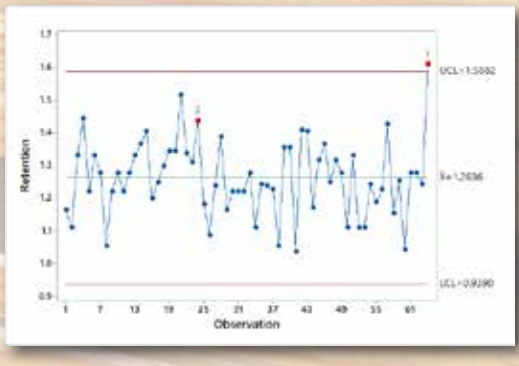
SPC Handbook for the Treated Wood Industries



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Description

This Statistical Process Control (SPC) Handbook introduces wood preservation industry personnel to the terminology and statistical process control (SPC) tools available for understanding and monitoring industrial processes. For those who want further information, references are provided at the end of each section. The content is for educational purposes only. The use of trade or firm names in this publication is for reader information and does not imply endorsement by the United States Department of Agriculture (USDA) or The University of Tennessee of any product or service.

This Handbook is organized as follows:

- Understanding variability and why we want to reduce it;
- Introducing important statistics;
- Tools for visualizing data;
- Understanding your process variability using control charts;
- Capability analyses;
- Root-cause analyses for reducing variation;
- Pareto principle;
- Appendices on statistical methods.

Know Your Enemy: Production Variability

"Funny how we don't have time to improve, but we have plenty of time to perform work inefficiently and to resolve the same problems over and over."

W. Edwards Deming

Monitoring and Reducing Variation

Reducing variation is the foundation for all Statistical Process Control (SPC) and continuous improvement philosophies, *e.g., Total Quality Management, Six-Sigma Quality, Toyota Production System, Lean Six-Six Sigma, etc.* Reducing variation in wood treatment is fundamental to long-term business profitability and meeting necessary treating targets. Less variation in the wood treatment process results in lower treating targets and reduced costs.

Variation in manufacturing is cost

There are many possible sources of variability in production of pressure-treated wood. Understanding and reducing this variability requires a systematic approach. This handbook outlines a strategy for wood treating companies to apply SPC and other continuous improvement techniques to understand and reduce variation in the process of treating wood.

Conformance to preservative penetration and retention standards is necessary for ensuring the long-term performance of pressure-treated wood. Accordingly, inspections of treatment quality by both the wood

treater and third-part inspectors are a critical component in the production process. Pressure-treaters currently produce material that passes these inspections for most charges. However, there is variability in both the treatment and inspection processes, and some charges fail inspections. Treatment companies can benefit by tracking variability, understanding the sources of treatment variability and, ultimately, minimizing the number of failing charges by reducing variability.

Causes of Variability

Wood Variability

Perhaps the greatest source of treatment variability is the wood itself. Some of this variability is inherent to differences in a species' microscopic anatomy and is difficult to predict or control. However, some of the other aspects of wood variability can be monitored and controlled by the treater:

> *Moisture Content and Drying: Wood that has not been adequately dried (moisture content above 26 - 30%) does not treat as well or as uniformly as drier wood. Although wood is usually kiln or Boulton dried before treatment there may be substantial differences in moisture content between kiln charges and between pieces in a charge. There have also been reports that drying conditions (for example kiln temperature) can affect treatability, but other studies have not found a strong relationship.*
>
> *See AWPA T1-17, FPL GTR-190 or Maclean 1952 for additional information.*
>
> *Geographic source: In some cases, the geographic of a wood species has been found to be influenced by the area where it was grown. The age and growth rate of trees can also vary substantially between*

locations. If treaters are aware of the regions from where the wood products are sourced then there is potential for reducing variability by grouping commodities of similar treatability into the same charge.

Treatment Process Variability

Wood Dimensions: Within charge treatment variability may be increased if pieces of substantially differing dimensions, sawing patterns, or log dimensions are treated in the same charge. The thickness and width of lumber and timbers affects where they are cut from a log, grain orientation, and heartwood content.

**Refer to Maclean 1952*

Charge Conditions: The intensity and duration of preservative treatment of the initial vacuum and subsequent pressure periods affect both penetration and retention, and these parameters are set by the treating plant operator. However, other aspects of the treatment process such as time to fill the cylinder, time to reach maximum pressure, and time to release pressure may not be directly controlled and can also affect treatment quality, especially with short treatment cycles.

**Refer to Maclean 1952, FPL GTR-190 for more info.*

Treating Solution: The concentration of actives in the treating solution directly affects retention and is measured and controlled by plant personnel. However, errors in the measurement of solution concentration or inadequate mixing has potential to affect charge retention. Other characteristics of the solution such as temperature, cleanliness of solution, and stability can also affect quality of treatment.

**See AWPA A standards for appropriate analytical method for a given preservative system and refer to AWPA P standards for standardized methods of application and approved retentions for a given preservative system.*

Equipment Reliability: Equipment malfunction or error can cause dramatic obvious impacts on a charge or more subtle affects that might be more difficult to detect.

**In general, refer to AWPA M*- standards as a reference for proper maintenance and required instrumentation for pressure treating equipment.

Inspection Process: The inspection process has variability, the greatest of which is a result of wood variability. Because of this wood variability, the retention of preservative within a charge varies between and even within each product. As an example, 20 increment cores removed from a charge may only represent a tiny fraction in some cases (e.g., with exception of small batches of poles) of the wood volume in that charge, and thus may provide only an estimate of charge retention. An additional set of 20 cores if/when available may provide a somewhat different estimate of retention. Much of this variability is inherent to wood properties and difficult to control, but some geographic factors such as uniform drying, grouping of material from a single source, and grouping of pieces of similar dimensions, can help to lessen within charge variability. There is also variability associated with the instrumental analysis of the wood sample. Even a well-calibrated instrument has some variability associated with measuring preservative concentration, but this variability can be greater if the instrument is not working properly.

**See AWPA M25-17 for additional information on Standards for Quality Control of treated products for residential and commercial use.*

Suggested References for Causes of Variability

AWPA. 2018. M25-18. Standard for Quality Control and Inspection of Preservative Treated Products for Residential and Commercial Use. Book of Standards, American Wood Protection Association, Birmingham, AL. 638p.

Conklin, S.W. 2011. Third party-style sampling versus plant sampling: impact on variability. In: Proceedings, Annual Meeting of the American Wood Protection Association, Fort Lauderdale, FL. May 15-17: American Wood Protection Association, Birmingham, AL. 107: 196-200.

Jewell, R.A., Mitchell, P.H. and N.P. Kutscha. Species effects on the penetration of CCA in southern pine lumber. In: Proceedings, American Wood Preservers' Association Annual Meeting, Nashville, TN. April 30-May 2. American Wood Preservers' Association, Woodstock, MD. 86:22-30.

Kleinknecht, D. 1999. The influence of variability In treated wood samples on "accept/reject" decisions. In: Proceedings, American Wood Preservers' Association Annual Meeting. May 16-19, Fort Lauderdale, FL. American Wood Preservers' Association, Granbury, TX. 95:105-115.

Lebow, S.T., Hatfield, C.A., and Halverson, S. 2007. Effect of source, drying method, and treatment schedule on treatability of Red Pine. Proceedings, 2006 American Wood-Preservers Association Annual Meeting, April 9 – 12, Austin TX. 102:39-43.

Lebow, P.K., Taylor, A.M. and T.M. Young. 2010. A tool for estimating variability in wood preservative treatment retention. Forest Prod. J. 60(5):447–452.

MacLean, J.D. 1952. Preservative treatment of wood by pressure methods. Agricultural Handbook No. 40. U.S. Department of Agriculture. Forest Service. US. Government Printing Office, Washington D.C. 158p.

Schultz, T.P. and D.D. Nicholas. 2011. Effect of sapwood/Heartwood, grain orientation, juvenile wood, and moisture content on the treatability of southern pine dimension lumber with two commercial copper preservatives. In: Proceedings, 107th Annual Meeting of the American Wood Protection Association, Fort Lauderdale, FL., May 15-17: 103:52-65.

Zahora, A.W. 2015. Within charge variability and its potential impact on charge retention analyses. In: Proceedings, Annual Meeting of the American Wood Protection Association, Asheville, NC., April12-14. 111:255-263.

Turning Data into Knowledge with Statistics

"The goal is to turn data into information, and information into insight"
Carly Fiorina

Statistics that Measure the Central Tendency of Data

Statistics helps us transform data into knowledge. For example, the '*average*' is a statistic that everyone sees almost daily in weather reports, economic reports, sports news, and other common information. The average is a '*location*' statistic and is the '*center of gravity*' of the data set. Even though the average helps us gain some knowledge, it is subject to influence from extreme values in the data. For example, economists report the '*median*' household income because if a billionaire's income was included in the average income statistic, it could greatly skew the average and be a false indicator of the wealth depending on the size of the population.

The average is typically called the "*Arithmetic Average*," "*Sample Mean*," *"X-bar,"* or $(\overline{X})$ and is calculated by summing the data and dividing by the number of data points in the data set. For manufacturing processes, it is sometimes referred to as the "*Process Center line (PCL)*." It is calculated for the example below for *n* = 5 samples, as the sum of the samples divided by *n*.

$$\overline{\mathcal{X}} = \frac{9.2 + 6.4 + 10.5 + 8.1 + 7.8}{5} = \frac{42.0}{5} = 8.4$$

The *"Median (M)"* of a set of *n* measurements is the middle value (*or "midpoint," "50th percentile"*) where the data are ordered from smallest to

largest. If *n* is an odd number, there is a unique middle value and it is the median. If *n* is an even number, there are two middle values and the median is typically defined as their average. M = 8.1 for the sample of *n* = 5 ordered example data below.

Example:	6.4	7.8	8.1	9.2	10.5

What is the average and median of: 1, 2, 3, 4, 5? $\bar{X} = 3$; M = 3

What is the average and median of: 1, 2, 3, 4, 100? $\bar{X} = 22$; M = 3

Retention data is typically plotted as a time series and the average and median can be of help in assessing trends and stability over time. Here we've plotted a hypothetical example of the retention of charges over time with the average and median (Figure 1).

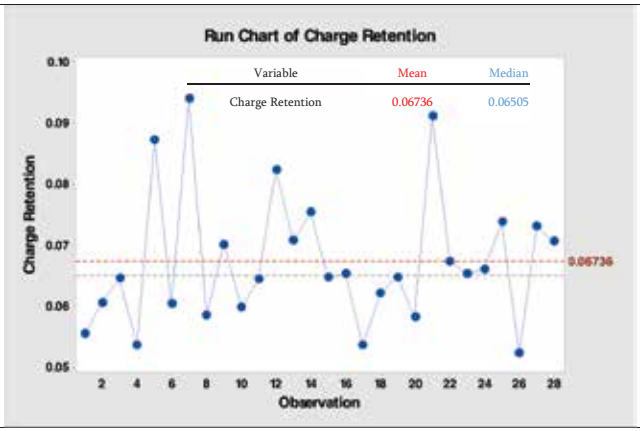


Figure 1. Trend chart of retention of charge over time with an average and median.

Statistics that Measure the Variability of Data

Statistics are helpful in helping us understand the variability in a set of data. For example, the figure above shows how individual charge retentions may vary around the average over time, assuming consistent inputs and processing parameters. Common measures of variability in statistical process control include the range, variance, and standard deviation. The Range (or R) is useful for estimating dispersion in small data sets, it is the largest value minus the smallest value.

Example: 6.3, 2.4, 3.1, 3.1, 5.8, 2.7, 8.1; R = 8.1 – 2.4 = 5.7

The sample variance (s^2) also measures dispersion and is calculated as:

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \approx \sigma^2 \ (population\ variance)$$

The sample standard deviation (s) is:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \approx \sigma \ (population\ standard\ deviation)$$

's' estimates variability in same unit of measure as the sample mean

The aforementioned statistics help describe the data and are called 'descriptive statistics' (more detail is given in Appendix A-Descriptive Statistics). In Statistical Process Control (SPC), we use these statistics to help us quantify the natural variation (or '*common-cause*' variation) of a process. The control chart is a key tool in SPC and distinguishes two types of variation '*natural variation*' from '*special-cause variation*.' Special-cause variation are '*events*' that occur in the process, *e.g., sensor failure, flow meter failure, plugging, leakage, etc*.

Visualizing Data

"Without data you're just another person with an opinion"
W. Edwards Deming

Histograms

The histogram is a frequency distribution (or specialized bar chart) that shows how often each different value occurs. Sometimes the frequency bins in histograms will be divided by a total to give percentage or fractional representations. A histogram is a tool to see the general shape of the data. The following is an example of constructing a *"Stem-and-Leaf"* histogram. The following data (n = 24 observations) was observed:

87.7 88.3 89.4 90.2 95.0 95.0 95.0 91.9 92.1 92.1 92.5 92.0 90.8 90.8
90.3 90.8 90.2 90.9 90.9 90.1 89.5 93.2 94.9 93.0

Create a scale from the smallest to the largest number by integers (whole numbers) and place the decimal associated with the integer next to each integer:

87	*7*
88	*3*
89	*4 5*
90	*2 8 8 3 8 2 9 9 1*
91	*9*
92	*0 1 1 5*
93	*2 0*
94	*9*
95	*0 0 0*

The '*Stem-and-Leaf*' plot is a simple form of a histogram. Histograms can also be easily generated in Excel® and most statistical software.

Figure 2 is another example of a histogram from the wood industry but not retention, where only sample measurements of conforming data were recorded (truncated data). In the histogram below, the statistical software that developed the histogram tries to fit a normal or bell-shaped curve to the data. As shown, there should be data below the lower specification. The histogram is a simple but highly effective tool for visualizing data and identifying issues related to the quality of the data.

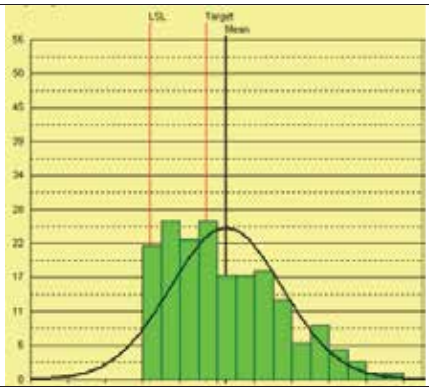


Figure 2. Histogram with truncated data ending at the lower specification limit (LSL).

There can be multiple reasons for the truncation, including re-treatment of charges that are initially below the lower specification limit (LSL) or discarding of charges that fall below the LSL. It may be an indicator that further data quality should be explored, including maintaining below specification limit values to better characterize the actual process. The curve overlay is a normal distribution assuming the same mean and variance as the observed data. The normal distribution curve is symmetric about the mean, while the observed data are asymmetric.

Scatter Plots

XY scatter plots graphically relate two sets of data. Such plots can be used to assess if one measurement variable is 'correlated' to another measurement variable made on the same sample. Each data point in the plot has an X value and a Y value. For example, suppose we're interested in whether mens' height and weight are related. If there is a sample of 50 observations of mens' weight and height, each observation can be plotted in the XY scatter plot to visualize the relationship.

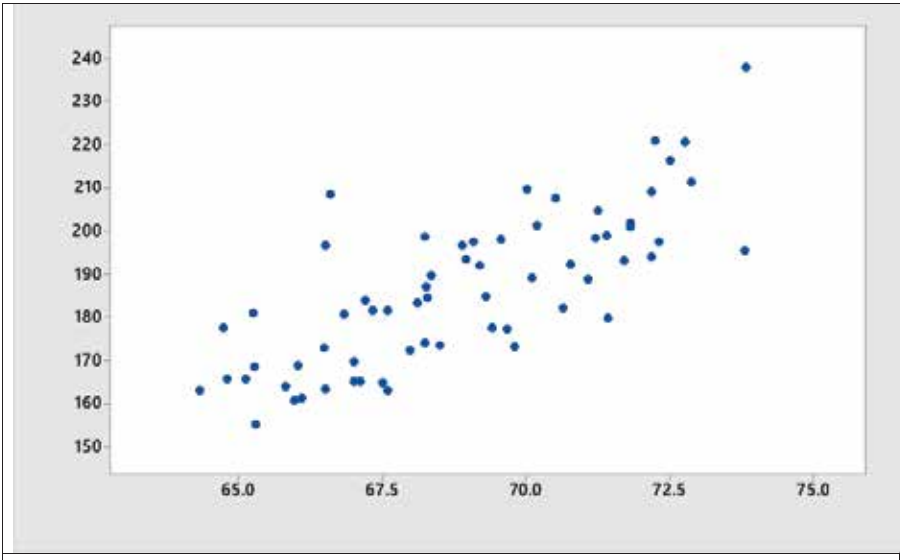


Figure 3. XY scatter plot of males' height and weight (*n* = 50).

Figure 3 shows us that there is a positive, linear relationship between these men's height and weight in this population: As men get taller, they generally weigh more. XY scatter plots are often used to assess the calibration curve for measurement equipment or on-line sensors.

For example, treated wood standards with known preservative concentrations can be analyzed in an XRF spectrometer (*e.g., ASOMA, Oxford, Rigaku units*) to help to make sure they are working correctly. In the figure 4 below, the XY scatter plot shows a consistent, positive and linear relationship between the copper in a series of treated wood standards and the output from the XRF spectrometer.

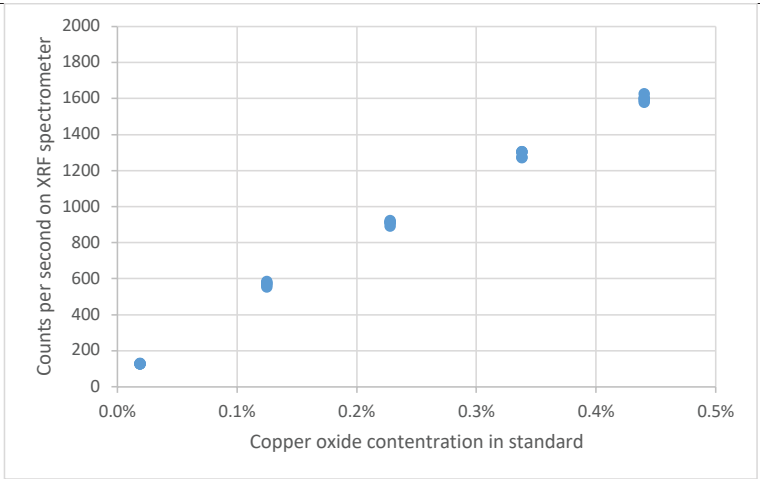


Figure 4. XY scatter plot for calibration data for an XRF analyzer.

Not all relationships shown in XY scatterplots will be so clear, and may be either negative and/or non-linear. The relationship may be strong, weak or non-existent. All of these trends can be seen in an XY scatterplot, which is a powerful tool. XY scatter plots can be easily created in Excel® and other software packages.

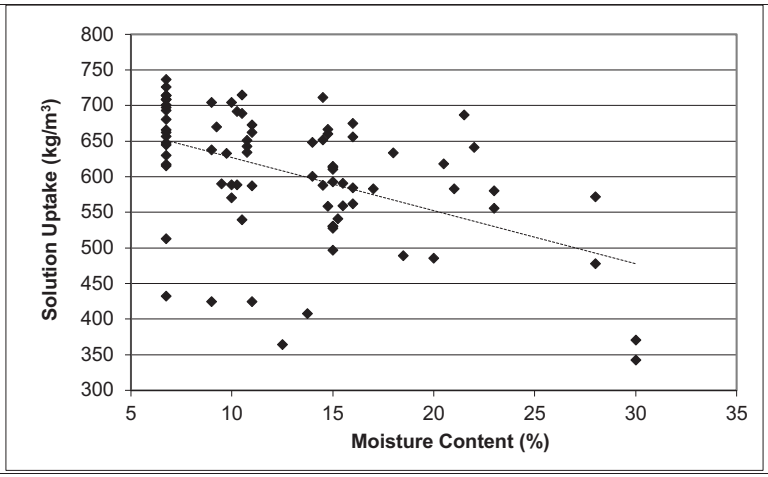


Figure 5. XY scatter plot of wood moisture content versus solution uptake illustrating a weak, negative correlation.

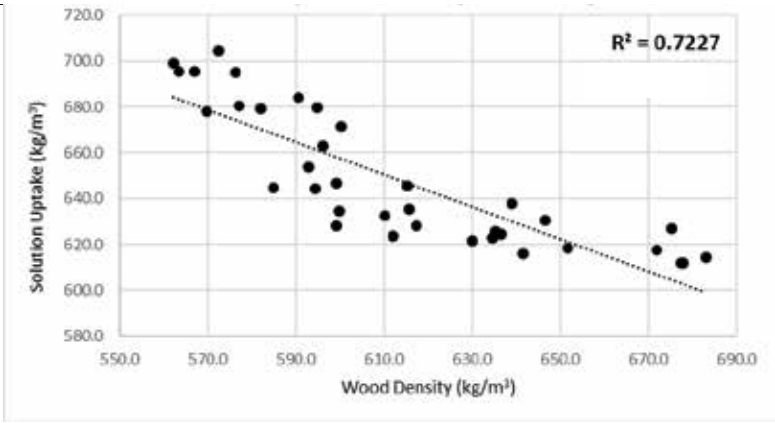


Figure 6. XY scatter plot of wood density versus solution uptake illustrating a strong negative correlation.

For a more detailed review of histograms and XY scatter plots, see the helpful links,

https://www.moresteam.com/toolbox/histogram.cfm , https://www.khanacademy.org/math/ap-statistics/quantitative-data-ap/histograms-stem-leaf/v/histograms-intro , https://www.mathsisfun.com/data/scatter-xy-plots.html .

Control Charts - Understanding Natural Variation

"You cannot manage or improve what you cannot measure"
Armand V. Feigenbaum

The control char t is the core tool of SPC and is the first step in quantifying the normal variation that is part of your operation. The control chart is a vital tool for ensuring that operational treatment targets can be maintained and determines where continuous improvement efforts have reduced variation.

There is variation in any wood treating operation. The first step in any quality improvement effort is to measure and monitor this variation. A main concept in SPC is that, for any measurable process characteristic, causes of variation can be separated into two classes:

1. Natural (*common, or chance*) causes of variation, *e.g.,*
    - *lumber,*
    - *chemical,*
    - *pressure,*
    - *new product setup, etc.*

2. Special (*assignable or 'events'*) causes of variation, *e.g.,*
    - *part failure,*
    - *machine stop,*
    - *shift change,*
    - *float valve stuck,*
    - *over-adjustment of set-point,*
    - *Monday-morning, etc.*

The 'Shewhart' Control Chart is used to distinguish between special-cause and natural variation. It is used to assess sources of variation in the process (see Figure 7).

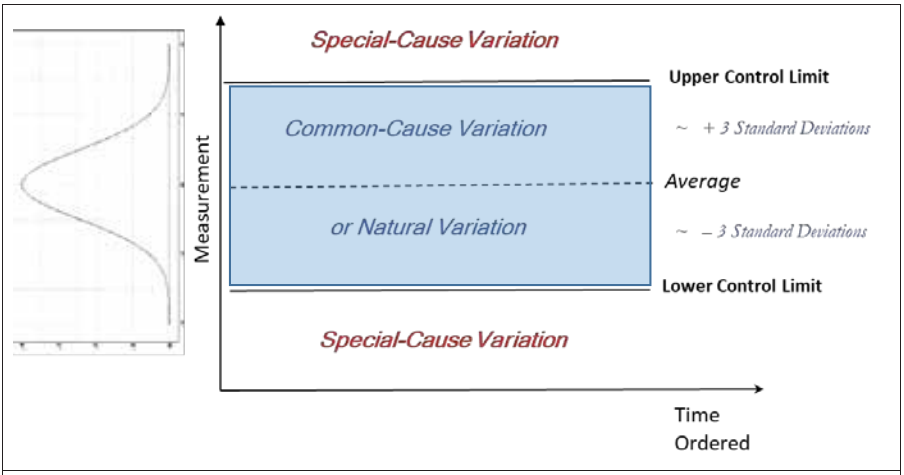


Figure 7. Illustration of Shewhart control chart and statistical foundations.

Controls charts are developed by recording the values of a production parameter over time. In a wood treatment operation, this could be charge retention values. Upper and lower control limits of approximately ± *3 standard deviations* on each side of the *average* are calculated from the data. The control limits contain 99.7% of the data from the system and cover the range of expected values for the process during the result of normal operations. The control chart assumes that the data come from a normal (bell-shaped or Gaussian) distribution. An example of a control chart for retention values that are almost in control is illustrated in Figure 8. The minimum retention of the preservative is 1.00, and the average retention of the charge is 1.26. The upper and lower control limits are 1.59 and 0.94, respectively. The differences in charge retentions between those values are

caused by natural variation in the process. The retention of one charge exceeds the upper control limit (red box #1) and is assumed to be a result a special cause variation, where something special happened to cause this to go over the limit value. This requires investigation! You might discover that a metering valve on the concentrate tank was broken, resulting in an overly-concentrated treating solution.

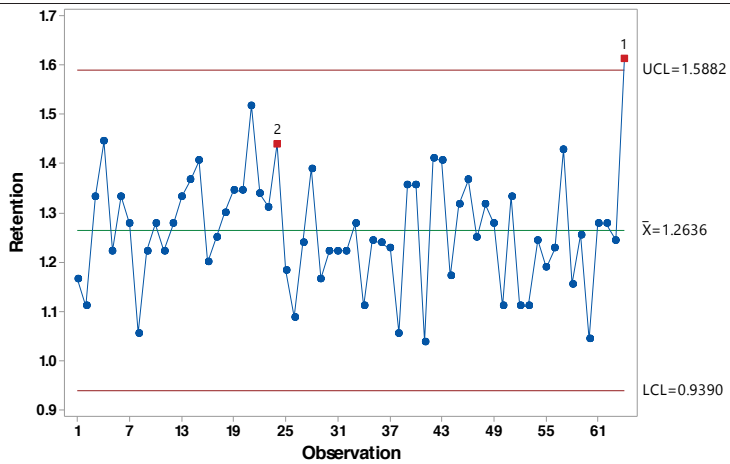


Figure 8. A control chart for retention values with special-cause variation (red box 1 is out of control, red box 2 is a run of seven points above the center line).

Depending on the parameter, other forms of control charts may be useful, such as the difference control chart described below or moving range charts discussed in Appendix A. Popular software packages for control charting with other quality control tools are JMP® (www.jmp.com) and Minitab® (www.minitab.com). Control charts can also be developed manually in Excel® or other types of spreadsheets. See Appendix A for a list of the formulas and more detail on control charting.

Run Tests for Control Charts

Sometimes there will be *out of control* patterns in a control chart, even when the data points are within the control limits. For example, the 6 values before the red box #2 in Figure 8 are all above the mean value. This run of above average values is very unlikely to occur simply by chance and thus this event deserves further exploration, just like the out-of-control event at red box #1. The statistical basis of the run tests or rules is simply that if the data are truly from the normal distribution, then there will not be any pattern to the points. Common run rules for detecting abnormal patterns in control include charts include:

- *Run Test 1: a point more than three standard deviations (LCL and UCL) from the average is an indication that the process is out of control.*
- *Run Test 2: 7 or more consecutive points same side of average is an indication that the process mean has shifted (Nelson).*
- *Run Test 3: 6 consecutive points increasing or decreasing is an indication that the process mean has shifted (a trend) (Nelson).*

A complete listing of the eight run rules with detailed explanations can be found at, http://www.smartspc.com/blog/tag/spc-trend-rules/ .

Difference Control Chart

The difference control chart is an extension of the control chart concept. It is an excellent tool to monitor process stability that quantifies all of the variation (common- and special-cause) of the difference between two numbers: *e.g., the actual measurement and the target.*

Consider having the following control chart (Figure 9), but we have now added a line for our target retention. To construct a difference chart from the data in the top chart, we construct a chart that looks similar but instead plots each observed value minus another value, such as the target retention level. The LCL and UCL are then determined as appropriate from those differences. The new target becomes zero, while the average value represents the average difference relative to the target, giving average over- or under-retention (Figure 9, bottom).

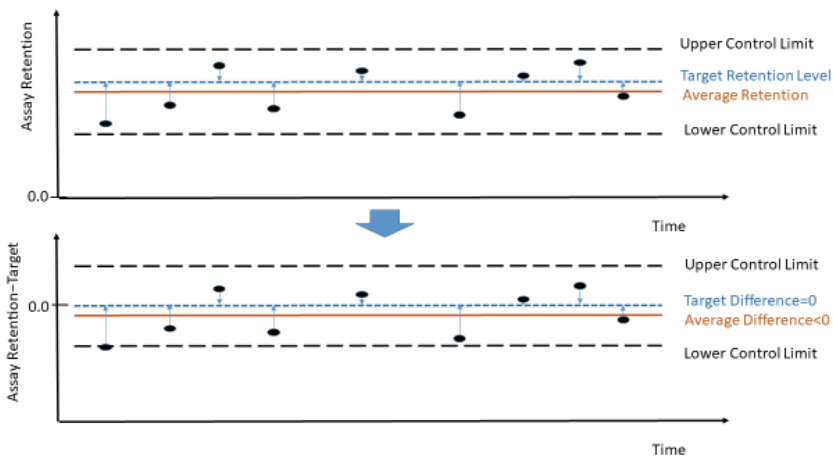


Figure 9. Control chart showing observed retentions relative to a target (top). Difference chart (bottom) plotting differences in retention from the target with shifted control limits.

The control chart shown in Figure 10 highlights the variation in the differences between individual charge assay retentions and the retention target value. Most of the data points are negative and the average difference is negative because in most cases the charge assay retention is slightly less

than the target retention. Notice the out-control signals identifying events or special-cause variation. They indicate charges where the wood was substantially under-treated.

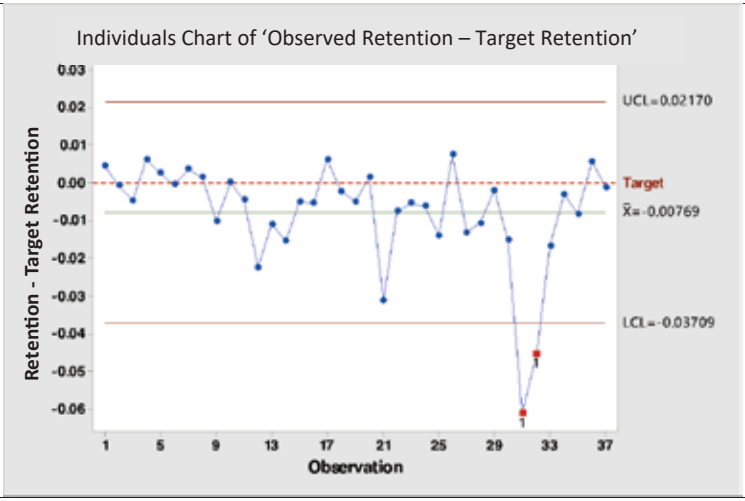


Figure 10. Control chart of differences between observed retention minus target retention highlighting out of control points as red boxes.

Suggested References for Control Charts

Deming, W.E. 1986. Out of the crisis. Massachusetts Institute of Technology, Center for Advanced Engineering Study. Cambridge, MA.

Montgomery, D.C. 2013. Statistical quality control: A modern introduction. John Wiley & Sons, Inc. 752p.

Shewhart, W.A. 1931. Economic control of quality of manufactured product. D. Van Nostrand Company. New York, NY. 501p.

Young, T.M. 2008. Reducing variation, the role of statistical process control in advancing product quality. Engineered Wood Journal. 11(2):41-42.

Capability Analyses

"Where there is no standard there can be no Kaizen (Improvement)"
Taiichi Ohno

Your company must determine if the treated wood products can meet a customer's standards. Typically, there is some lower limit that the tested product must exceed. In other cases, there can be both a lower and upper limit. Customers, regulating agencies, or engineers usually set these specifications. The specification limit(s) is called the engineering tolerance, or ET. In the example in Figure 11 there is only one limit for retention value, a lower specification limit (LSL).

As described in the previous section, there is a natural variation in any manufacturing process (the mean ± 3 standard deviations). This is also called the natural tolerance of the process, or NT. Comparing the natural variation of your product (*e.g., retention value*) to specification limits is a called a 'capability analysis.'

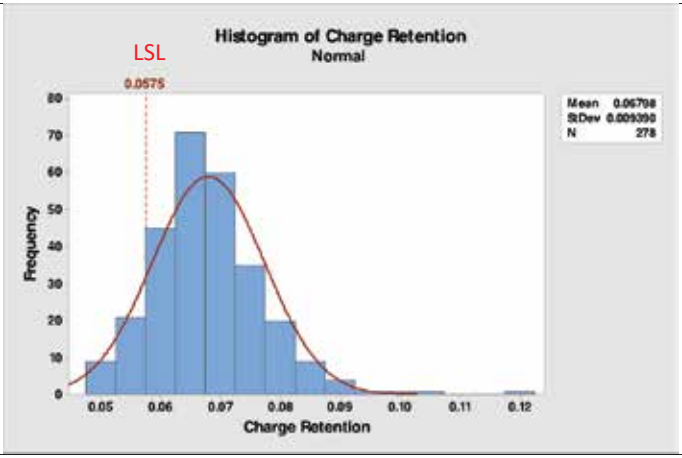


Figure 11. Histogram of retention with descriptive statistics.

Natural Tolerance (NT) = 6 × s
Engineering Tolerance (ET) = USL – LSL
Capability and Performance Indicators approximate ET/NT

Capability analyses typically include a histogram of the process values. A histogram shows the probability and relative frequency of values over the range. Individual data points are put into groups, and the groups (shown as bars) with the height of the bar corresponding to how many points are in that group. Figure 12 shows a histogram of charge retention data. For the 280 charges tested, the average (mean) value was 0.067, and most of the charges were close to that value. Notice the fit of the bell-shaped curve which is typical of a normal distribution for many datasets.

For a capability analysis, the specifications are often overlaid on the histogram, to show the relationship of the NT to the ET. In Figure 12 most of the data (in this case charge retention values) are above the target; however, due to the natural tolerance of the process, there are some charges that are out of specification. It is important in a capability analysis that the natural tolerance of the process is in a state of statistical control, *i.e., there are no out of control points*, see Figure 12 below (the LSL, Target and USL are theoretical for the sake of example).

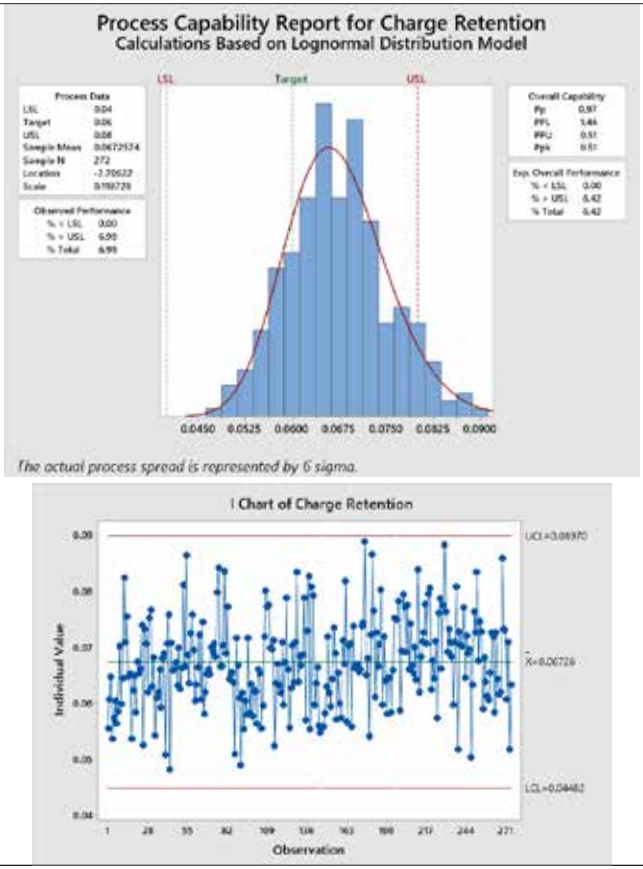


Figure 12. Histogram with theoretical specification limits and control chart illustrating state of statistical control of the data.

Capability analyses summarize process information by indicating how the natural process variation conforms or doesn't conform to the specification limits of the process. While a specification limit can be arbitrarily set at a given value, the natural variation of any process means that the target production value cannot simply be set at the specification limit. The target for production must include allowance for the natural variation that will occur. As the process becomes better understood, and the

causes of variability identified and controlled, then the target can be shifted closer to the specification limits.

Suggested References for Capability Analysis

ASTM E2281. 2015. Standard practice for process and measurement capability indices. ASTM International, West Conshohocken, PA.

Bothe, D.R. 2001. Measuring process capability. Landmark. Publishing, Cedarburg, WI. ISBN 0-07-006652-3

Graham J. and M. Cleary. 2000. Practical tools for continuous improvement, Vol. 2: Problem-Solving and Planning Tools. PQ Systems. Dayton, OH. ISBN-10: 1882683064

Pyzdek, T. 2003. Quality engineering handbook. Taylor and Francis. New York, NY. ISBN 0-8247-4614-7.

Rodriguez, R.N. 1992. Recent developments in process capability analysis. Journal of Quality Technology. 24(4):176-187. DOI:10.1080/00224065.1992.11979399

Root-Cause Analyses for Reducing Variation

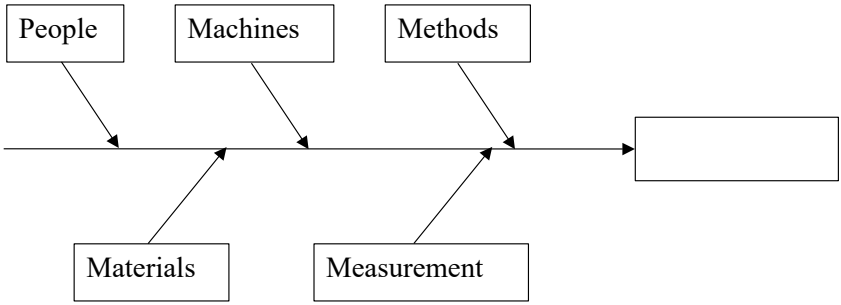
*"Ask '**Why?**' five times about every matter"*

Taiichi Ohno

Root-cause analysis focuses on identifying and understanding the potential factors that contribute to production problems. In a wood treating operation, such a problem could be inconsistent penetration or too many nonconforming charges. Root-cause analysis is typically done after an event has occurred with the goal being to improve process understanding by developing solutions to eliminate problems from reoccurring. To be effective, root-cause analysis should be performed as part of an investigation, usually as a team effort. Root-cause analysis should also be forward-looking, aiming to reduce the future occurrence of problems and not to cast blame on an operator.

"Fishbone" or Ishikawa Diagrams

Ishikawa first used a fishbone in the 1960s in the Japanese automotive industry (Ishikawa 1968). The idea of the Ishikawa diagram is that important sources of variation are categorized into five groups (see diagram below).



Ishikawa (1968) has some helpful points on how to construct the diagram:

1. *Place the main problem under investigation in a box on the right.*
2. *Have the team identify and clarify all the potential causes of the problem whether small or large (process variables).*
3. *Sort the process variables into naturally related groups. These groups become the major bones on the Ishikawa diagram.*
4. *Combine each bone in turn, if the combined process variables are specific, measurable and controllable. If they are not, branch or explode the process variables until the ends of the branches are specific, measurable, and controllable.*

Tips:

- *Take care to identify causes rather than symptoms.*
- *Post diagrams to stimulate thinking from other staff.*
- *Ensure that the ideas placed on the Ishikawa diagram are process variables, not special causes, tampering, etc.*

In a treating plant example situation, the frequent need to retreat charges could be considered a problem. A fishbone exercise could be a useful organized brainstorming technique to help to understand the causes of needing to retreat (Figure 13).

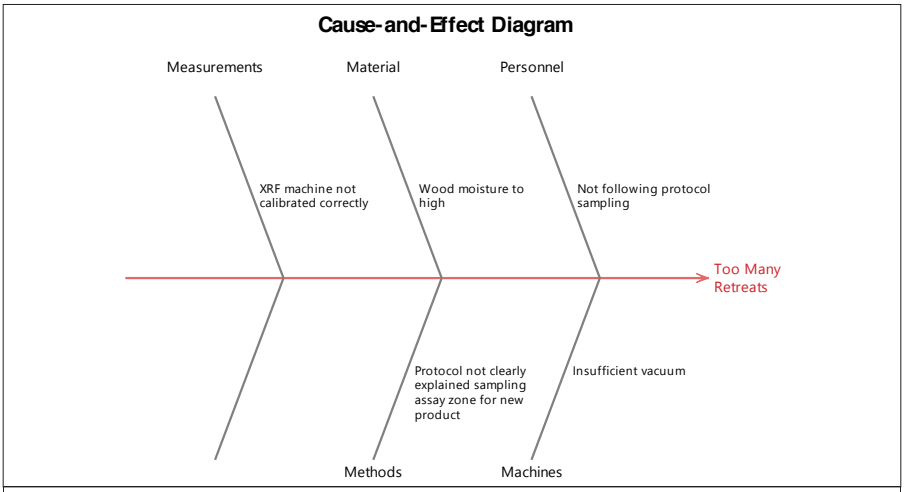


Figure 13. Fish-bone or Ishikawa diagram of charges.

An advantage of the fishbone process, is that it can draw on input from various people throughout the plant/mill. Each person in the mill has their own perspective and special knowledge, and the fishbone helps to draw these sources of knowledge together.

The '5 Whys' - Lean Root Cause

By repeatedly asking the question "Why?" (*five times is a good rule of thumb but not always root to get to the root cause*), you can peel away the layers of symptoms which can lead to the root cause of a problem.

Ohno (1988) gave the following example for a problem identified as the "Machine stopped functioning:"

1. ***Why did the machine stop?***

   There was an overload and the fuse blew.

2. ***Why was there an overload?***

   The bearing was not sufficiently lubricated.

3. ***Why was it not lubricated sufficiently?***

   The lubrication pump was not pumping sufficiently.

4. ***Why was it not pumping sufficiently?***

   The shaft of the pump was worn and rattling.

5. ***Why was the shaft worn out?***

   There was no strainer attached and metal scrap got in.

If this problem solving procedure was not carried through, one might simply replace the fuse or the pump shaft. In that case, you would expect that the problem would recur because the root cause was not addressed. The

symptom was addressed, but not the root cause. In the fishbone example shown previously, insufficient initial vacuum was identified as a cause of needing to retreat. But what caused the insufficient vacuum? This is an opportunity to ask 'Why?' in a systematic, repeated way to address this problem (Figure 13).

Cause Mapping

Cause Mapping expands on some of the basic ideas of lean root cause, the fishbone diagram and the '5 whys'. At every point in the Cause Map, investigators ask 'why' questions that move backward through time, studying effects and finding their causes.

Cause Maps Tie Problems to an Organization's Overall Goals

As Ishikawa (1968) illustrated, the fishbone better defines one problem by identifying potential causes. *Cause Mapping* involves pursuing the causes, asking "why?" repeatedly to identify root causes and determining potential solutions.

Assume that the plant has experienced several treatment charges failing that had assay retention levels. The goal impacted by charges failing would be treatment quality. Two possible initial reasons for failing charges could be a treating solution that had too low of a strength or that was a mistake in the

retention measurement. Following possible causes repeatedly leads to potential initial causes and to some potential solutions (Figure 14).

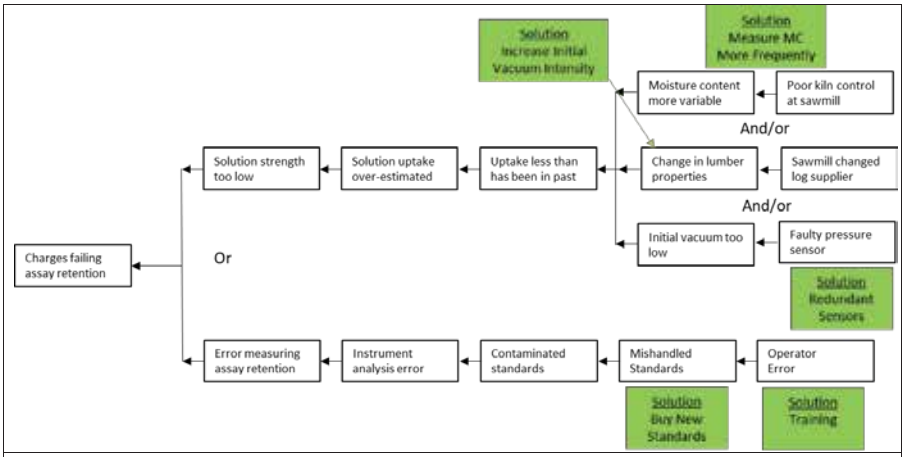


Figure 14. Cause map of reasons for charges failing assay retention specification.

Suggested References for Root Cause Analysis

Deming, W.E. 1986. Out of the crisis. Massachusetts Institute of Technology, Center for Advanced Engineering Study. Cambridge, MA.

Gano, D.L. 2007. Apollo root cause analysis: a new way of thinking. Apollonian Publications. Richland, WA.

Ishikawa, K. 1968. Guide to Quality Control. Asian Productivity Organization. Tokyo.

Ohno, T. 1988. Toyota production system: beyond large-scale production. Productivity Press. Portland, OR. ISBN 0-915299-14-3.

Rooney, J.J. and Vanden Heuvel, L.N. 2004. Root cause analysis for beginners. Quality Progress. 37(7)45-53.

Pareto Principle – "The Pareto Chart"

"For many events, roughly 80% of the effects come from 20% of the causes"
Vilfredo Pareto

Sutton (2014) documents the history of the Pareto Chart and the 80/20 principle, *"In the late nineteenth century the Italian economist and misanthrope Vilfredo Pareto famously noted that most of the wealth in any community was held by a small proportion of the population. From this insight he developed the 80/20 rule, or the Pareto Principle, which, in the case of community wealth, meant that about 20% of any population owns about 80% of the wealth. His principle, which has no theoretical underpinning, is widely observed to be true in many fields of human activity, including risk analysis."*

Of course in many cases the actual proportions might not be exactly 80% and 20%. But the point is that an '*important few*' or the '*vital few*' have a great impact on the business, whereas the '*unimportant many*' are much less significant. For example, a safety manager is likely to be more effective by directing his or her program toward the few individuals that are causing the most incidents. Spending time on the *'unimportant many'* is not likely to have much benefit.

"Pareto Principle – Reliability Example"

Sutton (2014) has a very good Pareto principle example as related to an electrically-driven pump that has a probability of failure to start of 0.1, meaning it will not start one times in ten. Management has decided that this

failure rate is too high; they wish to reduce the rate to lower than 0.02, *i.e., one time in fifty*. As Sutton (2014) notes, a survey of plant records for this and similar pumps is made. The following reasons for a pump of this type failing to immediately start are identified:

- *Operator busy elsewhere,*
- *Electrical power not available,*
- *Start switch does not work properly,*
- *P-101B motor fails,*
- *Discharge valve sticks close, and*
- *Operator starts the wrong pump.*

The number of occurrences for each of the six failure types are listed below. The events are sorted by failure frequency and given an importance ranking.

Table 1. Reasons for pump failure

Reasons for Failure	*Number of Incidents*	*% of Total*	*Cumulative %*	*Rank*
Operator busy elsewhere	123	60.6	60.6	1
Electric power not available	44	21.7	82.3	2
Motor fails	18	8.9	91.2	3
Operator starts the wrong pump	12	5.9	97.1	4
Start switch does not work	5	2.4	99.5	5
Discharge valve sticks closed	1	0.5	100.0	6
Totals:	**203**	**100.0**		

Cumulative Failure Rate

The data in Table 1 above show that the items '*Operator busy elsewhere*' and '*Electrical power not available*' contributes 82.3% toward the overall failure rate. In terms of the Pareto Principle, these two items are the '*important few,*' with the others being the '*unimportant many*.'

Therefore, to improve the system reliability, all efforts should be directed toward ensuring that the operator has sufficient time to start the

spare pump, see the Pareto chart of this data in Figure 15. If this failure mode can be removed from the system, the system reliability will increase by 60%. If the second ranked item, '*Electrical Power Not Available*' can be eliminated also, system reliability will improve by more than 80%.

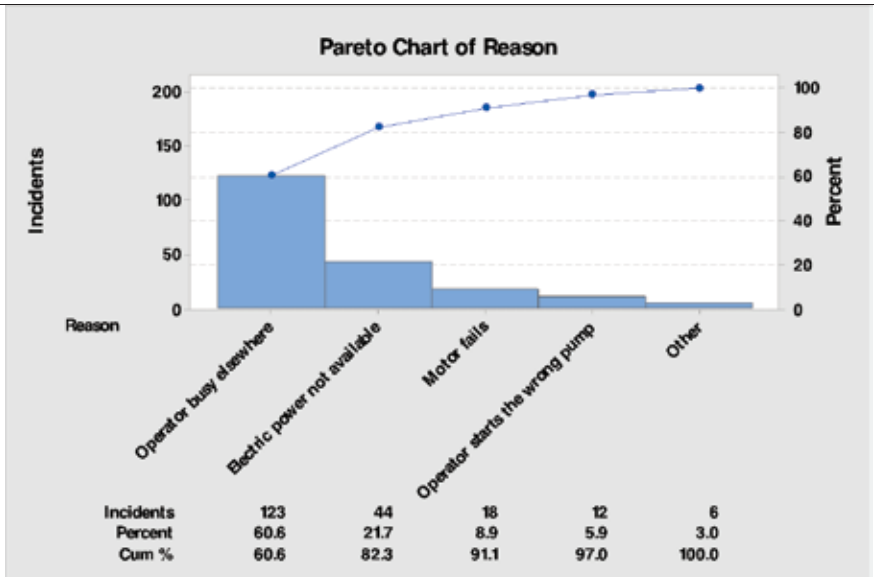


Figure 15. Pareto chart of incidents for pump failing to start.

The logic of the Pareto principle can be applied to a treating plant's operation. It can be used for any problem that occurs repeatedly and has multiple causes. It makes sense for the improvement process selected since it focuses on those few causes that occur most frequently. Because it is usually not possible to fix every potential problem-causing situation, the most efficient path to improvement focuses on the most commonly occurring failure modes.

Suggested References for the Pareto Principle

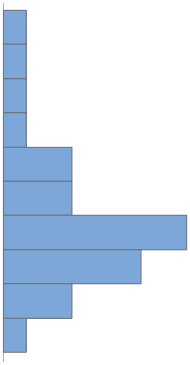
Dunford, R., Su Q., Tamang E., and Wintour A. 2014. The Pareto principle The Plymouth Student Scientist. 7(1):140–148.

Pareto, V. 2005. Pareto optimality. Oxford University Press. Oxford, UK. ISBN-13: 9780199264797.

Sutton, I. 2014. Process risk and reliability management. Elsevier.

APPENDIX A – Descriptive Statistics

Statistics that Estimate the Central Tendency of the Distribution of the Data



Process Center Line (PCL) is typically the "Arithmetic Average," "Arithmetic Mean," or "Sample Mean":

- Average or Sample Mean is the "center of gravity of the data set" $(\overline{X})$
- Average in Statistical Process Control (SPC) is stated as "X-bar"
- If you have n observations, x_1, x_2, …, x_n, then the formula for the Average or Sample Mean ("Arithmetic Mean") is

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \approx \mu \ (population\ mean)$$

- Example with *n* = 5 observations:

$$\overline{\mathcal{X}} = \frac{9.2 + 6.4 + 10.5 + 8.1 + 7.8}{5} = \frac{42.0}{5} = 8.4$$

Median = 50th Percentile

Median (M or C; or $\tilde{\mu}$):

- The Sample Median (M) of a set of *n* measurements is the middle value (*or midpoint, 50th percentile*) when the measurements are ordered from smallest to largest.

- If *n* is an odd number, there is a unique middle value and it is the median (*i.e.,* the (n+1)/2-st ordered value).

- If *n* is an even number, there are two middle values and the median is defined as their average.

Example: 6.4 7.8 $\boxed{8.1}$ 9.2 10.5

M = 8.1

What is the average and median of the data set: 1, 2, 3, 4, 5?

$\bar{X} =$

M =

What is the average and median of the data set: 1, 2, 3, 4, 100?

$\bar{X} =$

M =

Statistics that Measure the Variation or Dispersion of the Distribution of Data

Sample Variance (s^2):

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \approx \sigma^2 \ (population\ variance)$$

Sample Standard Deviation (s):

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \approx \sigma \ (population\ standard\ deviation)$$

's' estimates variability in same unit of measure as the observations and the mean

Range (or R): R = Largest value minus the smallest value

= maximum value – minimum value

Example: 6.3, 2.4, 3.1, 3.1, 5.8, 2.7, 8.1

R = 8.1 – 2.4 = 5.7

Notice the range depends on the maximum and minimum of the observed sample, therefore, it is more useful for representing variation in small data sets.

Coefficient of Variation (CV)

Is a scaled measure of dispersion, which is the standard deviation, divided by the mean (often multiplied by one hundred to represent percent).

$$CV\% = \frac{s}{\bar{x}} \times 100$$

Helpful when comparing dispersion statistics across sets of data with varying scales of measure and means, *e.g., product types, etc*.

This is the same as the relative standard deviation (RSD or %RSD); sometimes only positive values are considered (*i.e., using the absolute value of the mean in the formula*).

Control Charts *without* Subgrouping

"X-Individual and Moving Range" Control Chart (or "ImR")

X-Individual Control Chart Formula:

$$UCL = \bar{X} + 2.66 \times (\overline{mR})$$
$$LCL = \bar{X} - 2.66 \times (\overline{mR})$$

Moving Range Control Chart Formula:

$$UCL_{mR} = 3.267 \times (\overline{mR})$$

where, $(\overline{mR})$ = "*average moving range*"

$$\overline{mR} = \frac{\sum_{i=2}^{n} mR_i}{n-1}$$

with each moving range $(mR)_i = |x_i - x_{i-1}|$ for 2 neighboring observations .

Control Charts *with* Subgrouping

X-bar and Range Control Charts (or X-*Bar and R*)

- Organizing measurements data into subgroups often to help manage data streams.

- Each subgroup should be selected from some small space, time, or product to assure relatively homogeneous conditions within the subgroup – idea of "*RATIONAL SUBGROUP*"

- Emphasis is on minimizing the variation within the subgroups.

X-Bar Control Chart Formula:

Upper Control Limit (X-bar): $UCL_{\bar{x}} = \bar{\bar{X}} + A_2 \times \bar{R}$

Lower Control Limit (X-bar): $LCL_{\bar{x}} = \bar{\bar{X}} - A_2 \times \bar{R}$

Where: $\bar{\bar{X}}$ = grand average of subgroup averages

$\bar{R}$ = average of the subgroup ranges

Range Control Chart Formula:

Upper Control Limit (Range): $UCL_R = D_4 \times \bar{R}$

Lower Control Limit (Range): $LCL_R = D_3 \times \bar{R}$

Constants associated with X-bar and Range Control Charts

Subgroup Size *n*	A_2	D_3	D_4
2	1.880	--	3.267
3	1.023	--	2.574
4	0.729	--	2.282

5	0.577	--	2.114
6	0.483	--	2.004
7	0.419	0.076	1.924
8	0.373	0.136	1.864
9	0.337	0.184	1.816
10	0.308	0.223	1.777

The constants are used to standardize distributions under the assumption of normally distributed individual values, *i.e.,* that the sample standard deviation is a biased statistic for estimating the population standard deviation

IMPORTANT

"Rational Subgrouping Rules-of-Thumb"

- Keep parallel operations in separate subgroups.
- A subgroup should **not** include data from a different lot or of a different nature.
- Each subgroup must be logically homogeneous, i.e., data within the subgroups must be collected under essentially the same conditions.

Other Control Charts ***with*** Subgrouping

<u>X-bar and s Charts:</u>

Control Limit Formula for XBar and s Control Charts:

Upper Control Limit (XBar): $UCL_{\bar{x}} = \bar{\bar{X}} + A_3 \times \bar{s}$
Lower Control Limit (XBar): $LCL_{\bar{x}} = \bar{\bar{X}} - A_3 \times \bar{s}$

where, $\bar{\bar{X}}$ = grand average of subgroup averages
$\bar{s}$ = average of the subgroup standard deviations

Upper Control Limit (Std): $UCL_s = B_4 \times \bar{s}$
Lower Control Limit (Std): $LCL_s = B_3 \times \bar{s}$

"Constants associated with X-bar and s Control Charts"

n=subgroup size	A_3	B_3	B_4
2	2.659	--	3.267
3	1.954	--	2.568
4	1.628	--	2.266
5	1.427	--	2.089
6	1.287	0.030	1.970
7	1.182	0.118	1.882
8	1.099	0.185	1.815
9	1.032	0.239	1.761
10	0.975	0.284	1.716

Control Charts for Attribute Data

Data Based on Counts

Concept of *Area of opportunity during sampling*:

- Background against which the count must be interpreted.
- Before any two counts may be directly compared they must have equal Areas of Opportunity. Examples include looking at number of nonworking electrical drills out of every 1000 produced or number of cores without sufficient penetration per 20 cores tested.
- If the Areas of Opportunity are not equal, then the counts must be turned into rates before they may be meaningfully compared.
- When the total *n* (total sample number) is known:

"*np chart*" control limits

Upper Control Limit (np chart):

$$UCL_{np} = n \times \bar{p} + 3\sqrt{n \times \bar{p} \times (1 - \bar{p})}$$

Lower Control Limit (np chart):

$$LCL_{np} = n \times \bar{p} - 3\sqrt{n \times \bar{p} \times (1 - \bar{p})}$$

Average Proportion Nonconforming:

$$\bar{p} = \frac{\text{total number nonconforming in baseline samples}}{\text{total number items examined in baseline samples}}$$

Center Line: $CL_{np} = n \times \bar{p}$

"*p chart*" control limits (when n varies per sample)

Upper Control Limit (*p chart*):

$$UCL_p = \bar{p} + 3 \times \sqrt{\frac{\bar{p} \times (1 - \bar{p})}{n_i}}$$

Lower Control Limit (*p chart*):

$$LCL_p = \bar{p} - 3 \times \sqrt{\frac{\bar{p} \times (1 - \bar{p})}{n_i}}$$

Average Proportion Nonconforming:

$$\bar{p} = \frac{total\ number\ of\ nonconforming\ in\ baseline\ samples}{total\ number\ items\ examined\ in\ baseline\ samples}$$

Center Line: $CL_p = \bar{p}$

Nonconforming product: $p_i = Y_i / n_i$ for sample *i*

Charts for Nonconformities

(Can only count defects, impossible to count 'non-defects')

Formula for "*c chart*" control limits

Upper Control Limit (c chart):

$$UCL_c = \bar{c} + 3 \times \sqrt{\bar{c}}$$

Lower Control Limit (c chart):

$$LCL_c = \bar{c} - 3 \times \sqrt{\bar{c}}$$

Average Count per Sample:

$$\bar{c} = \frac{total\ count\ of\ nonconformities\ in\ baseline\ samples}{number\ of\ baseline\ samples}$$

Center Line:

$$CL_c = \bar{c}$$

"*u chart*" control limits

Upper Control Limit (u chart):

$$UCL_u = \bar{u} + 3\sqrt{\frac{\bar{u}}{a_i}}$$

Lower Control Limit (u chart):

$$LCL_u = \bar{u} - 3\sqrt{\frac{\bar{u}}{a_i}}$$

Average Rate of Nonconformities per Unit Area:

$$\bar{u} = \frac{total\ count\ for\ the\ baseline\ samples}{total\ area\ of\ opportunity\ in\ baseline\ samples}$$

Center Line: $CL_c = \bar{u}$

Control Chart Guide

Control Charts

Measurement Data

n=1

XmR or ImR

X-Individual (long term):

$UCL/LCL = \bar{X} \pm 2.66(\overline{mR})$

Moving Range (short term):

$UCL_{mR} = 3.268\ (\overline{mR})$

n>1 (rational subgrouping)

$\bar{X}$R

X-bar:

$UCL/LCL = \bar{\bar{X}}\ \pm A_2\bar{R}$

Range:

$UCL_R = D_4\bar{R}$

$LCL_R = D_3\bar{R}$

$\bar{X}$s

X-bar:

$UCL/LCL = \bar{\bar{X}}\ \pm A_3\bar{s}$

Range:

$UCL_R = B_4\bar{s}$

$LCL_R = B_3\bar{s}$

Binomial

(count good and bad)

np

n (or sample area) is constant

$UCL/LCL = n\bar{p}\ \pm 3\sqrt{n\bar{p}(1-\bar{p})}$

p

n (or sample area) changes

$$UCL/LCL = \bar{p}\ \pm 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}}$$

Poisson

(only possible to count bad)

c

n (or sample area) is constant

$UCL/LCL = \bar{c}\ \pm 3\sqrt{\bar{c}}$

u

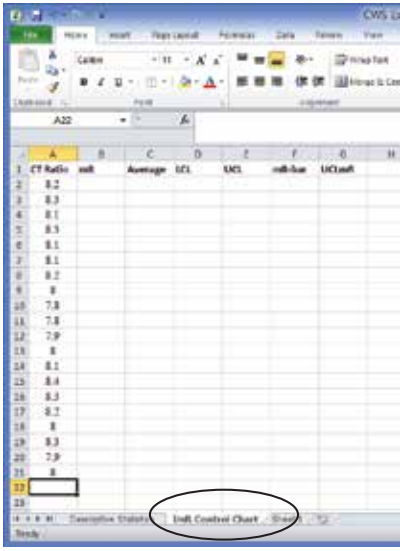
n (or sample area) changes

$$UCL/LCL = \bar{u}\ \pm 3\sqrt{\frac{\bar{u}}{a_i}}$$

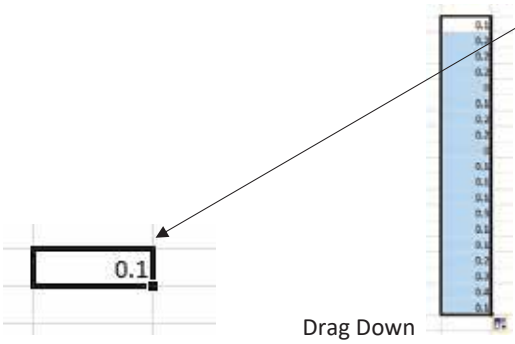
subgroup							
n	**d_2**	**A_2**	**A_3**	**B_3**	**B_4**	**D_3**	**D_4**
2	1.128	1.880	2.659	-	3.267	-	3.268
3	1.693	1.023	1.954	-	2.568	-	2.574
4	2.059	0.729	1.628	-	2.266	-	2.282
5	2.326	0.577	1.427	-	2.089	-	2.114
6	2.534	0.483	1.287	0.030	1.970	-	2.004
7	2.704	0.419	1.182	0.118	1.882	0.076	1.924
8	2.847	0.373	1.099	0.185	1.815	0.136	1.864
9	2.970	0.337	1.032	0.239	1.761	0.184	1.816
10	3.078	0.308	0.975	0.284	1.716	0.223	1.777

Developing an 'Individuals' and 'Moving Range' Control Chart in Excel

1. In a new Worksheet Tab > Copy your data to Column A > create the following headers in columns B through G:



2. In cell B3 > calculate the moving range of cells A3 and A2 > type: =**ABS(A3-A2)** and hit Enter key, you will have 0.1 in cell B3. Highlight cell B3 > grab the small square in bottom right corner of cell and drag down to the end of data (B21)



3. Now let's calculate the 'averages' for the data and its 'moving range' > type in word **Average** in cells A22 and B22 > in cell A23 type **=AVERAGE(A2:A21)** then hit the Enter key

   Grab the small square in bottom right corner of cell A23 and drag it one cell to the right to B23, this will give you the average of the moving ranges

   You should get these following statistics:

18	8	0.2
19	8.3	0.3
20	7.9	0.4
21	8	0.1
22	**Average**	**Average**
23	8.1	0.157895
24		

4. Now let's copy/paste these corresponding averages in columns C and D (Note we will need to 'LOCK' the cells in place)
   a. Type in cell C2 **=$A$23** and hit Enter key (**or type in =A23 and hit the F4 key on your keyboard**); this locks cell A23 in cell C2 for future use
   b. Do the same for cell F2 **=$B$23** (**or type in =B23 and hit the F4 key on your keyboard**)
   c. Highlight cell C2 and drag it down to C21
   d. Highlight cell F2 and drag it down to F21

You should have the following:

	A	B	C	D	E	F	G
1	CT Ratio	mR	Average	LCL	UCL	mR-bar	UCLmR
2	8.2		8.1			0.157895	
3	8.3	0.1	8.1			0.157895	
4	8.1	0.2	8.1			0.157895	
5	8.3	0.2	8.1			0.157895	
6	8.1	0.2	8.1			0.157895	
7	8.1	0	8.1			0.157895	
8	8.2	0.1	8.1			0.157895	
9	8	0.2	8.1			0.157895	
10	7.8	0.2	8.1			0.157895	
11	7.8	0	8.1			0.157895	
12	7.9	0.1	8.1			0.157895	
13	8	0.1	8.1			0.157895	
14	8.1	0.1	8.1			0.157895	
15	8.4	0.3	8.1			0.157895	
16	8.3	0.1	8.1			0.157895	
17	8.2	0.1	8.1			0.157895	
18	8	0.2	8.1			0.157895	
19	8.3	0.3	8.1			0.157895	
20	7.9	0.4	8.1			0.157895	
21	8	0.1	8.1			0.157895	
22	Average	Average					
23	8.1	0.157895					

5. Let's calculate the <u>Control Limits for the 'Individuals Chart'</u>

   a. In cell D2, type **=$A$23-2.66*$B$23**

   b. In cell E2, type **=$A$23+2.66*$B$23**

   c. Highlight cells **D2** & **E2** and drag down to cells **D21** & **E21**

You should have the following:

	A	B	C	D	E	F	G	H
1	CT Ratio	mR	Average	LCL	UCL	mR-bar	UCLmR	
2	8.2		8.1	7.68	8.52	0.157895		
3	8.3	0.1	8.1	7.68	8.52	0.157895		
4	8.1	0.2	8.1	7.68	8.52	0.157895		
5	8.3	0.2	8.1	7.68	8.52	0.157895		
6	8.1	0.2	8.1	7.68	8.52	0.157895		
7	8.1	0	8.1	7.68	8.52	0.157895		
8	8.2	0.1	8.1	7.68	8.52	0.157895		
9	8	0.2	8.1	7.68	8.52	0.157895		
10	7.8	0.2	8.1	7.68	8.52	0.157895		
11	7.8	0	8.1	7.68	8.52	0.157895		
12	7.9	0.1	8.1	7.68	8.52	0.157895		
13	8	0.1	8.1	7.68	8.52	0.157895		
14	8.1	0.1	8.1	7.68	8.52	0.157895		
15	8.4	0.3	8.1	7.68	8.52	0.157895		
16	8.3	0.1	8.1	7.68	8.52	0.157895		
17	8.2	0.1	8.1	7.68	8.52	0.157895		
18	8	0.2	8.1	7.68	8.52	0.157895		
19	8.3	0.3	8.1	7.68	8.52	0.157895		
20	7.9	0.4	8.1	7.68	8.52	0.157895		
21	8	0.1	8.1	7.68	8.52	0.157895		
22	Average	Average						
23	8.1	0.157895						

6. Let's calculate the Control Limit for the 'Moving Range' Chart

    a. In cell G2, type **=3.268*$B$23**

    b. Highlight cell **G2** and **drag down to G21**

You should have the following:

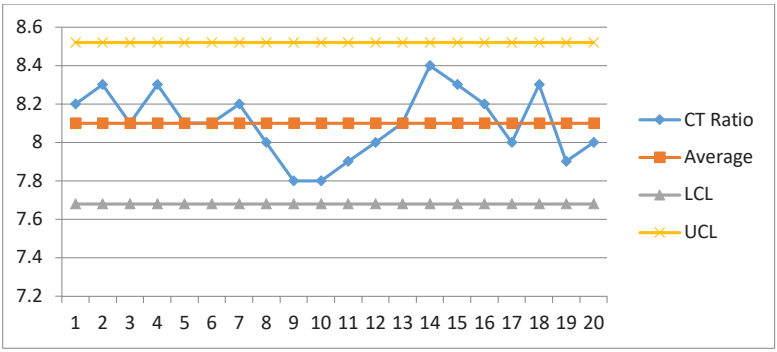
	A	B	C	D	E	F	G
1	CT Ratio	mR	Average	LCL	UCL	mR-bar	UCLmR
2	8.2		8.1	7.68	8.52	0.157895	0.516
3	8.3	0.1	8.1	7.68	8.52	0.157895	0.516
4	8.1	0.2	8.1	7.68	8.52	0.157895	0.516
5	8.3	0.2	8.1	7.68	8.52	0.157895	0.516
6	8.1	0.2	8.1	7.68	8.52	0.157895	0.516
7	8.1	0	8.1	7.68	8.52	0.157895	0.516
8	8.2	0.1	8.1	7.68	8.52	0.157895	0.516
9	8	0.2	8.1	7.68	8.52	0.157895	0.516
10	7.8	0.2	8.1	7.68	8.52	0.157895	0.516
11	7.8	0	8.1	7.68	8.52	0.157895	0.516
12	7.9	0.1	8.1	7.68	8.52	0.157895	0.516
13	8	0.1	8.1	7.68	8.52	0.157895	0.516
14	8.1	0.1	8.1	7.68	8.52	0.157895	0.516
15	8.4	0.3	8.1	7.68	8.52	0.157895	0.516
16	8.3	0.1	8.1	7.68	8.52	0.157895	0.516
17	8.2	0.1	8.1	7.68	8.52	0.157895	0.516
18	8	0.2	8.1	7.68	8.52	0.157895	0.516
19	8.3	0.3	8.1	7.68	8.52	0.157895	0.516
20	7.9	0.4	8.1	7.68	8.52	0.157895	0.516
21	8	0.1	8.1	7.68	8.52	0.157895	0.516
22	Average	Average					
23	8.1	0.157895					

7. Now, let's make the Control Charts > Highlight cells A1:A21 > hold the 'Ctrl' key down and highlight cells C1:E21 (it should be highlighted in blue, see below)

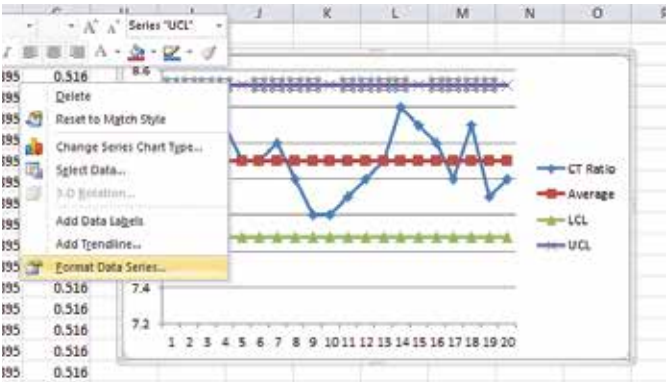
	A	B	C	D	E	F	G	H
1	CT Ratio	mR	Average	LCL	UCL	mR-bar	UCLmR	
2	8.2		8.1	7.68	8.52	0.157895	0.516	
3	8.3	0.1	8.1	7.68	8.52	0.157895	0.516	
4	8.1	0.2	8.1	7.68	8.52	0.157895	0.516	
5	8.3	0.2	8.1	7.68	8.52	0.157895	0.516	
6	8.1	0.2	8.1	7.68	8.52	0.157895	0.516	
7	8.1	0	8.1	7.68	8.52	0.157895	0.516	
8	8.2	0.1	8.1	7.68	8.52	0.157895	0.516	
9	8	0.2	8.1	7.68	8.52	0.157895	0.516	
10	7.8	0.2	8.1	7.68	8.52	0.157895	0.516	
11	7.8	0	8.1	7.68	8.52	0.157895	0.516	
12	7.9	0.1	8.1	7.68	8.52	0.157895	0.516	
13	8	0.1	8.1	7.68	8.52	0.157895	0.516	
14	8.1	0.1	8.1	7.68	8.52	0.157895	0.516	
15	8.4	0.3	8.1	7.68	8.52	0.157895	0.516	
16	8.3	0.1	8.1	7.68	8.52	0.157895	0.516	
17	8.2	0.1	8.1	7.68	8.52	0.157895	0.516	
18	8	0.2	8.1	7.68	8.52	0.157895	0.516	
19	8.3	0.3	8.1	7.68	8.52	0.157895	0.516	
20	7.9	0.4	8.1	7.68	8.52	0.157895	0.516	
21	8	0.1	8.1	7.68	8.52	0.157895	0.516	
22	Average	Average						
23	8.1	0.157895						

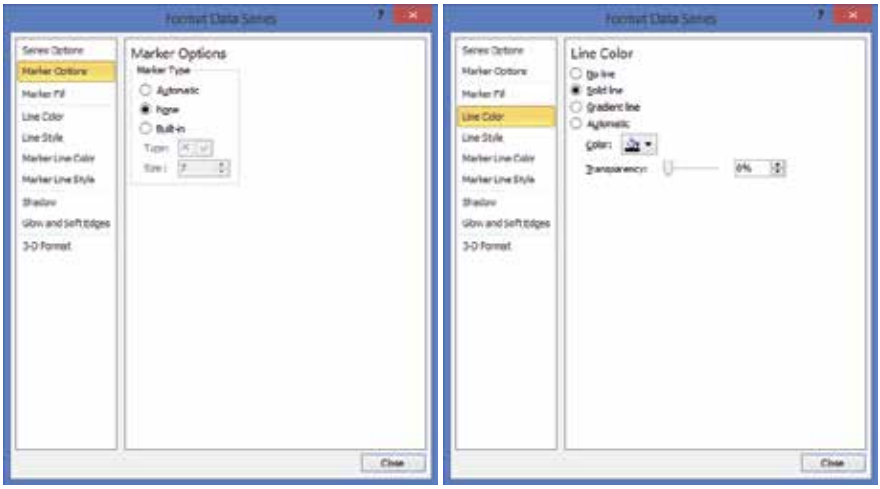
8. Now, from the Main Menu (top of Excel) > click on ‘Insert tab’ > then click on the ‘Line’ Icon > click on ‘Line with Markers’

You will get the following chart:

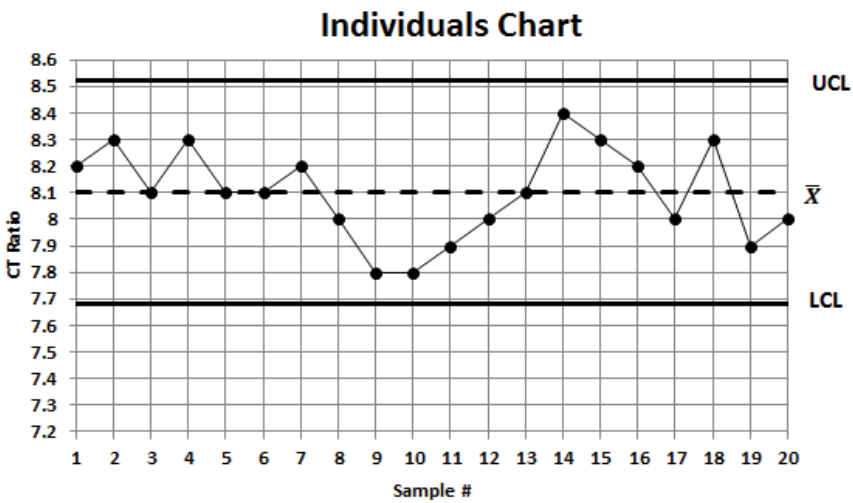


9. You can now customize your chart any way you would like:
   a. Right click on the data points to customize your chart

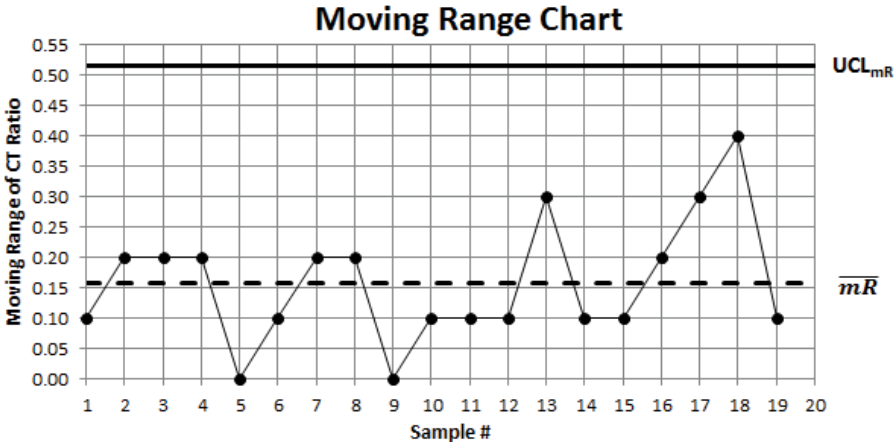




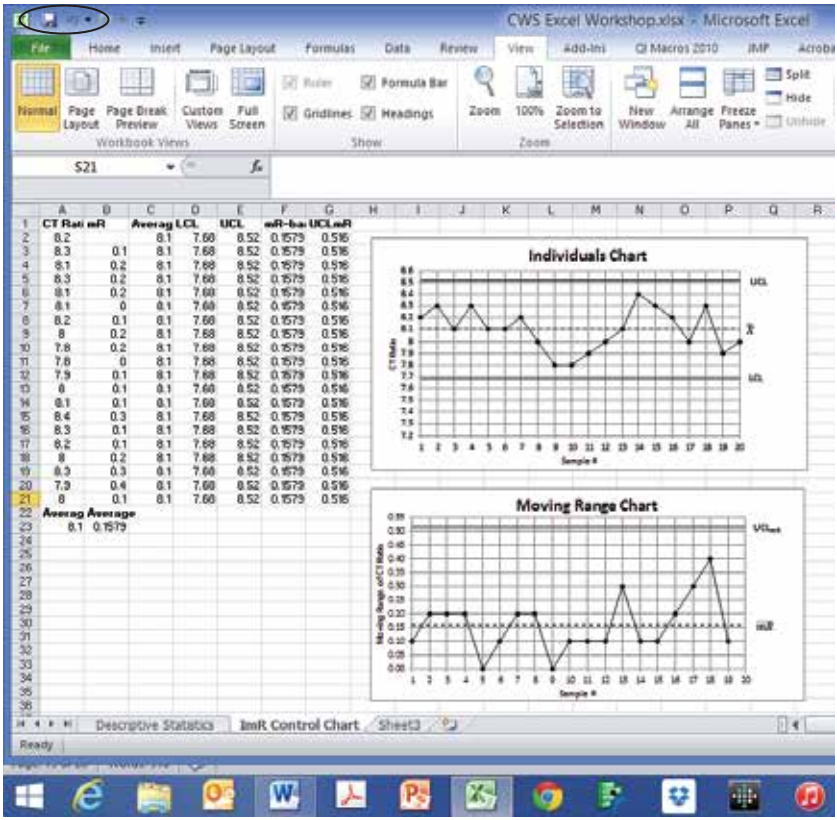
This is a possible chart:



10. Develop the 'Moving Range' chart for practice



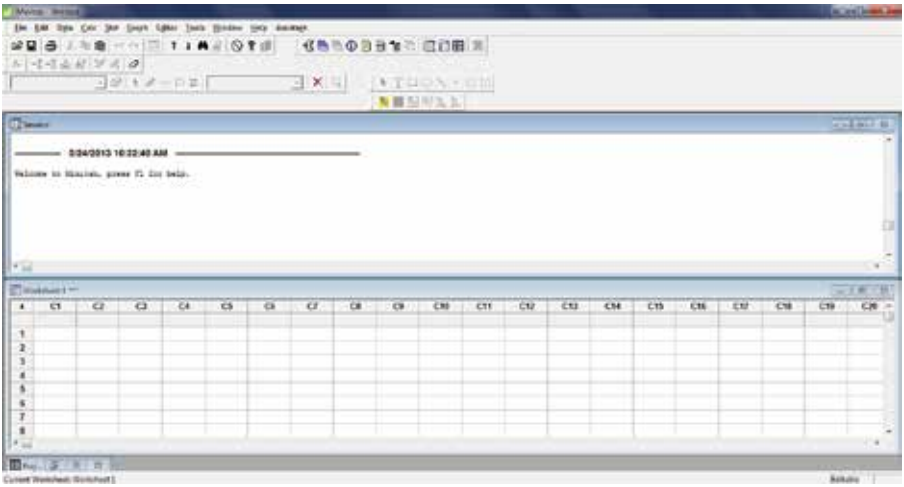
Save your Workbook:

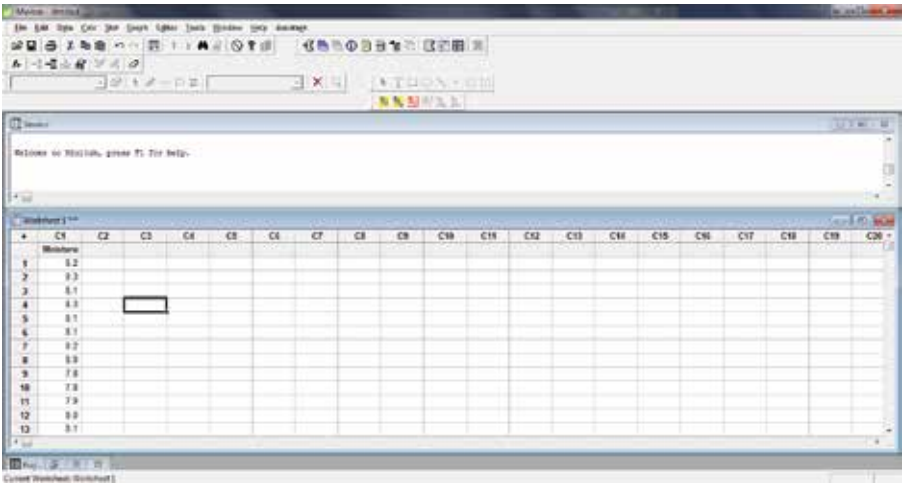


Developing a Control Chart in Minitab 18
Moisture Example

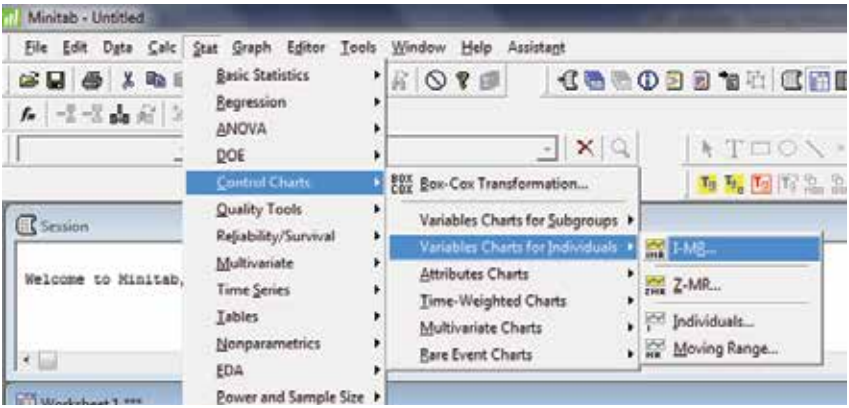
1. Start Minitab software

2. Type in your data in Column 1 and change the column header to "Moisture"; you can also copy and paste from Excel or open directly from an Excel file or .csv (comma delimited) file



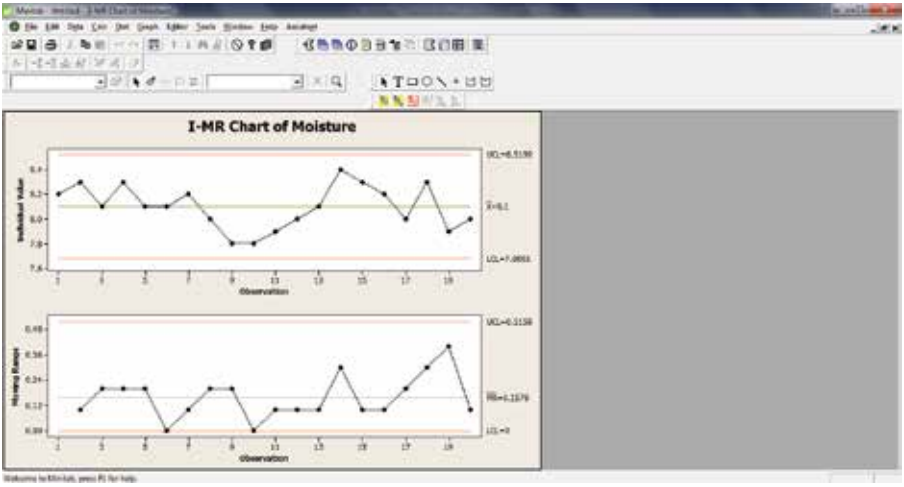


3. Click “Stat” from the main menu bar > click > “Control Chart” > “Variables Chart for Individuals” > click > “I-MR” (*for Individuals and Moving Range Charts*). Note: if you want just one chart, click on “Individuals” or “Moving Range”

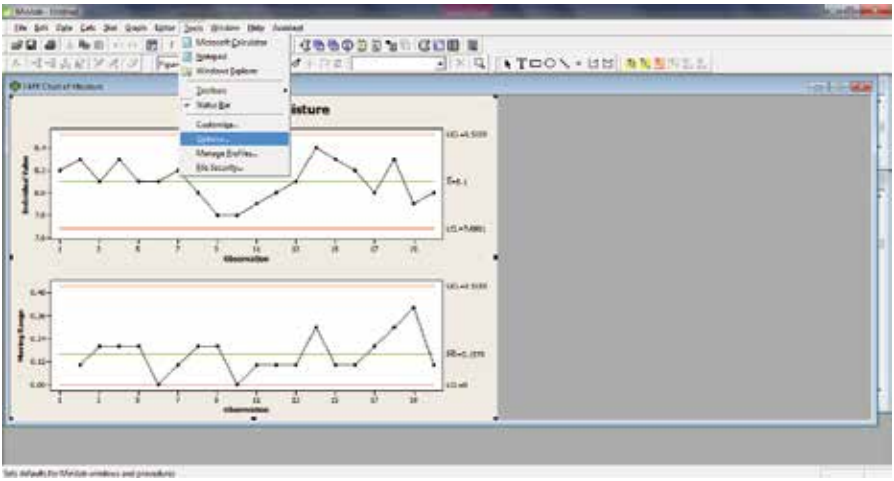


4. Click on “Moisture” > and the “Select Button” to add this variable to the one that you would like control charted > click “OK”

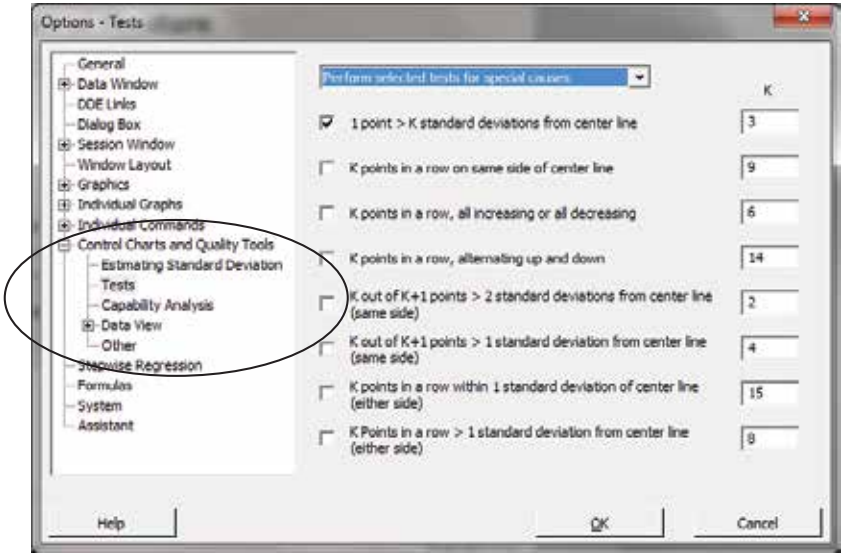
You will get the following *"Individuals and Moving Range Charts"* from Minitab



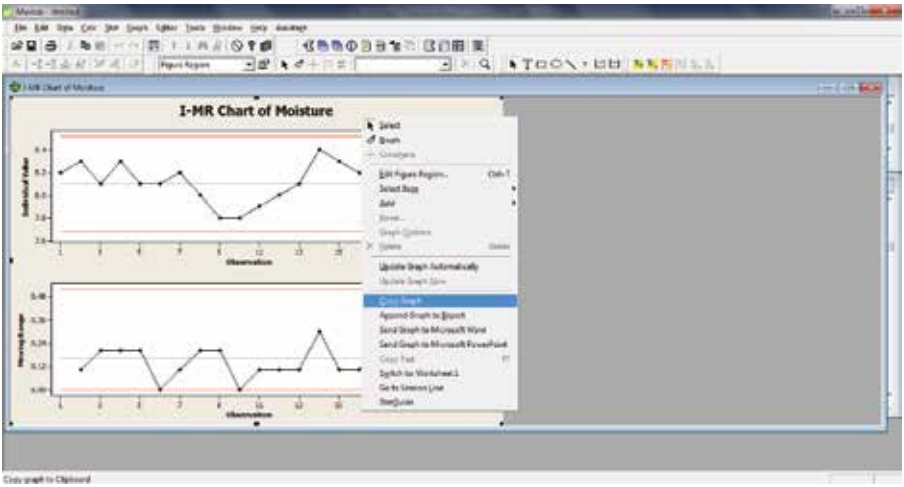
<u>Note</u>: to access the "Options" features of the control charts, click on >"Tools" in the main menu bar > you will get the "Options – General" windows to pop up



Expand the “Control Charts and Quality Tools” > Click on “Tests”



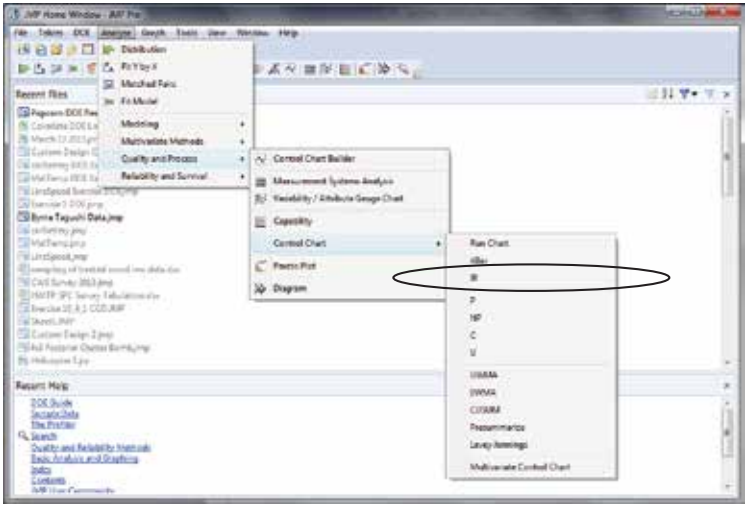
To copy paste your graph into Microsoft “Word” or Apple “Pages” editors > right click on the control chart image > Copy Graph > go to Word or Pages and > go “Edit Paste” or “Ctrl-V” and it will paste graph in document file



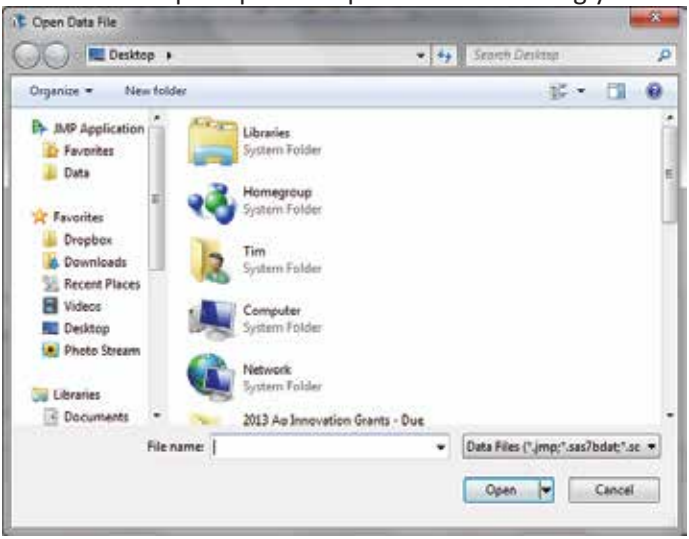
Developing a Control Chart in JMP 14

1. Start JMP.
2. Click > “Analyze” > “Quality and Process” >”Control Chart”

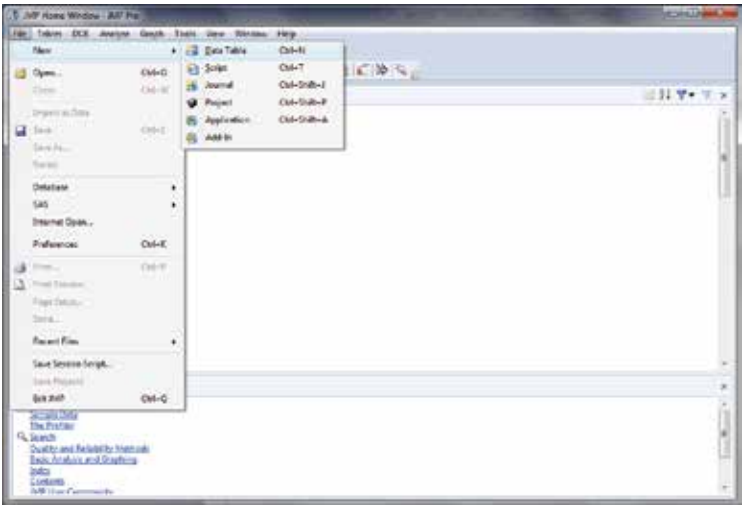
3. Select type of control chart; for the sake of example, we will select “IR” chart in JMP which is the “X-Individual and Moving Range Chart”



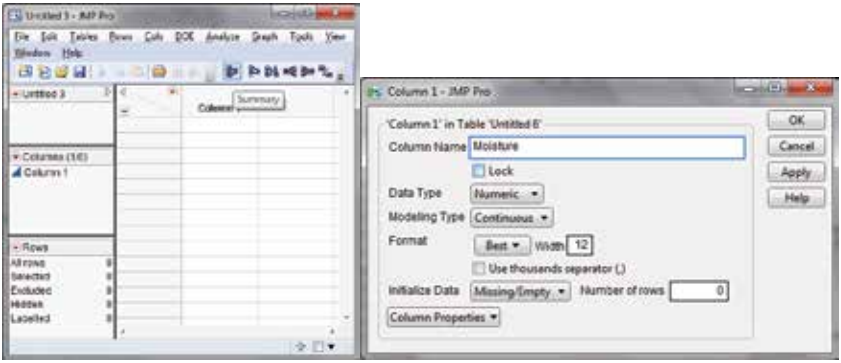
4. You will be prompted to open a file containing your data

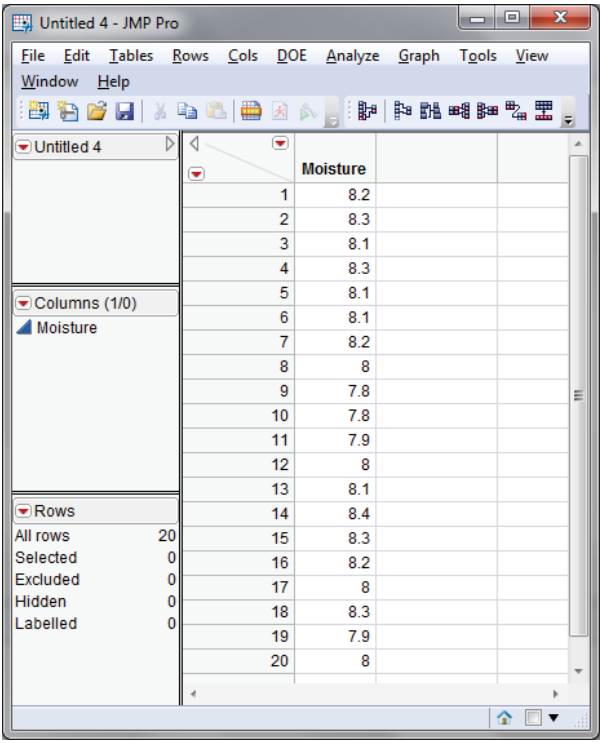


5. For example we will directly enter data from an example. Go to JMP Home Window > Click > “File” > “New” > “Data Table”

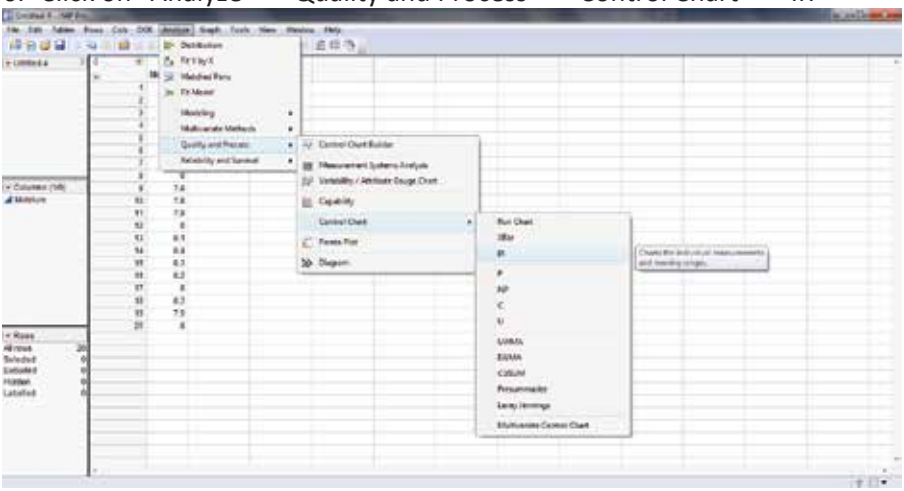


Type in Your Data in Column 1 (Note: you can double-click on column header and you will get the “column properties window” > change column name to “*Moisture*”



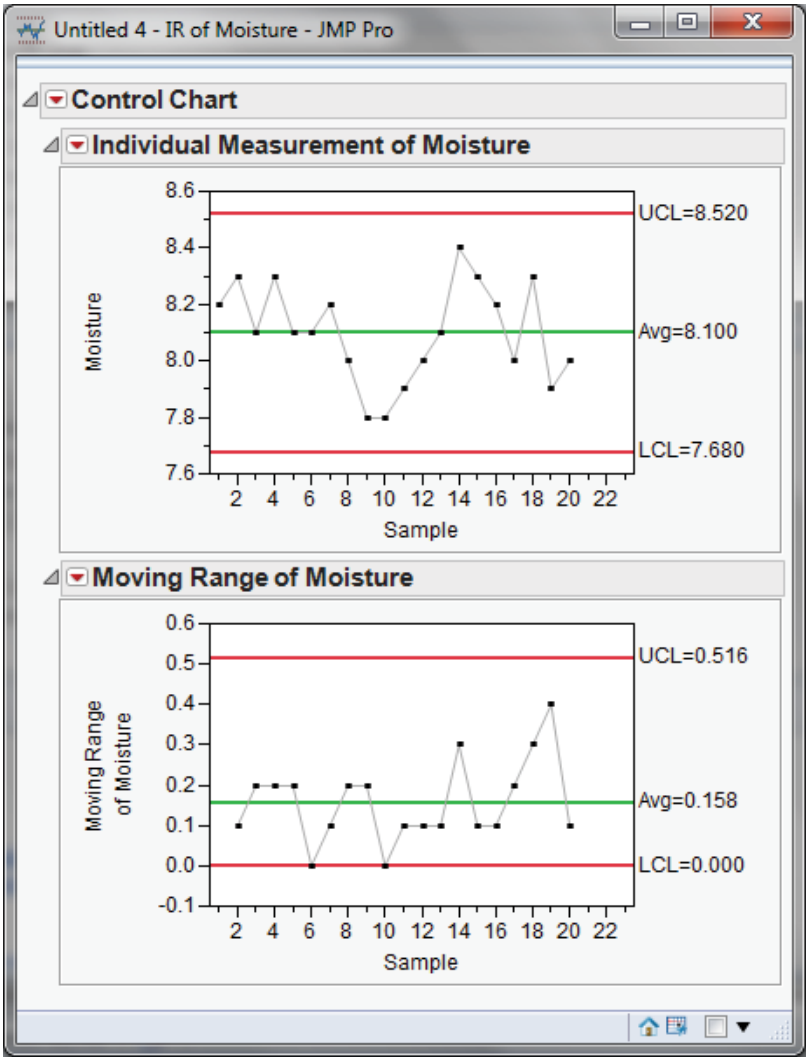


6. Click on “Analyze” > “Quality and Process” > “Control Chart” > “IR”

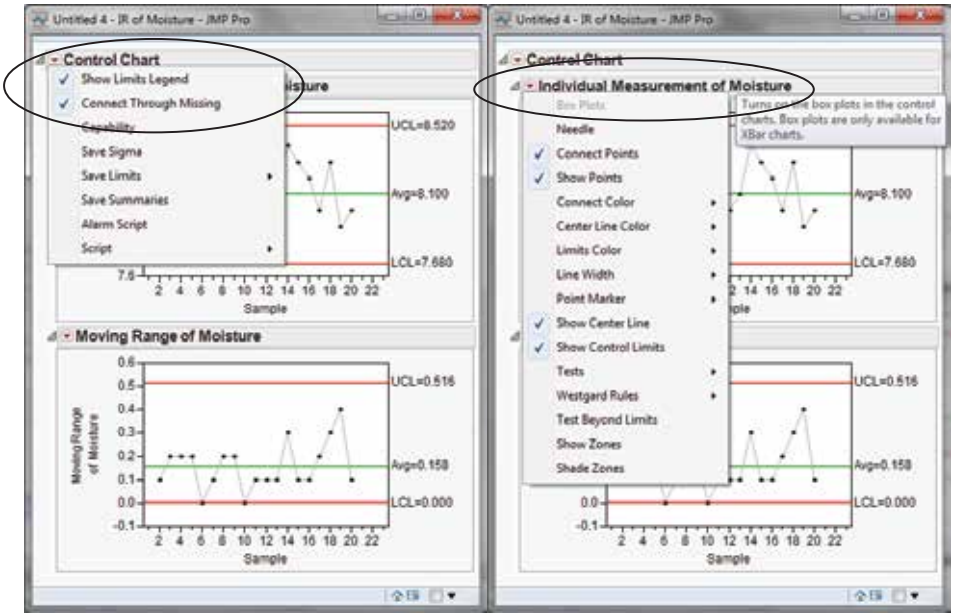


7. Click > “Moisture” > click on “Process Button” > “Moisture” will be added as the variable to be control charted > click “OK”

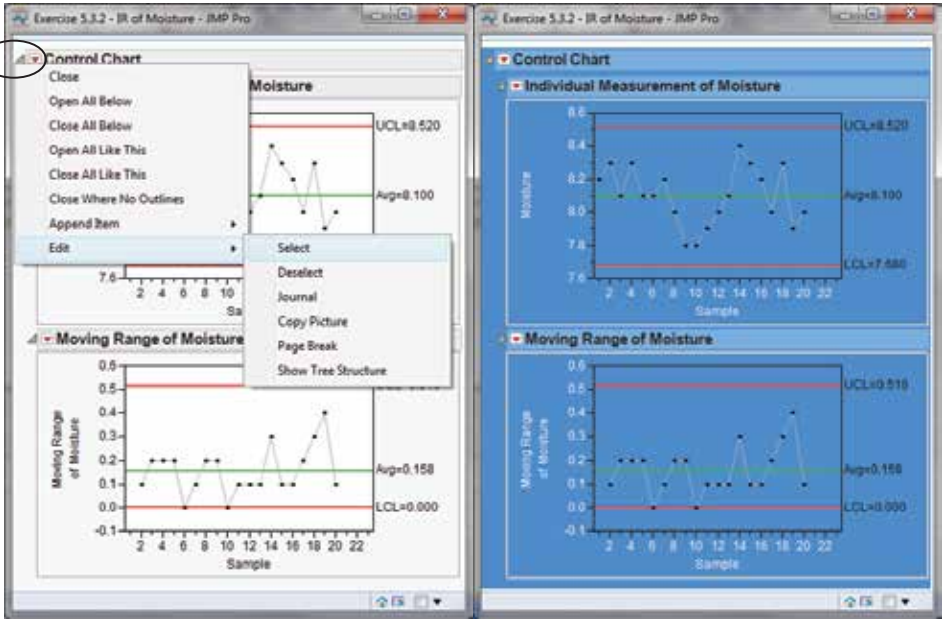
You will get the following X-Individual and moving Range Control Charts in JMP (next page)

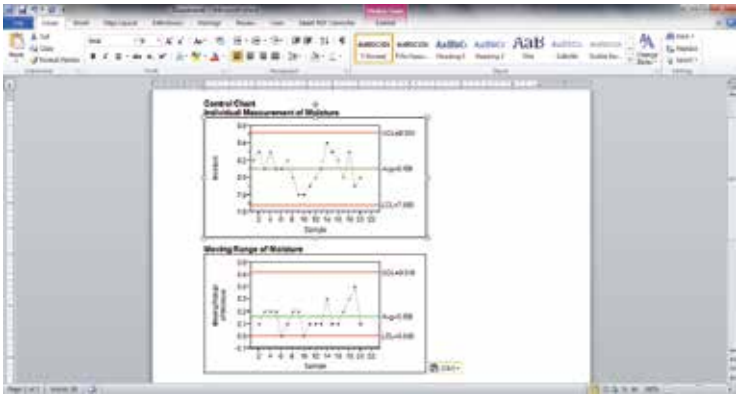

Untitled 4 - IR of Moisture - JMP Pro
Control Chart
Individual Measurement of Moisture
Moisture
8.6
8.4
8.2
8.0
7.8
7.6
UCL=8.520
Avg=8.100
LCL=7.680
2 4 6 8 10 12 14 16 18 20 22
Sample
Moving Range of Moisture
Moving Range of Moisture
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
UCL=0.516
Avg=0.158
LCL=0.000
2 4 6 8 10 12 14 16 18 20 22
Sample

Many statistical-feature options are available to you in JMP under the “red arrow pulldown” for the “Control Chart” and many charting display features are available to you under the “Individual Measurement of Moisture”



To copy paste your graph into Microsoft “Word” or Apple “Pages” editors > right click on “green right triangle” > “Edit” > “Select” > the graphs will turn blue > hold down “Ctrl-C” from your keyboard > go to your Word document > right click “edit-paste” or “Ctrl-V” and it will paste graph in document file


Exercise 5.3.2 - IR of Moisture - JMP Pro
Control Chart
Close
Open All Below
Close All Below
Open All Like This
Close All Like This
Close Where No Outlines
Append Item
Edit
Select
Deselect
Journal
Copy Picture
Page Break
Show Tree Structure
Moisture
UCL=8.520
Avg=8.100
Moving Range of Moisture
Moving Range of Moisture
Avg=0.158
LCL=0.000
Sample
Exercise 5.3.2 - IR of Moisture - JMP Pro
Control Chart
Individual Measurement of Moisture
Moisture
UCL=8.520
Avg=8.100
LCL=7.680
Sample
Moving Range of Moisture
Moving Range of Moisture
UCL=0.518
Avg=0.158
LCL=0.000
Sample



APPENDIX B – Capability Indices

Indices or Assessing Short-Term Capability

1. C_p Index

$$C_p = \frac{USL - LSL}{6 \times (\overline{R}/d_2)}$$

Recall Control Charting use of $\overline{R}/d_2$

$\overline{R}/d_2$ is an unbiased estimator of σ for small samples sizes, *i.e.,* $\bar{R}/d_2 \approx s$

Subgroup size	d_2
2	1.128
3	1.693
4	2.059
5	2.326
6	2.534
7	2.704
8	2.847
9	2.970
10	3.078

2. C_{pk} Index

$$C_{pk} = \min\left[\frac{\overline{X} - LSL}{3 \times (\overline{R}/d_2)}, \frac{USL - \overline{X}}{3 \times (\overline{R}/d_2)}\right]$$

If the actual average is equal to the midpoint or target of the specification range then $C_p = C_{pk}$

3. C_{pm} Index ("Taguchi Index")

$$C_{pm} = \frac{USL - LSL}{6\sqrt{(\bar{X} - T)^2 + (\bar{R}/d_2)^2}}$$

where, T = target, $\bar{X}$ = process average, $\bar{R}/d_2$= process variance

The relationship of C_{pm} centers around Taguchi's championed approach of reducing variation from the target value as the guiding principle to quality improvement

Indices for Assessing Long-Term Capability

4. *Process Performance Indices – (P_p)*

$$P_p = \frac{USL - LSL}{6 \times s} = \frac{ET}{NT}$$

(Uses standard deviation to estimate long-term variation)

$$s = \sqrt{\frac{\sum_{i=0}^{n}(x_i - \bar{x})^2}{n-1}}$$

(Only valid for large *n* ~ *n* > 100)

P_p	Total product outside two-sided specification limits
0.5	13.36%
0.67	4.55%
1.00	0.3%
1.33	64 ppm
1.63	1 ppm
2.00	0

5. *P_{pk} Index*

$$P_{pk} = minimum\left[\frac{\bar{X} - LSL}{3 \times s}, \frac{USL - \bar{X}}{3 \times s}\right]$$

If the actual average is equal to the midpoint or target of the specification range then $P_p = P_{pk}$

6. *P_{pm} Index ("Taguchi Index")*

$$P_{pm} = \frac{USL - LSL}{6 \times \sqrt{(\bar{X} - T)^2 + s^2}}$$

where, T = target, $\bar{X}$ = process average, s^2 = process variance

Example Capability Analysis

Given the following data of 18 samples of thickness, estimate the Process Performance and Capability Indices

Subgroup	Thickness
1	0.407
2	0.405
3	0.405
4	0.405
5	0.395
6	0.395
7	0.402
8	0.396
9	0.393
10	0.397
11	0.399
12	0.395
13	0.400
14	0.404
15	0.404
16	0.408
17	0.407
18	0.400

$\bar{x}$= .401 s= .0049 $\overline{mR}$= .0035

USL: 0.405" LSL: 0.395" Target: 0.400"

See Calculations on next page

Note: there is not enough data in this example for a long-term capability analysis, calculations are just for illustrative purposes

$$C_p = \frac{USL - LSL}{6 \times (\bar{R}/d_2)} = \frac{.405 - .395}{6 \times (.0035/1.128)} = \frac{.010}{.01862} = 0.537$$

$$C_{pk} = min\left[\frac{[\bar{X} - LSL]}{3 \times (\bar{R}/d_2)}, \frac{[USL - \overline{X}]}{3 \times (\bar{R}/d_2)}\right]$$

$$= min\left[\frac{[.401 - .395]}{3 \times (\frac{.0035}{1.128})}, \frac{[.405 - .401}{3 \times \left(\frac{.0035}{1.128}\right)}\right]$$

$$= min[0.645, 0.430] = 0.430$$

(If interest is only on the lower specification, then C_{pk}=C_{pl}=0.645.)

$$C_{pm} = \frac{.405 - .395}{\left(6 \times \sqrt{(.401 - .400)^2 + (\frac{.0035}{1.128})^2}\right)} = 0.511$$

$$P_p = \frac{USL - LSL}{6 \times s} = \frac{.405 - .395}{6 \times (.0049)} = \frac{.010}{.029} = 0.34$$

$$P_{pk} = min\left[\frac{[\bar{X} - LSL]}{3 \times (s)}, \frac{[USL - \overline{X}]}{3 \times (s)}\right]$$

$$= min\left[\frac{[.401 - .395]}{3 \times (.0049)}, \frac{[.405 - .401}{3 \times (.0049)}\right]$$

$$= min[0.408, 0.272] = 0.272$$

$$P_{pm} = \frac{.405 - .395}{\left(6 \times \sqrt{(.401 - .400)^2 + (.0049)^2}\right)} = \frac{.010}{.030} = 0.333$$

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