LSL and USL
○ One-Sided, set only LSL
○ One-Sided, set only USL

This finds the normal probabilities outside the k-sigma tails, finds the quantiles for these probabilities in the fitted distribution, and then proposes these quantiles for spec limits.

5. Click **OK**. The limits are shown in Figure 3.36.

Figure 3.36 Lognormal Probability Limits for Resistivity Data



Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	98.37954	Below LSL	0.0000
Spec Target	.	Above USL	0.0000
Upper Spec Limit	544.137	Total Outside	0.0000

Quantile Sigma

Capability	Index
CP	1.000
CPK	1.000
CPM	.
CPL	1.000
CPU	1.000

Portion	Percent	PPM	Sigma Quality
Below LSL	0.1350	1349.8980	4.500
Above USL	0.1350	1349.8980	4.500
Total Outside	0.2700	2699.7961	4.282

Quantiles: Uncentered and Unscaled

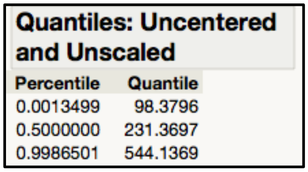
Percentile	Quantile
0.0013499	98.3795
0.9986501	544.1370

These quantiles are the LCL and UCL for the control chart

The requested quantiles are displayed and a capability analysis launches using the calculated limits (Figure 3.36). The lognormal quantiles associated with 3⊚ limits are 98.3795 (LCL) and 543.1370 (UCL). While the K sigma approach for obtaining the limits does not require you to memorize the exact percentiles, it does not automatically produce the centerline (CL) needed for the control chart. To obtain the CL for the control chart, the quantile for the 50% percentile must be calculated from the lognormal distribution.

6. Click on the red triangle next to **Fitted LogNormal** and deselect **Quantiles** and then select **Quantiles**. A dialog box appears allowing up to three probabilities. Enter **0.5** in the first field for the CL and **0.0013499** and **0.9986501** in the other two fields for the LCL and UCL (these two values are the Percentiles in Figure 3.36). Click **OK**.

Figure 3.37 Lognormal Centerline and Limits



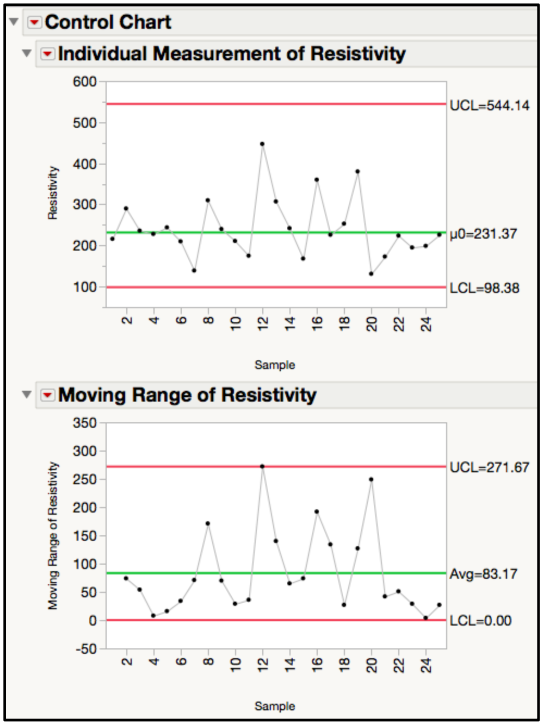
Quantiles: Uncentered and Unscaled

Percentile	Quantile
0.0013499	98.3796
0.5000000	231.3697
0.9986501	544.1369

Now that we have the lognormal limits (Figure 3.37), we must add them as Column Properties for the Resistivity variable in the JMP table and rerun the control chart, as we did in previous examples. Alternatively, we can use a JMP script to automatically calculate the lognormal quantiles and save them to a JMP table, which can be used to create the control chart.

7. Open Lognormal Quantile Limits.jsl and run the script. The limits are automatically calculated and placed in a JMP table. The table name is Chapter 3 – ISQC Table 6.8 Limits.
8. Save the table as Chapter 3 – ISQC Table 6.8 Limits.
9. Select **Analyze** ▶ **Quality and Process** ▶ **Control Chart** ▶**IR**. In the launch window, select **Resistivity** as the **Process variable**. Then select **Sample** and click **Sample Label** to identify the subgroup variable. Click **Get Limits,** select the control limits JMP table that we saved in Step 8, and click **Open**. Click **OK**. The chart is shown in Figure 3.38.

Figure 3.38 XmR Control Chart for Resistivity using Lognormal Limits



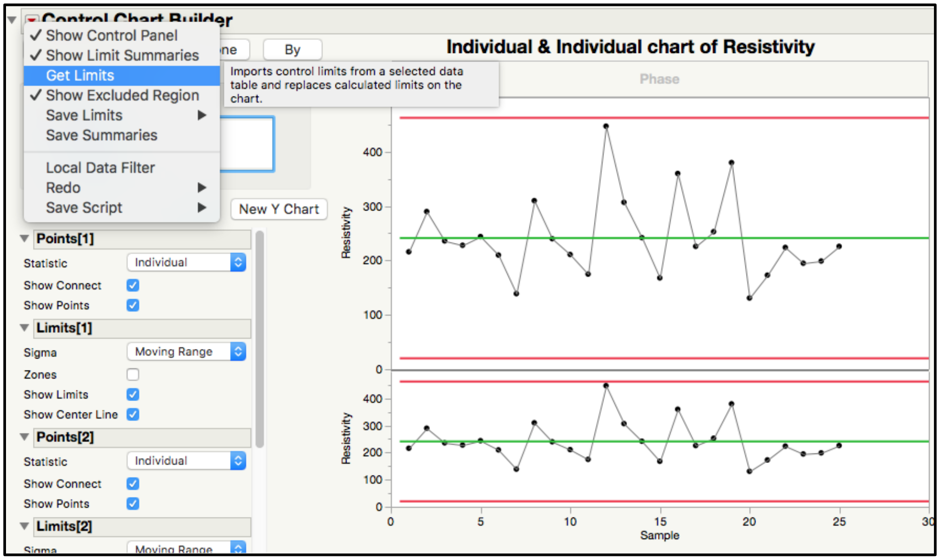
The control limits for the XmR control chart are now adjusted using the lognormal distribution and maintain the original scale of the data. In Figure 3.38, the limits are asymmetric around the centerline, which reflects the skew of the lognormal distribution. Note that only the limits for the Individual Measurement chart have changed. The limits on the Moving Range chart remain the same.

Statistics Note 3.4: There are times when the normality assumption should not be ignored and a more appropriate distribution should be used to calculate control limits. Some things to consider include excessive skew in the data, data that is close to a natural boundary condition (for example, 0 or 100), and normal-based limits that are non-sensible, such as negative values for a positive quantity. Appropriate distributions are well-documented for many physical and scientific phenomena.

The chart in Figure 3.38 can also be generated using the **Control Chart Builder** platform.

1. Select **Analyze** ► **Quality and Process** ► **Control Chart Builder**.
2. Drag **Resistivity** from the left-hand window to the **Y** zone (Y axis). Similarly, drag **Sample** from the left-hand window to the **Subgroup** zone (X axis).
3. Once the chart appears, click on the red triangle next to the **Control Chart Builder** title, and select **Get Limits** as shown in Figure 3.39.

Figure 3.39 XmR Control Chart for Resistivity using Lognormal Limits

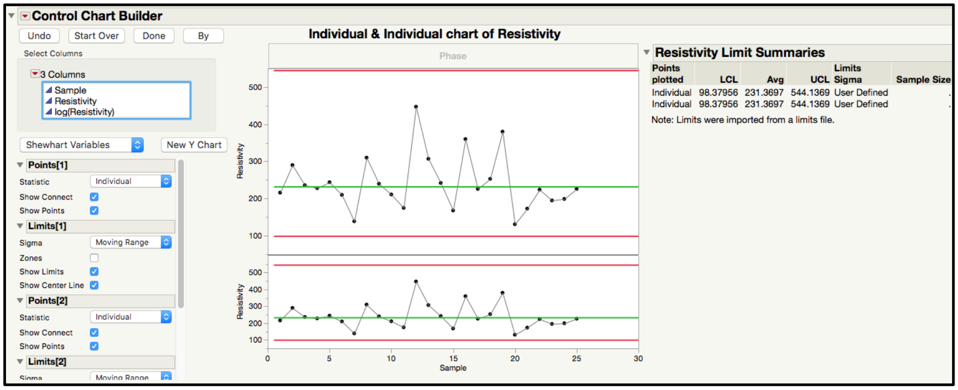


Imports control limits from a selected data table and replaces calculated limits on the chart.

Points[1]
Statistic: Individual
Show Connect ☑
Show Points ☑
Limits[1]
Sigma: Moving Range
Zones ☐
Show Limits ☑
Show Center Line ☑
Points[2]
Statistic: Individual
Show Connect ☑
Show Points ☑
Limits[2]
Sigma: Moving Range

4. Then select the control limits JMP table that we saved in Step 8 in the previous example and click **Open**. Click **OK**. The chart with lognormal limits is shown in Figure 3.40. The Resistivity Limits Summaries report shows a note indicating that limits were imported from a limits file.

Figure 3.40 XmR Control Chart for Resistivity using Lognormal Limits



Points[1]

Statistic: Individual

Show Connect ☑

Show Points ☑

Limits[1]

Sigma: Moving Range

Zones ☐

Show Limits ☑

Show Center Line ☑

Points[2]

Statistic: Individual

Show Connect ☑

Show Points ☑

Limits[2]

Sigma: Moving Range

Resistivity Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Individual	98.37956	231.3697	544.1369	User Defined	.
Individual	98.37956	231.3697	544.1369	User Defined	.

Note: Limits were imported from a limits file.

3-Way Control Chart and Variance Components

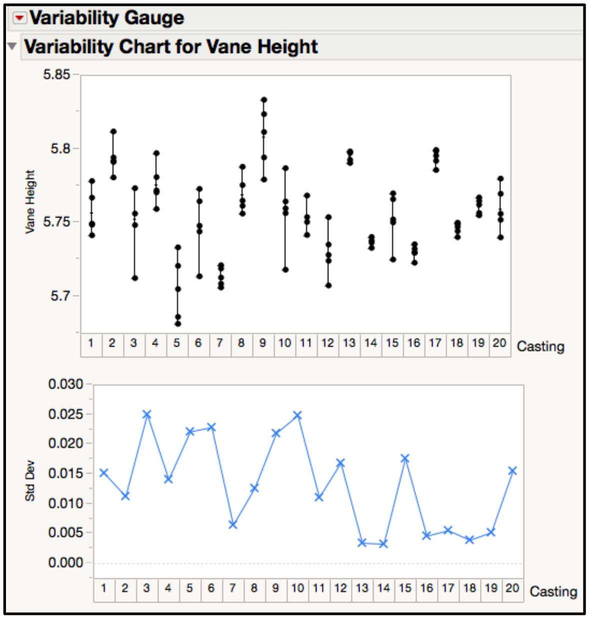
In ISQC Example 6.11, we observed many subgroup means that were outside of the control limits on the original XBar chart. For this data set, the violations are not due to assignable cause variation but to using the wrong source of within subgroup variation in the calculation of the control limits for the means. For each subgroup, because all five measurements are taken on the same casting, the assumption of independent samples might not hold. A violation of independent samples might deflate the within-subgroup variation and result in limits that are too narrow on the XBar chart.

There are many processes that require the use of 3-way charts to accommodate this issue, and they are usually easy to spot. As is the case with this example, almost all of the subgroup means will be outside of the control limits. However, there might be cases where it isn't as obvious. A variance components analysis (VCA) of the data can add insight into the between- and within-subgroup variation. A VCA can be done in JMP using the **Fit Model** platform within the **Analyze** menu, or the **Variability / Attribute Gauge Chart** platform in the **Quality and Process** menu.

The following steps illustrate how to perform a variance components analysis using the **Variability / Attribute Gauge Chart** platform:

1. Open Chapter 3 – ISQC Table 6.11.jmp, which has variables called *Sample Number*, *Vane*, and *Vane Height*. Sample Number is the subgroup variable and Vane Height is the measurement.
2. Select **Analyze** ► **Quality and Process** ► **Variability / Attribute Gauge Chart**. A launch window appears.
3. Highlight **Sample Number** in the left-hand window and click **Y, Response**. Similarly, highlight **Vane Height** and click **X, Grouping**. Click **OK**. The default variability chart appears (Figure 3.41).

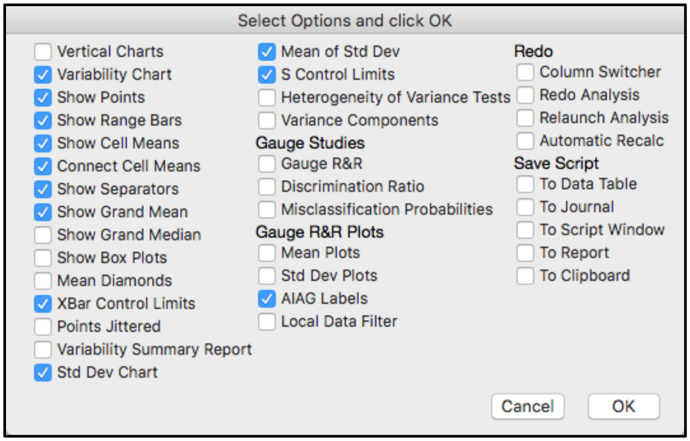
Figure 3.41 Default Variability Chart for Vane Height



The top graph shows the raw data, organized by subgroup, while the bottom graph shows the standard deviation estimates for each subgroup. There are many options that can be adjusted on the default output.

4. Hold down Alt and click on the red triangle at the top of the window. A menu for all of the available options is displayed (Figure 3.42a). For example, to re-create the XBar and Standard Deviation charts in the Options window, click **Connect Cell Means**, **XBar Control Limits,** and **S Control Limits**. Then click **OK**. The output is shown in Figure 3.42b.

Figure 3.42a Re-creation of the XBar and Standard Deviation Chart



Select Options and click OK

☐ Vertical Charts
☑ Variability Chart
☑ Show Points
☑ Show Range Bars
☑ Show Cell Means
☑ Connect Cell Means
☑ Show Separators
☑ Show Grand Mean
☐ Show Grand Median
☐ Show Box Plots
☐ Mean Diamonds
☑ XBar Control Limits
☐ Points Jittered
☐ Variability Summary Report
☑ Std Dev Chart

☑ Mean of Std Dev
☑ S Control Limits
☐ Heterogeneity of Variance Tests
☐ Variance Components

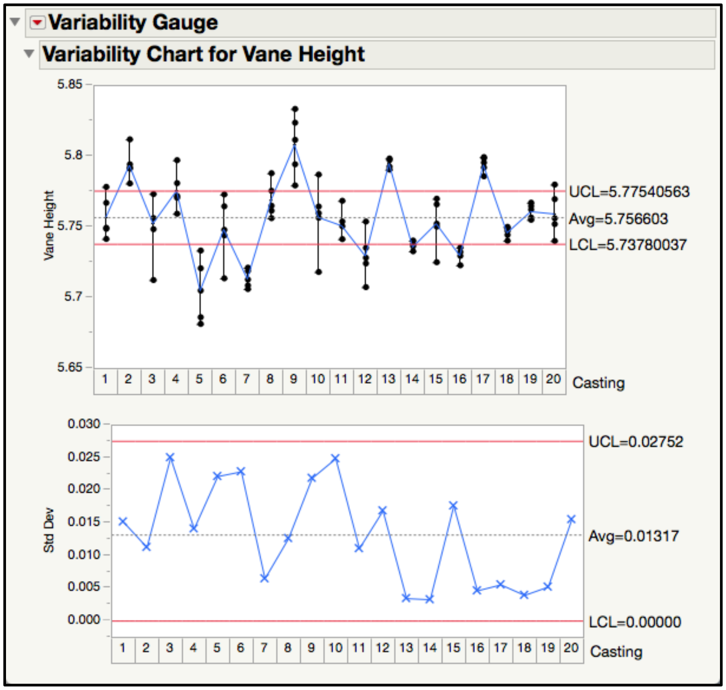
Gauge Studies
☐ Gauge R&R
☐ Discrimination Ratio
☐ Misclassification Probabilities

Gauge R&R Plots
☐ Mean Plots
☐ Std Dev Plots
☑ AIAG Labels
☐ Local Data Filter

Redo
☐ Column Switcher
☐ Redo Analysis
☐ Relaunch Analysis
☐ Automatic Recalc

Save Script
☐ To Data Table
☐ To Journal
☐ To Script Window
☐ To Report
☐ To Clipboard

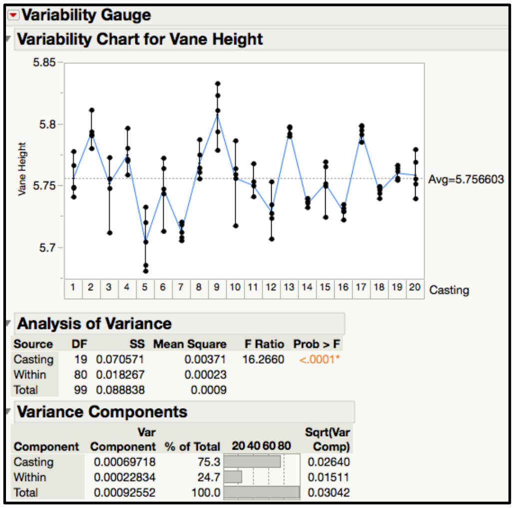
Figure 3.42b Re-creation of the XBar and Standard Deviation Chart



This is a similar chart to the one shown in Figure 3.26. However, because this is a variance components analysis, let's remove the bottom chart and the control limits for the top chart.

5. Hold down Alt and click on the red triangle to launch the Options window. Deselect **XBar Control Limits**, **S Control Limits**, and **Std Dev Chart**. Select **Variance Components** and click **OK**. The results are shown in Figure 3.43.

Figure 3.43 Variance Components Analysis of Vane Heights



Analysis of Variance

Source	DF	SS	Mean Square	F Ratio	Prob > F
Casting	19	0.070571	0.00371	16.2660	<.0001*
Within	80	0.018267	0.00023		
Total	99	0.088838	0.0009		

Variance Components

Component	Var Component	% of Total	20 40 60 80	Sqrt(Var Comp)
Casting	0.00069718	75.3		0.02640
Within	0.00022834	24.7		0.01511
Total	0.00092552	100.0		0.03042

The variance components output includes an Analysis of Variance (ANOVA) table, where subgroups are treated as a fixed effect, and a Variance Components Estimates table, where the subgroups are treated as random effects. The F Ratio in the ANOVA is large and indicates that at least one of the subgroup averages is different from the overall mean, based on the within-subgroup variation. This result supports the many out-of-control points in the XBar chart.

The variance component analysis of this data reveals that the subgroup-to-subgroup (casting-to-casting) variation accounts for 75% of the total variation, while the within-subgroup (vane-to-vane) variation accounts for 25% of the total variation. It is difficult to provide an exact cutoff for what percent of the subgroup-to-subgroup variation will result in the need for a 3-way chart. However, in the authors' experience, when a process is in control and the samples are independent, a VCA will result in a subgroup-to-subgroup variance component that contributes 1% or less to the total variation. If there is assignable cause variation with some out-of-control points, the subgroup variation might account for 25% of the total. Any subgroup contribution of 50% or more to the total variation is highly suspect, and the reader should consider the use of a 3-way control chart.

Statistics Note 3.5: Whenever the subgroup size is > 1, the data hierarchy structure should be investigated to set meaningful control limits for the XBar chart. When the subgroup-to-subgroup variation is substantially larger than the within-subgroup variation, the XBar limits will be too tight and there will be many points outside of the control limits. This occurs in many batch processes, where multiple measurements are taken per each run of a batch (for example, rolled goods, semiconductor wafers, and vats of chemicals).

Rational Subgrouping

Rational subgrouping is a key concept when designing efficient process behavior charts because, depending on how the subgroups are organized, different signals might appear or not appear in the charts. ISQC Section 6.2.2 discusses the important rational subgroups play "in the use of XBar and R charts", and Section 5.6 of Wheeler and Chambers (1992) provides a good description of the issues you might face if the subgroups are not matched to the structure present in the data.

In their article *Designing Insightful Process Behavior Charts*, Ramírez and Zangi (2014) define rational subgrouping as "the process of organizing the data into groups of like things that reflect the context and sources of variation present in the data." They use the injection molding example of Section 5.6 of Wheeler and Chambers to demonstrate how easy it is to use the **Control Chart Builder** to investigate different organizations of the data and how "the careful design of the process behavior chart can reveal patterns that a "default" software chart might mask." They also point out that "even when the charts are designed carefully, it is important to rationally think about the allocation of the different sources of variation to subgroups."