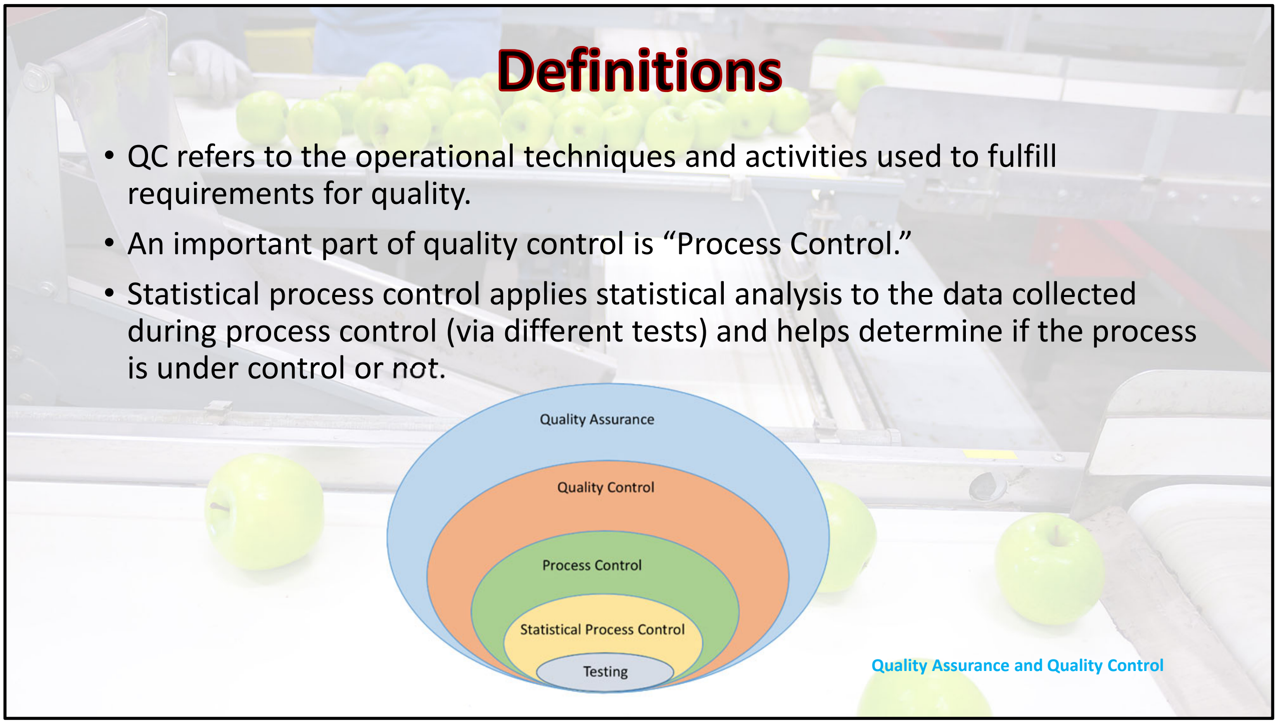
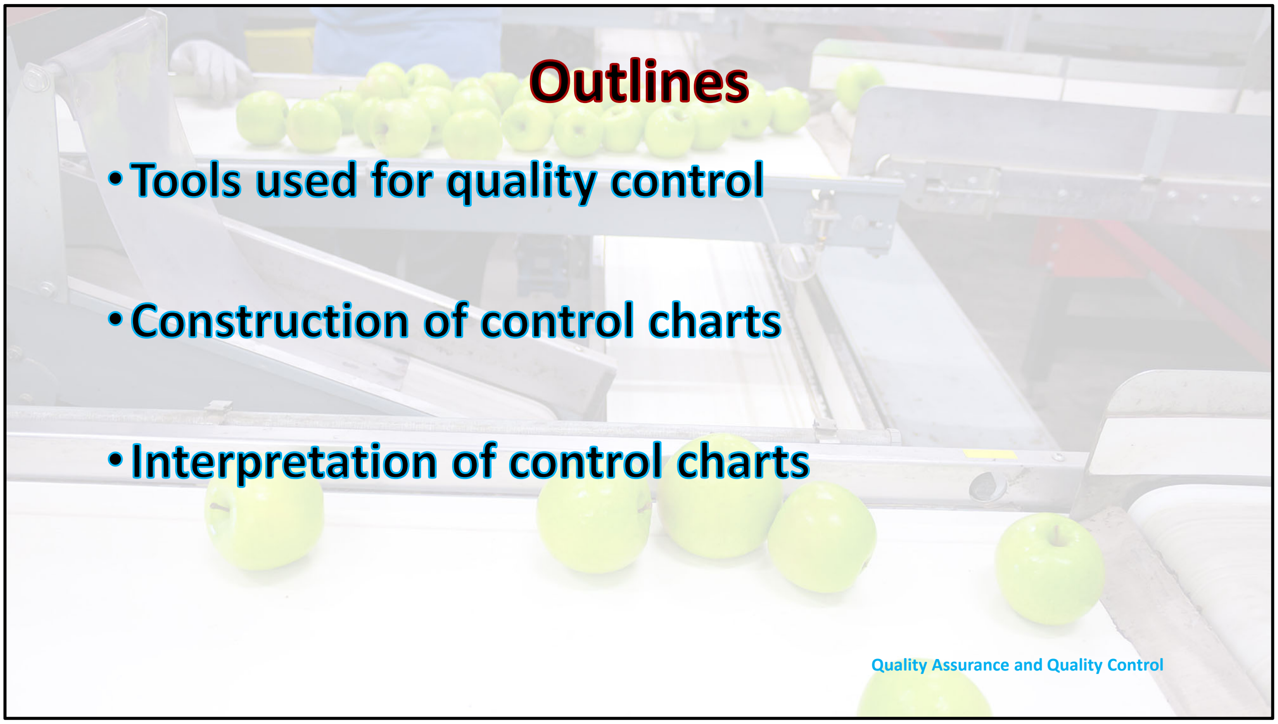

Tools for Quality Control and Control Charts

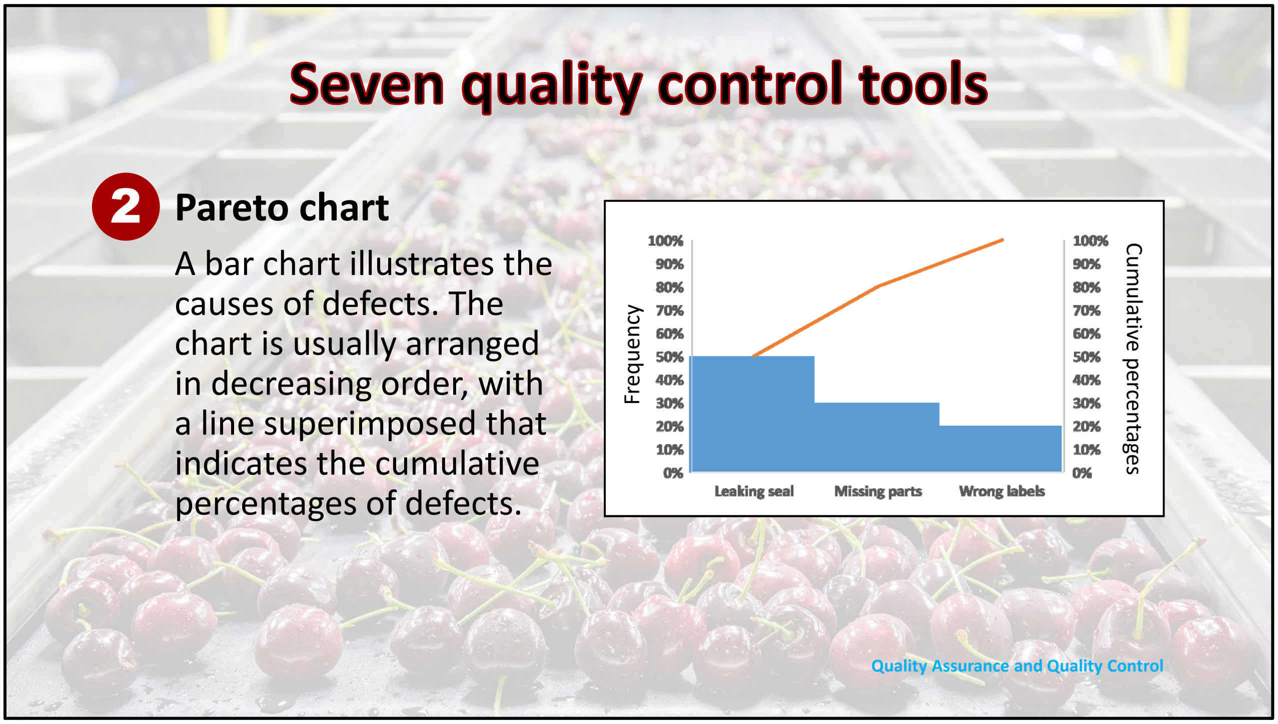


Before I start talking about control charts and tools for quality control, I would like to quickly review a figure that is shown on this slide, along with some terminology discussed in an earlier webinar named "Overview of Quality Assurance." To get back to our review, quality assurance is a system that ensures the quality of our products. One dimension of quality is conformance. Conforming to different food safety standards is part of product quality. QA puts a lot of emphasis on management and management strategies. In contrast to QA, QC refers to the operational techniques and activities used to fulfill the requirement for quality. An important part of quality control is "process control." At different processing points, quality data can be collected by conducting various tests, such as microbial analyses, chemical testing, and sensory evaluation. These data allows us to conduct statistical analysis, also called statistical process control, to determine if the process and quality is under control.

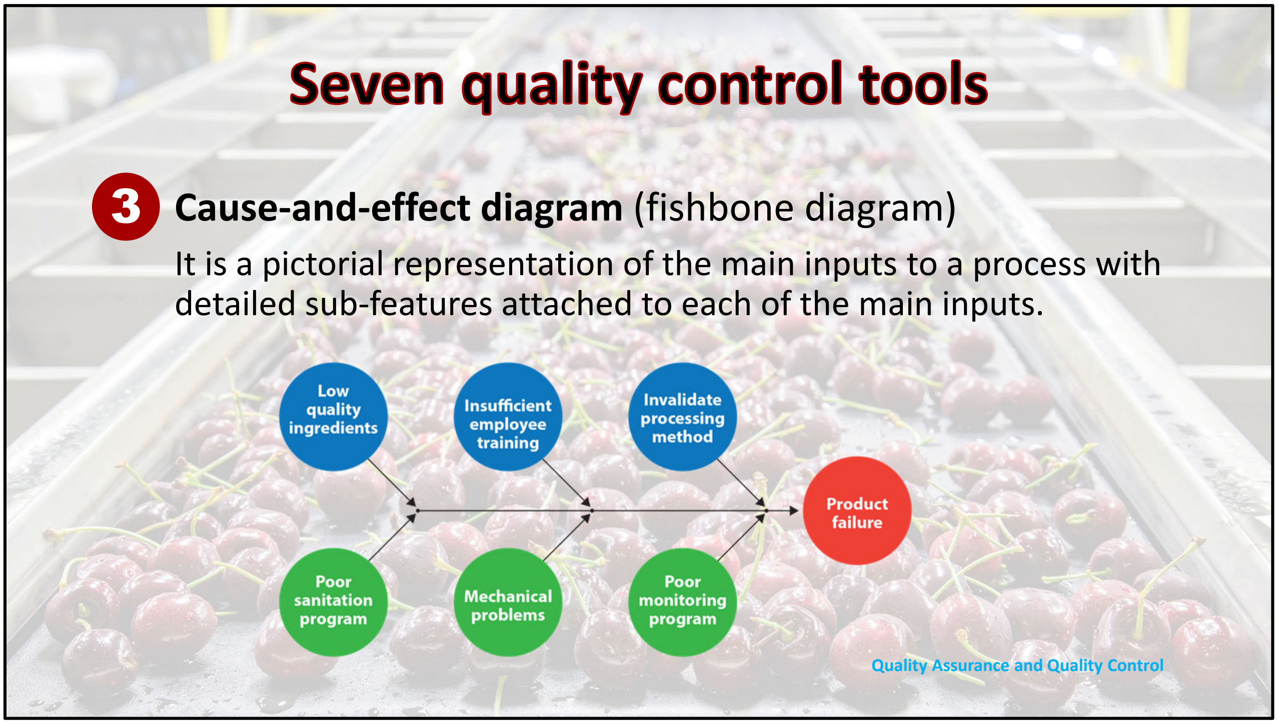


In this lecture, we will focus on quality control. I will start with introducing seven major quality control tools, followed by discussing some common ways of constructing control charts. In the end, I will talk about how to interpret and use control charts.

The first quality control tool is "check sheet," which is very easy to use and is a direct way to show how often specific problems/defects occur in your processing line. As shown on your right-hand side, you can use a check sheet for counting and calculating different product defects. This is an example of a cookie assembly line. The checklist lists two major defects, broken cookies and missing fillings. Each day, the number of every defect is recorded. At the end of each week, the total number of defects can be calculated for the entire week for each type of defect. Or, the total defect for every day can be seen as well.



The second tool is called a pareto chart. It is a bar chart that illustrates percentages of various defects. There are two components on this chart, as shown on your right-hand side. The height of the bar represents the frequency of each defect. The orange line on top represents the cumulative percentages. The final total of defects equals 100%. Taking the figure on this slide as an example, the leaking seal is the No.1 defect, accounting for 50% of total defects observed. Missing parts and wrong labels are No. 2 and No. 3.



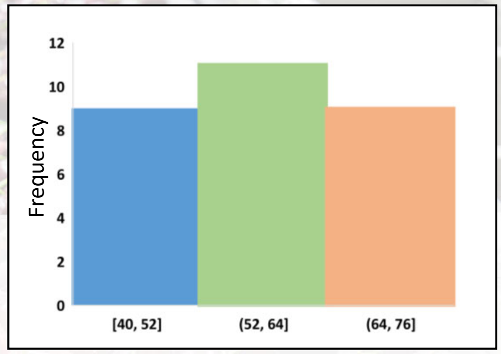
The third quality control tool is called the “cause-and-effect diagram” or fishbone diagram. The idea is to identify all possible reasons that could account for a final product failure. It provides a pictorial representation of the main inputs/causes. A fishbone diagram is typically used when a product failure has been identified and potential causes of the failure need to be identified. For this particular example, all six factors (from low quality ingredients to a poor sanitation program) can contribute to the product failure.

Seven quality control tools

4 Histogram

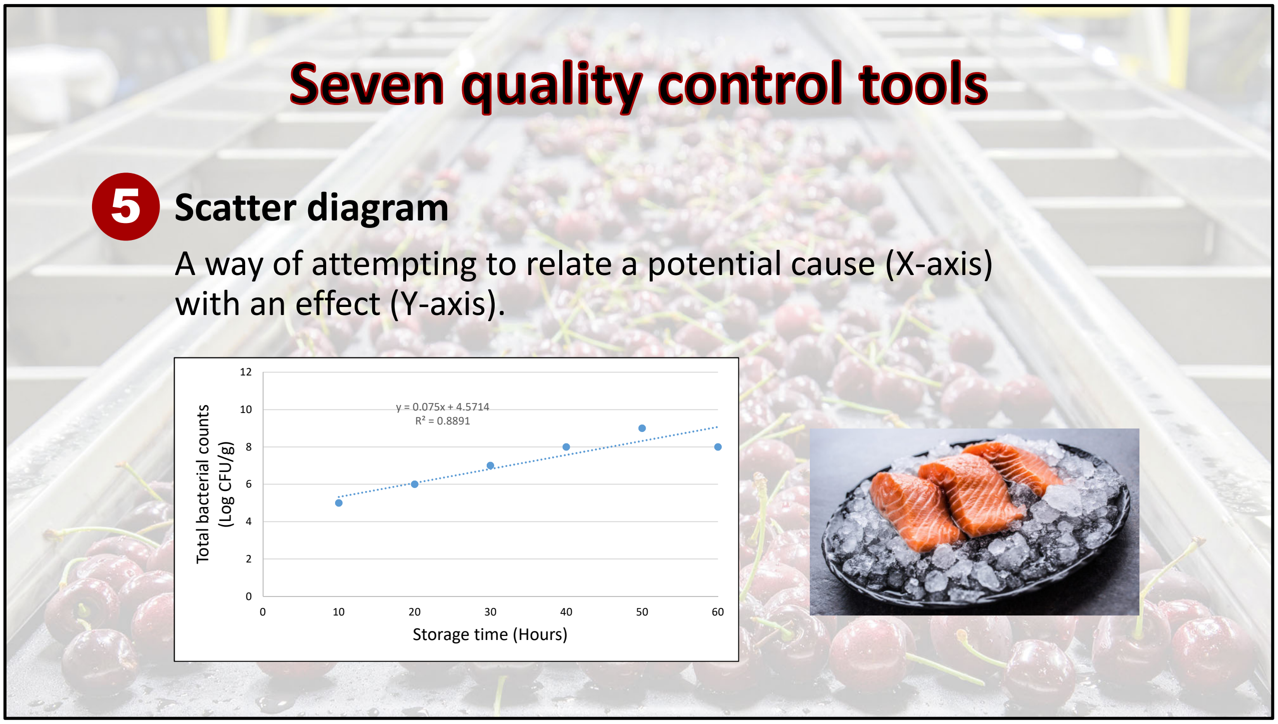
It is a diagram showing the frequency distributions of a set of data observed in a process.

Total of 28 measurements (size of plums)
Small (40-52 mm) 9
Medium (52-64 mm) 11
Large (64-76 mm) 8



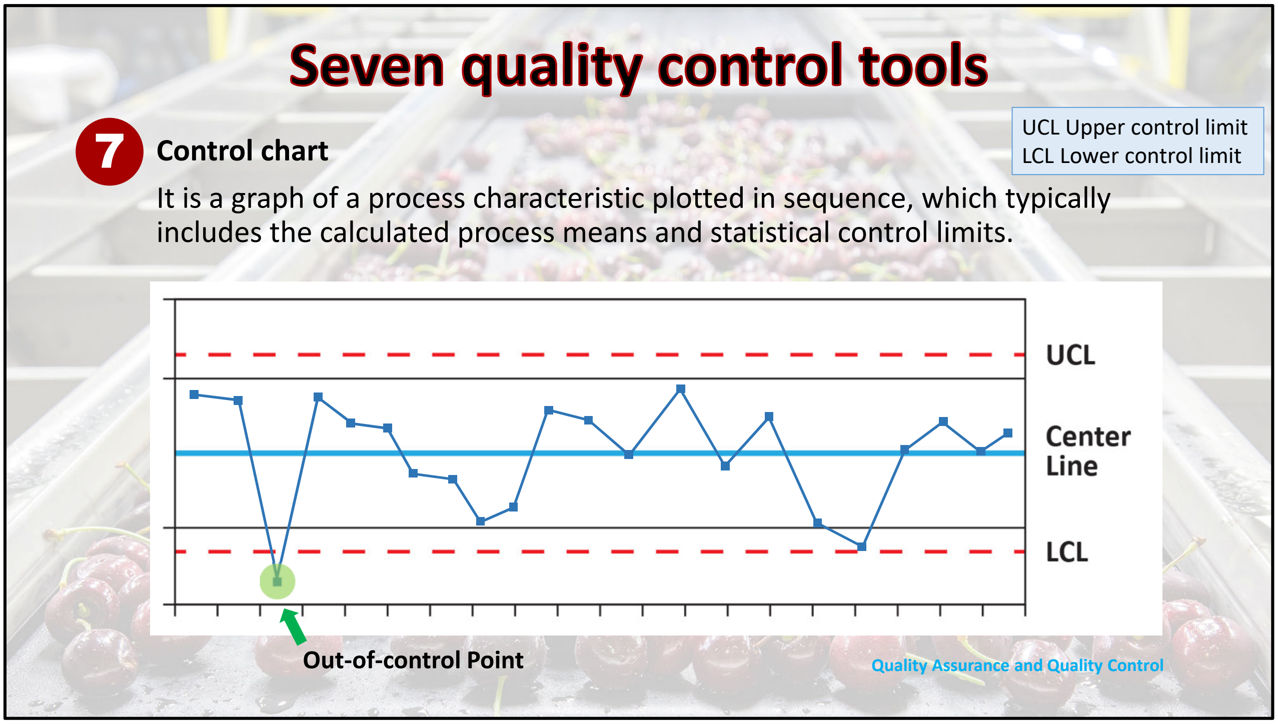
Quality Assurance and Quality Control

A histogram is the fourth quality control tool. It is a diagram showing the frequency distributions of a set of data. This example shows a total of 28 measurements. These measurements were taken for plums that were received at a parking house. Among the 28 randomly selected samples, 9 fell into the range of 40-52 mm, 11 fell into the range between 52-64 mm, and 8 fell into the range between 64-76 mm. If we define the ones above 64 mm as large, the ones between 52 to 64 mm as medium, and the ones less than 52 mm as small, we have an idea about how many large products we will have for this shipment of plums.

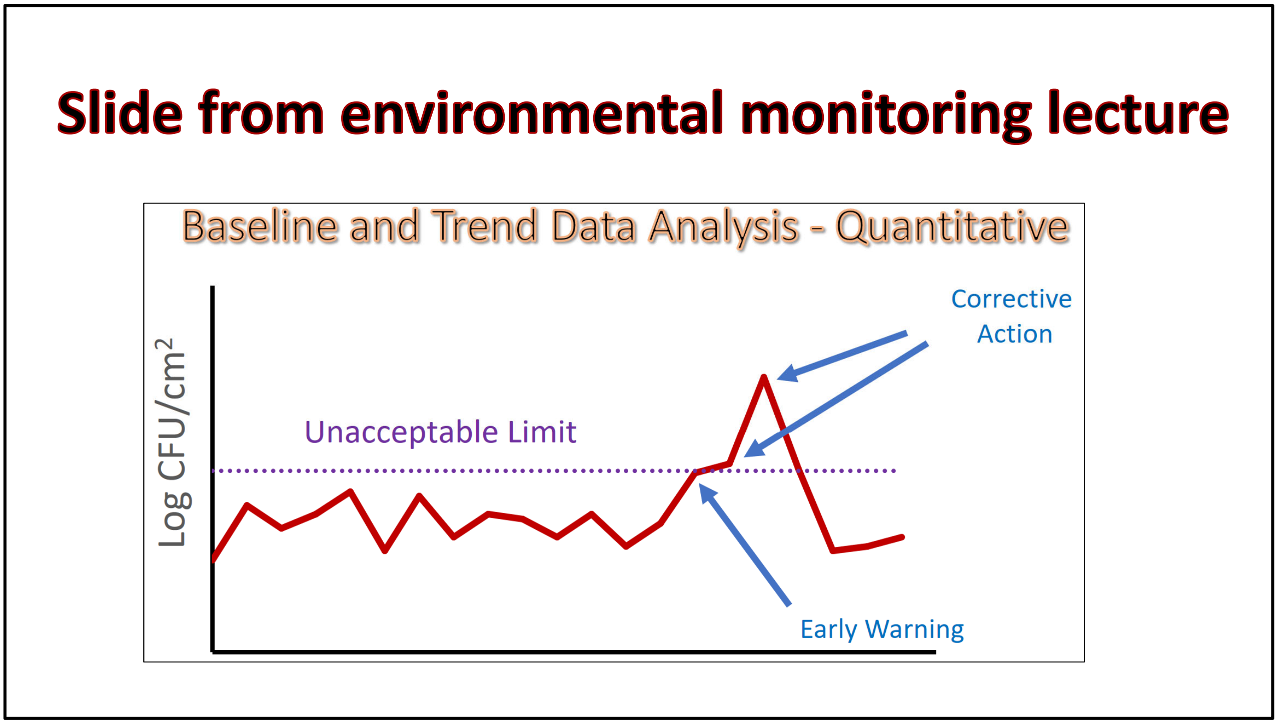


The fifth quality control tool is a scatter diagram. It is a way to present data and identify potential correlations between the causes and effects. The example given here shows the correlation between the total bacterial counts of a raw salmon product and storage time. As the storage time increases, the total bacterial counts increase. The regression line indicates quite strong correlations between the two.

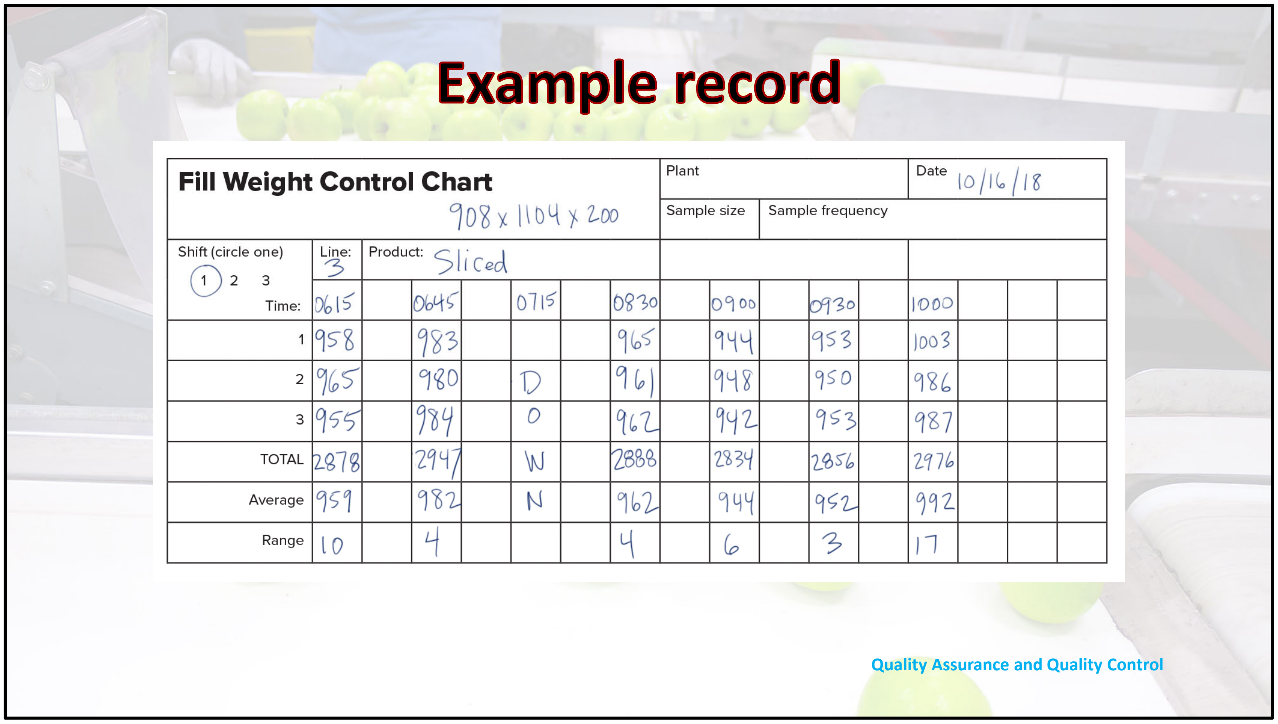
A flowchart is also a quality control tool. It is a direct pictorial representation of the order of processing procedures. Symbols or boxes with words can be used for establishing a flowchart. A flowchart is used as the first step for establishing a food safety plan or HACCP. A flowchart allows us to go over the entire process and identify steps at which control measures can be implemented and verified.



A control chart is also a type of quality control tool. A graph of a process characteristic plotted in sequence, a control chart can be built manually by inputting data in programs such as Excel or generated by monitoring systems installed within the processing machine. One example is the smart-wash system for injecting chlorine into wash water for fresh produce. The monitoring system can check the pH and free chlorine levels in the system in a timely fashion. A typical control chart contains four major lines. The UCL is the upper control limit, and the LCL is the lower control limit. The center line typically represents the population mean, and the fourth line represents the individual measurements. That's the line going up and down. By plotting all measurements into the figure, we can easily identify the "out of control" point.



If you recall, this is a slide from Dr. Linda Harris' environmental monitoring lecture. Based on this figure, we can find the early warning and also times at which corrective actions need to take place. In this figure, the unacceptable limit can be your upper control limit. In some cases, this can also be your lower control limit (LCL). When your measurement is above the upper control limit or below your lower control limit, corrective actions are needed. If the control limits are built based on your operational limits, then corrective actions may not needed but actions are needed to identify the causes of this out-of-control point. As one can see from this figure, control charts are important monitoring tools to have in order to ensure the quality control programs work. In the second part of this talk, we will go through some examples of control charts.



Example record

Fill Weight Control Chart 908 x 1104 x 200

Plant | Date 10/16/18

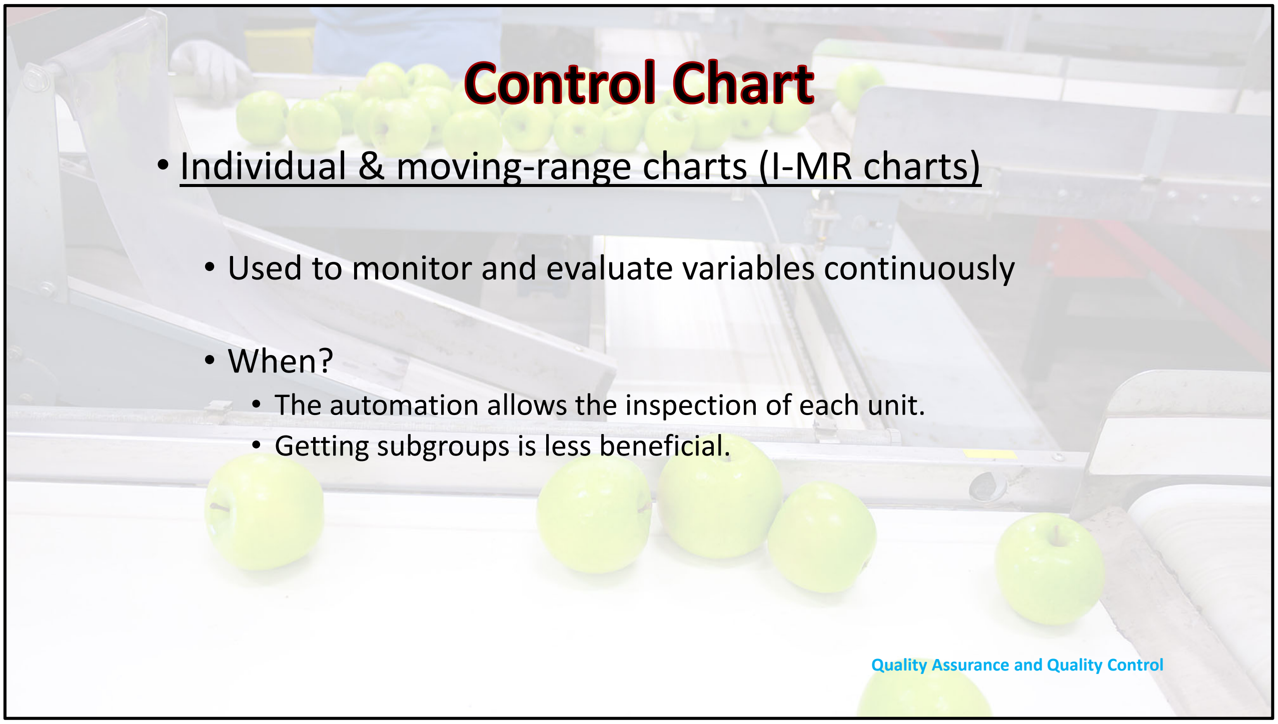
Sample size | Sample frequency

Shift (circle one) (1) 2 3 | Line: 3 | Product: Sliced

Time:	0615		0645		0715		0830		0900		0930		1000			
1	958		983				965		944		953		1003			
2	965		980		D		961		948		950		986			
3	955		984		O		962		942		953		987			
TOTAL	2878		2947		W		2888		2834		2856		2976			
Average	959		982		N		962		944		952		992			
Range	10		4				4		6		3		17			

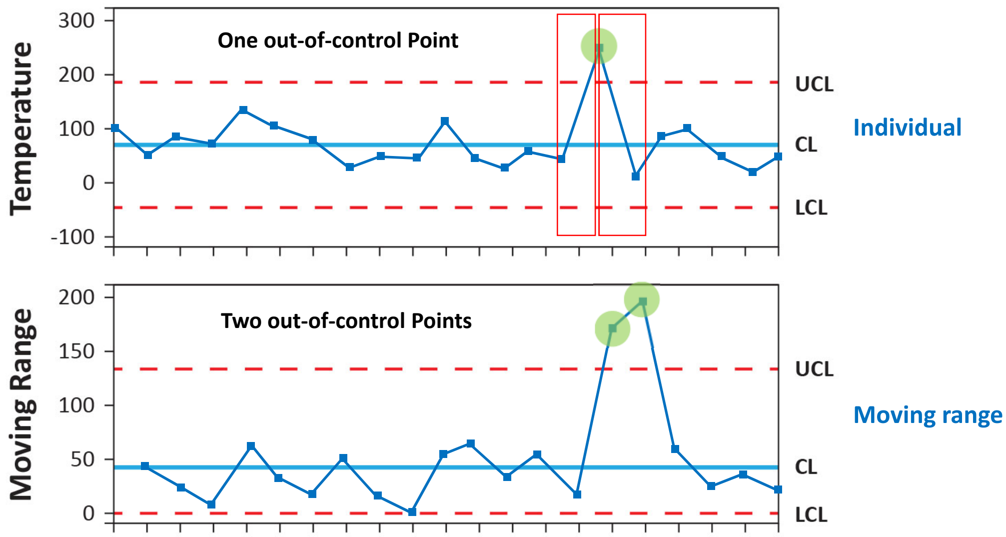
Quality Assurance and Quality Control

What we have on the screen now is a quality check log from a tomato processing plant. On each production date, samples were taken at different time points to check if the filler was working properly or not. As you can see, at 6:15 AM, three samples were taken and weighed. They weighed 958, 965, and 955 grams. The total weight, average weight. and range were calculated. These numbers are the base for establishing control charts. However, taking subsamples or collecting multiple samples at each time point may not be feasible or needed for certain processing lines. The first set of control charts I would like to talk about is named “Individual and moving range charts”.



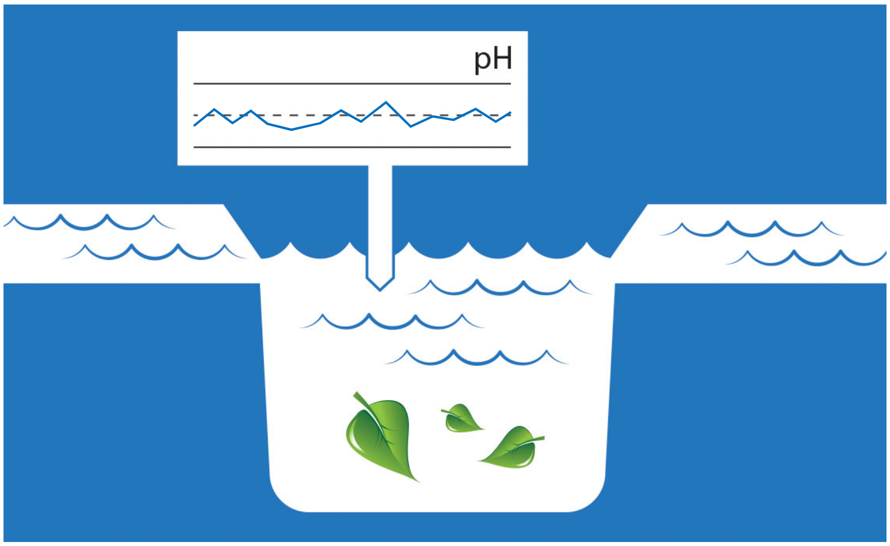
Control charts are typically built and used in pairs, with the first one representing the individual measurements and the second one used for expressing the changes between measurements. For the individual and moving-range charts, you can get the idea from the names. While the individual chart is for each measurement and the moving range chart is for monitoring the changes from one measurement to the next. This set of control charts is used when measurements can be taken continuously and taking subgroups is not feasible or is less beneficial.

Individual and Moving Range Charts



Using an individual chart and a moving range chart together can provide different information. For example, the top individual chart indicates that one point was out of control. However, when looking at the moving range chart, we see that two values are out of control. The period between the out-of-control point and its previous measurement and the period between the out-of-control point and its following measurement should both be checked because they potentially could have caused product failure.

pH Monitoring

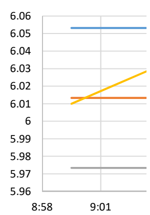


One typical example for individual and moving range charts is the pH monitoring system in wash tanks.

Control Chart

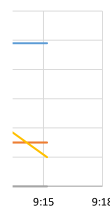
- Individual & moving-range charts (I-MR charts)

pH	9:00 AM	9:02 AM	9:04 AM	9:06 AM	9:08 AM	9:10 AM	9:12 AM	9:14 AM	9:16 AM
Individual	6.01	6.02	6.03	6.01	6.00	6.02	6.00	6.02	6.01
MR		0.01	0.01	-0.02	-0.01	0.02	-0.02	0.02	-0.01

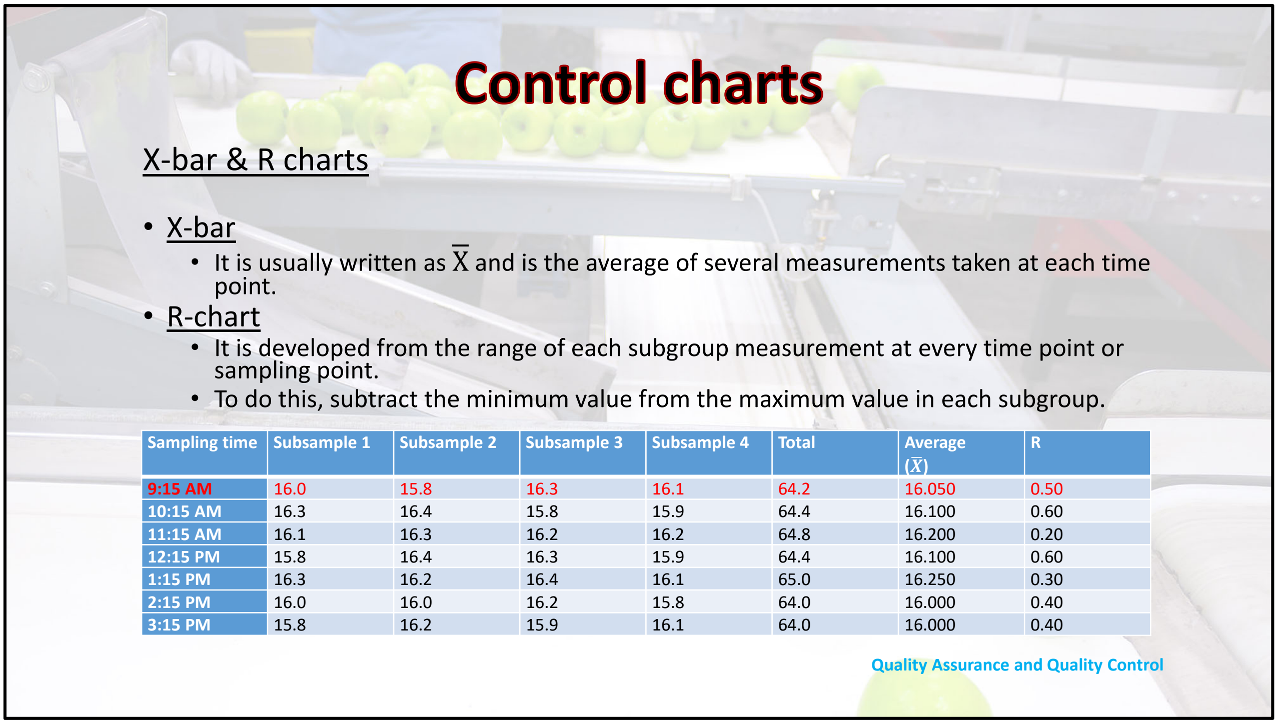


- **I-chart calculation**
- $MR_i = |x_i - x_{i-1}|$
- $\overline{MR} = MR_i$/i-1
- $UCL = \overline{x} + 2.66 * \overline{MR}$
- $Center\ line = \overline{x}$
- LCL= $\overline{x} - 2.66 * \overline{MR}$

- **MR-chart calculation**
- $MR_i = |x_i - x_{i-1}|$
- $UCL = D_4\overline{MR}$
- $Center\ line = \overline{MR}$
- LCL= $D_3\overline{MR}$



The table shows the measurements taken every two minutes continuously in a wash tank, and moving range is calculated between every two numbers. Once these values are calculated, equations listed here are used for calculating the UCL and LCL values for each chart. The D4 and D3 values are constant values that can be identified based on the degree of freedom. For the moving range chart, the degree of freedom is 2.



Control charts

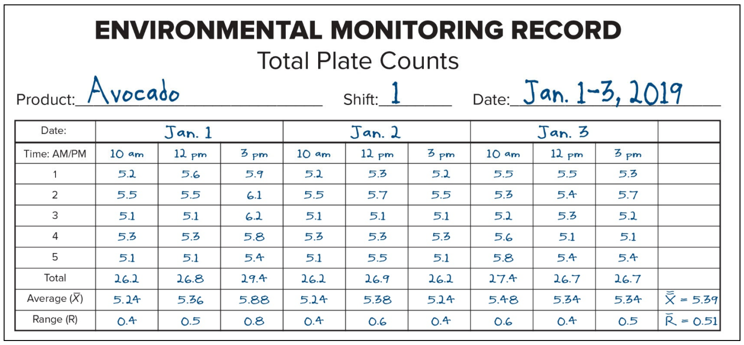
X-bar & R charts

- X-bar
  - It is usually written as $\overline{X}$ and is the average of several measurements taken at each time point.
- R-chart
  - It is developed from the range of each subgroup measurement at every time point or sampling point.
  - To do this, subtract the minimum value from the maximum value in each subgroup.

Sampling time	Subsample 1	Subsample 2	Subsample 3	Subsample 4	Total	Average ($\bar{X}$)	R
9:15 AM	16.0	15.8	16.3	16.1	64.2	16.050	0.50
10:15 AM	16.3	16.4	15.8	15.9	64.4	16.100	0.60
11:15 AM	16.1	16.3	16.2	16.2	64.8	16.200	0.20
12:15 PM	15.8	16.4	16.3	15.9	64.4	16.100	0.60
1:15 PM	16.3	16.2	16.4	16.1	65.0	16.250	0.30
2:15 PM	16.0	16.0	16.2	15.8	64.0	16.000	0.40
3:15 PM	15.8	16.2	15.9	16.1	64.0	16.000	0.40

Quality Assurance and Quality Control

The second set of charts combines an X-bar chart and an R chart. They are used for scenarios where subsamples are taken, like the tomato processing plant example we discussed earlier. The X-bar represents the average of all measurements taken at each time point. R represents the range of the measurements taken at each time point. For example, at 9:15 AM, four samples were taken and measured. The weights ranged from 15.8 to 16.3. Thus, the X bar is 16.05 and the R is 0.5. These calculated X-bar and R values are the basis for establishing the charts.



ENVIRONMENTAL MONITORING RECORD

Total Plate Counts

Product: Avocado Shift: 1 Date: Jan. 1-3, 2019

Date:	Jan. 1			Jan. 2			Jan. 3			
Time: AM/PM	10 am	12 pm	3 pm	10 am	12 pm	3 pm	10 am	12 pm	3 pm	
1	5.2	5.6	5.9	5.2	5.3	5.2	5.5	5.5	5.3	
2	5.5	5.5	6.1	5.5	5.7	5.5	5.3	5.4	5.7	
3	5.1	5.1	6.2	5.1	5.1	5.1	5.2	5.3	5.2	
4	5.3	5.3	5.8	5.3	5.3	5.3	5.6	5.1	5.1	
5	5.1	5.1	5.4	5.1	5.5	5.1	5.8	5.4	5.4	
Total	26.2	26.8	29.4	26.2	26.9	26.2	27.4	26.7	26.7	
Average ($\bar{X}$)	5.24	5.36	5.88	5.24	5.38	5.24	5.48	5.34	5.34	$\bar{\bar{X}} = 5.39$
Range (R)	0.4	0.5	0.8	0.4	0.6	0.4	0.6	0.4	0.5	$\bar{R} = 0.51$

Record from the lab notebook

Date:	Jan. 1			Jan. 2			Jan. 3			
Time	10 AM	12 PM	3 PM	10 AM	12 PM	3 PM	10 AM	12 PM	3 PM	
1	5.2	5.6	5.9	5.2	5.3	5.2	5.5	5.5	5.3	
2	5.5	5.5	6.1	5.5	5.7	5.5	5.3	5.4	5.7	
3	5.1	5.8	6.2	5.1	5.1	5.1	5.2	5.3	5.2	
4	5.3	5.3	5.8	5.3	5.3	5.3	5.6	5.1	5.1	
5	5.1	5.4	5.4	5.1	5.5	5.1	5.8	5.4	5.4	
Total	26.2	26.8	29.4	26.2	26.9	26.2	27.4	26.7	26.7	
Average ($\bar{X}$)	5.24	5.36	5.88	5.24	5.38	5.24	5.48	5.34	5.34	$\bar{\bar{X}} = 5.39$
Range (R)	0.4	0.5	0.8	0.4	0.6	0.4	0.6	0.4	0.5	$\bar{R}$ =0.51

Copy of the data in Excel

Here is one example for an X-bar and R chart. An extensive environmental monitoring program was implemented before the company started production. For this pilot trial, five swab samples were taken from five sampling spots at each time point, and the total aerobic plate counts were obtained by plating. The sampling was done at 10 AM, 12 PM, and 3 PM each day for three days. Taking 10 AM on day 1 as an example, the bacterial counts ranged from 5.1 to 5.5 Log CFU/swab. The average was 5.24 and the range was 0.4.

For X-bar chart:

UCL = $\overline{\overline{X}} + A_2\overline{R}$

CL= $\overline{\overline{X}}$

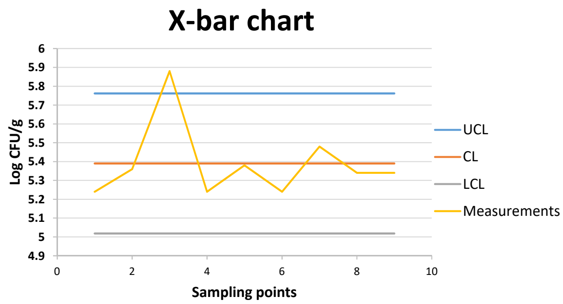
LCL=$\overline{\overline{X}} - A_2\overline{R}$

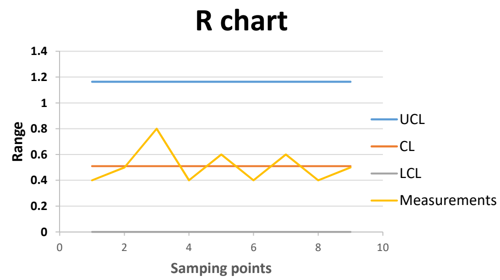
For R chart:

UCL = $D_4\overline{R}$

CL = $\overline{R}$

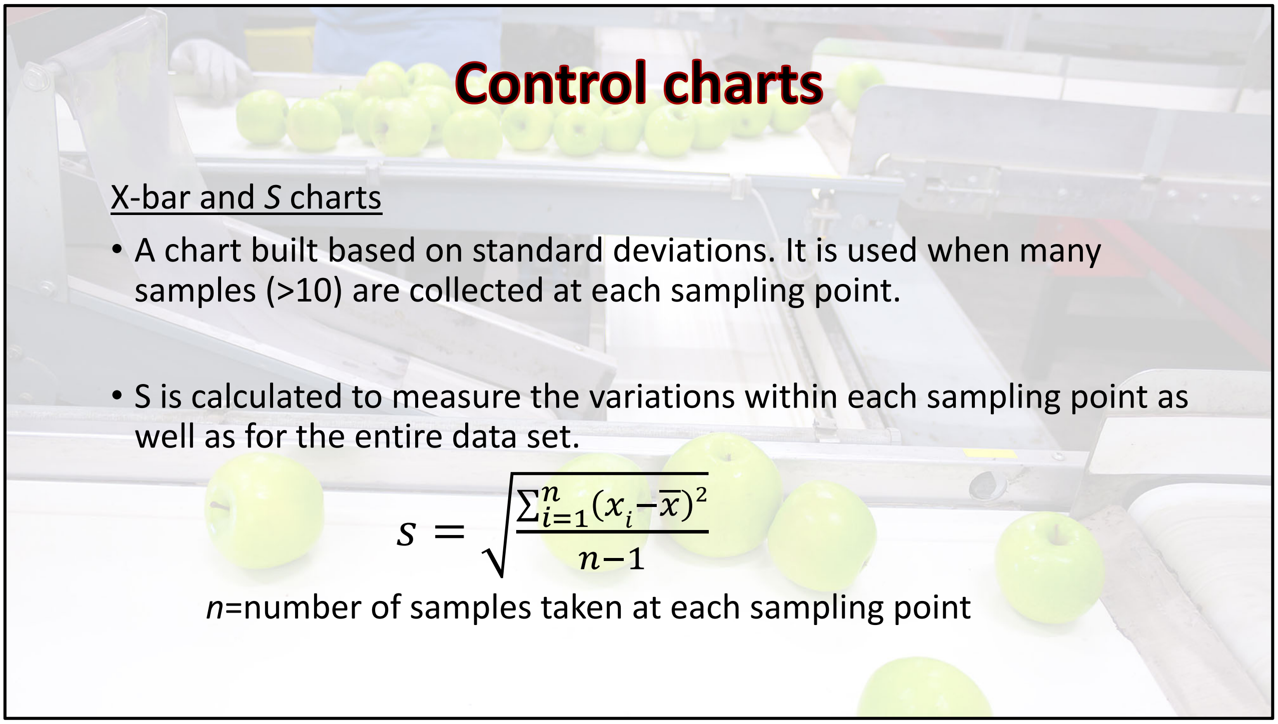
UCL = $D_3\overline{R}$



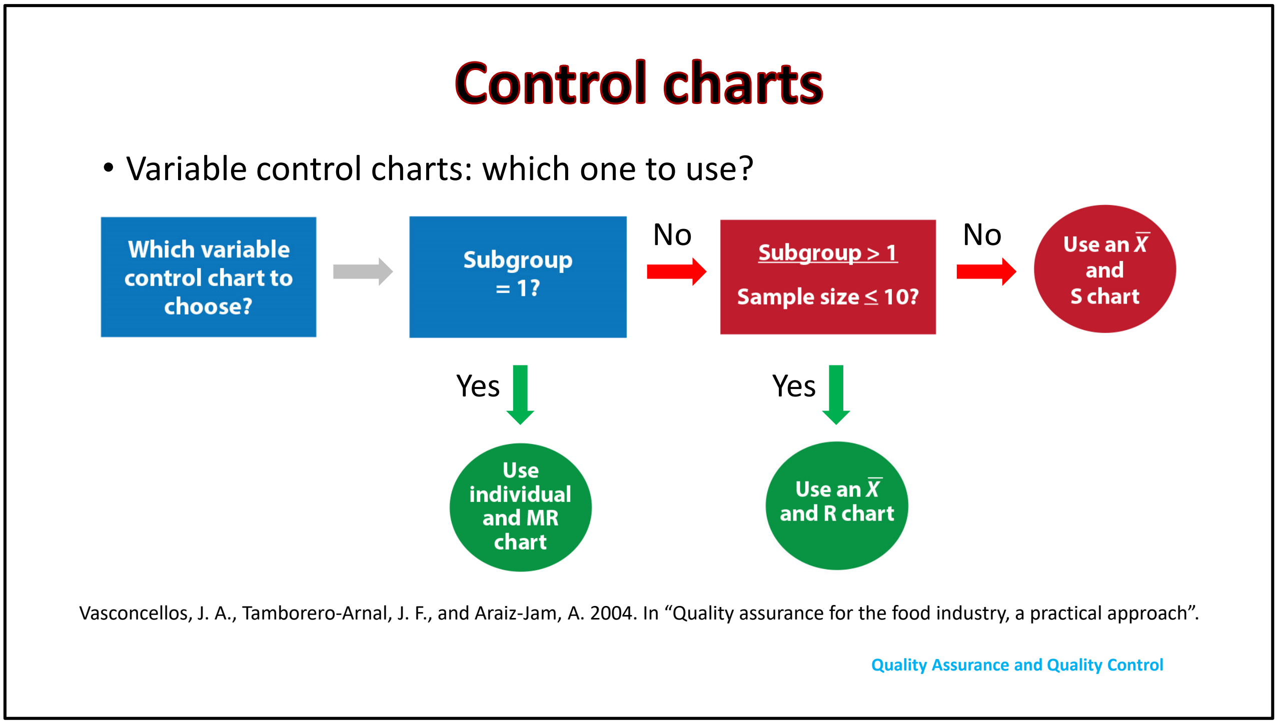


Similar equations are used for calculating the UCL, CL, and LCL values. The A2, D4, and D3 values are constant values determined by the degree of freedom. The degree of freedom for this example is 3. As four samples were taken, the degree of freedom is 4-1.

X bar is the average of all measurements. R bar is the average of all R values calculated at each time point.



When more than 10 measurements are taken at one time point, Range is no longer efficient to reflect the changes among measurements. In this case, standard deviation will be used to illustrate the variations. The equation used for calculating standard deviation is listed here, with X bar representing the average of all measurements taken at each time point, and Xi is the individual measurement taken at each time point. N is the number of measurements taken at each time point. Similar equations like shown on the previous slide will be used for building the control charts. With the degree of freedom determined by the number of subsamples taken at each time point and the R-range replaced with S standard deviation.



Here's a quick summary of the three sets of control charts. When measurements can be taken continuously, the set of individual and moving range charts is the best fit. This is also considered only one subgroup. When subsamples are taken at each sampling point and the number of samples taken at each time point is less than 10, the X bar and Range charts are a good fit. If more than 10 samples are taken at each time point, X bar and S charts are better to reflect the changes and variations.

Attribute charts

- Conforming or non-conforming products are counted rather than measured.
- Defective or nonconforming charts
  - *p*-chart
    - Shows the percentages of samples that are nonconforming or defective in a manufacturing process and determines if the process is under control or not
  - *np*-chart (or *m*-chart)
    - Number of nonconforming samples

	Total samples tested	*Listeria* spp. positive	Percentages
January	150	10	6.67%
June	125	15	12%
December	138	8	5.79%

Quality Assurance and Quality Control

Control charts can also be built based on the numbers or the percentages of conforming products. In this case, the conforming or non-conforming products are counted rather than measured. For example, in this table the number of listeria spp positive samples was counted each month and the percentages were calculated. To determine if the cleaning and sanitation program still work or not, a chart needs to be built based on the number of non-conforming products. This type of control chart is also named an “attribute chart.” Here I have two examples. One is a p-chart, which shows the percentages of non-conforming products. An np chart is built based on the numbers of non-conforming products.

P-chart example

Central line = $\overline{p}$

Control limits= $\overline{p} \pm 3\sqrt{\frac{\overline{p}(1-\overline{p})}{\overline{n}}}$

$$\overline{p} = \frac{\sum m}{\sum n} = \frac{515}{15{,}565} = 0.033 \text{ (or 3.3\%)}$$

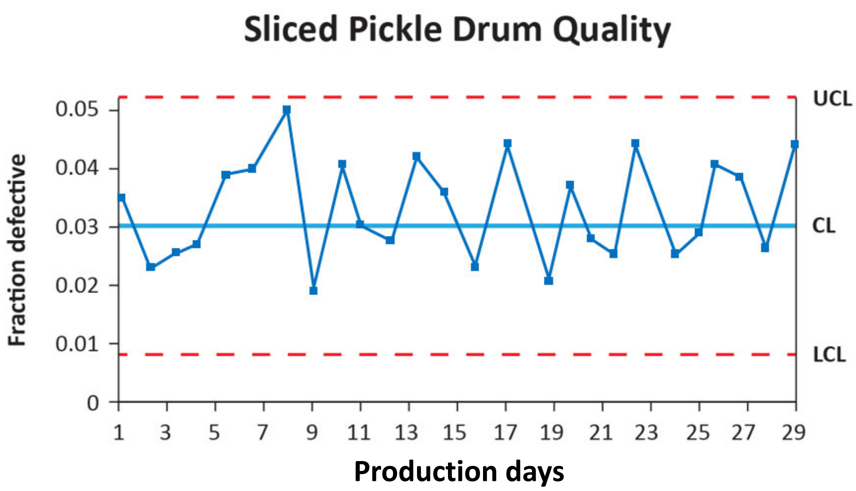
Upper control limit = $0.033 + 3\sqrt{\frac{0.033(1-0.033)}{519}} = 0.056$

Lower control limit= 0.033 - 0.023= 0.010

Defective Pickle Drums

Sample no.	Date	No. of drums n	Defectives m	Fraction defective p
1	4 Oct	502	18	0.036
2	5	530	13	0.025
3	8	480	13	0.027
4	9	510	15	0.029
5	10	540	21	0.039
6	11	520	17	0.040*
7	12	580	28	0.048*
8	15	475	10	0.021
9	16	570	23	0.040*
10	17	520	16	0.031
11	18	510	15	0.029
12	19	536	22	0.041*
13	22	515	18	0.035
14	23	480	12	0.025
15	24	548	24	0.044*
16	25	500	11	0.022
17	26	515	19	0.037
18	29	520	16	0.031
19	30	485	13	0.027
20	31	520	14	0.027
21	1 Nov	515	12	0.023
22	2	545	25	0.046*
23	5	515	16	0.031
24	6	505	13	0.026
25	7	518	15	0.029
26	8	484	12	0.025
27	9	520	22	0.042*
28	12	535	22	0.041*
29	13	518	14	0.027
30	14	554	26	0.045*
	Total	**15,565**	**515**	

Here is an example. The table on your right shows the number of drums of pickles produced every day from October 4th to November 14th. The number of defective products was also recorded. The percentage of defects for each day was calculated. To build a control chart for this, there are two main numbers that need to be calculated. One is the p bar. It represents the average of all percentages calculated for the entire month. The other is the n bar, which represents the average of drums that produced every day. For this particular example, the P bar is 3.3% and the n bar is 519. When building the chart, the P bar will be the center line. The upper control limit is 0.056 and the lower control limit is 0.01.



The process is under control

Quality Assurance and Quality Control

Here is the control chart built based on the number collected. You have UCL, CL, and LCL, and the percentage of defect of each production day shown on this figure and the process can be seen as under control.

np-chart (or *m*-chart) example

The average number of defectives

$$\overline{m} = \frac{\sum m}{days} = \frac{129}{10} = 12.9$$

Average fraction defective

$$\overline{p} = \frac{\overline{m}}{n} = \frac{12.9}{500} = 0.026$$

Center line=12.9

U/LCL= $\overline{m} \pm 3\sqrt{\overline{m}(1-\overline{p})}$

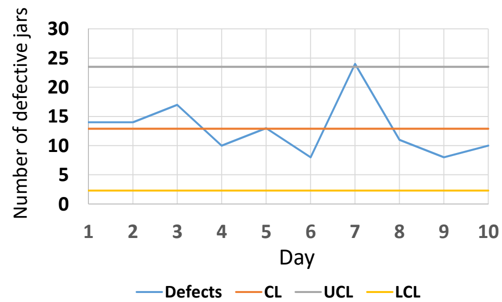
$= 12.9 \pm 3\sqrt{12.9(1-0.026)} = 12.9 \pm 10.6$

UCL = 23.5

LCL = 2.3

Defective Olive Jars

Day	Jars produced per day	Number of defective jars (*m*)	Percentage of defectives (*P*)
1	500	14	0.028
2	500	14	0.028
3	500	17	0.034
4	500	10	0.02
5	500	13	0.026
6	500	8	0.016
7	500	24	0.048
8	500	11	0.022
9	500	8	0.016
10	500	10	0.02
Total	$\sum n = 5,000$	$\sum m = 129$	$\overline{P} = 0.0258$

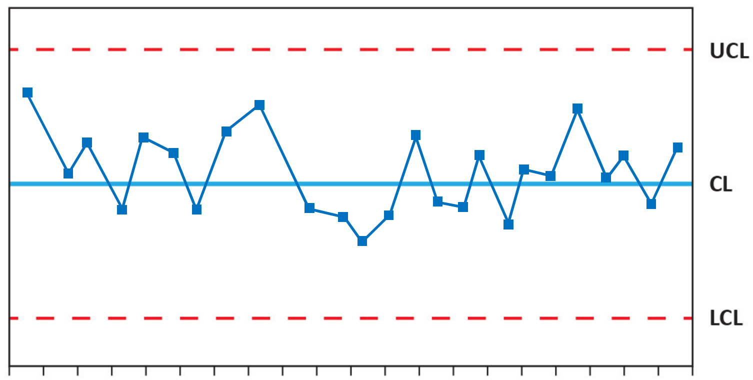


The only difference between an np chart and a p chart is that percentages of defects are not calculated and the number of defects for each day is used directly for calculation. Here the m bar is the central line and is calculated as the average defect numbers for the 10 days. The P bar is the average defect percentages for all 10 days. The UCL is 23.5 and the LCL is 2.3. By plotting all numbers on the figure, it can be seen that the process is generally under control with one point very class to the UCL. If this happens, QA team may want to find out what happened on that day that made the defect number on that day higher than the other days.

Interpretation of control charts/chart patterns

Normal, in control

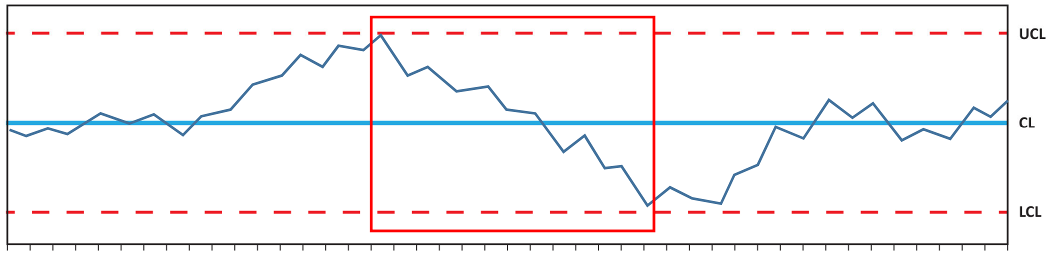
The pattern is random and within the control limits. No action is needed or desirable.



Quality Assurance and Quality Control

Once the control charts are built, the next step is to look at the charts and determine whether there are some potential problems within the processing line. We do expect that variance will happen, as shown in this figure. All values are between UCL and LCL, so this figure indicates that the process is under control and is normal.

Trend (up or down)

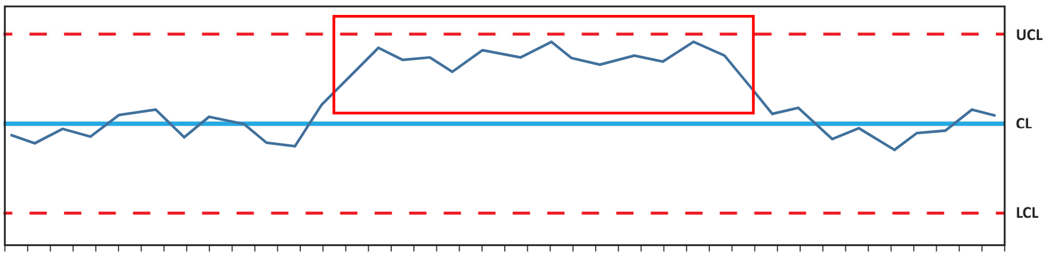


- The trend of the averages at each sampling point is going in one direction.
- Gradual deterioration of equipment or continuous change in the environment (temperature drops in the winter) can produce a trend.
- Other factors, such as the deterioration of a worker's skill, changes in the production rate, and changes in the number of components reaching the process, can also lead to "trend."

Quality Assurance and Quality Control

For this one, we start to see a trend. The measurements are going down in one direction during this period of time. The measurements may also go up in one direction. This situation indicates gradual deterioration of the equipment, continuous change in the environmental conditions, or deterioration of the worker's skill. Whenever a trend is observed, one needs to identify the root cause and prevent it from happening again. That is because if the cause is not identified and this trend happens again, the measurement might drop below the LCL and cause problems to final products.

Abnormal uniformity

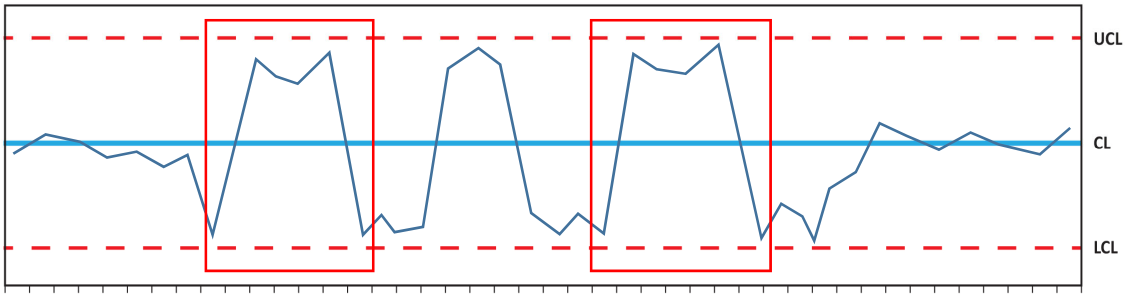


- Charts show a reduced scattering of observations.
- This abnormal uniformity may be caused by an employee with superior skills, omission of a key step or key ingredient, or introduction of defect-free raw materials.
- It may also be caused by unusually favorable environmental conditions or the setting of the wrong control limits.

Quality Assurance and Quality Control

This figure represents another pattern called "abnormal uniformity." The measurements are all at high values with very small variations for a period of time. This abnormal uniformity may be caused by an employee with superior skills, or it might indicate that a key ingredient was not added. For example, the pH might be higher if one acid is missed in the food. The pattern might also be caused by environmental conditions, or the wrong control limits were set. Just like with the previous example, every time a pattern is identified a root cause needs to be found and corrected.

Recurring cycles

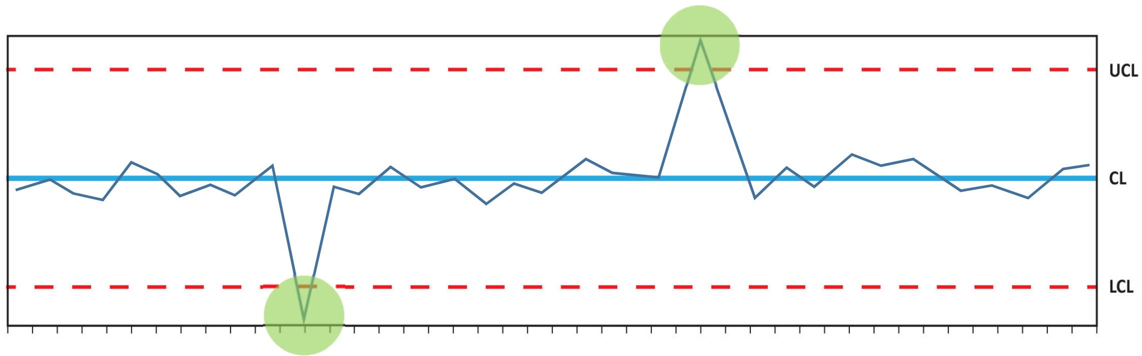


- Charts show cycles that may be related to activities that occur at repeated times (days, shifts, hours, break periods).
- Due to changes in the process or the environment that occur regularly.

Quality Assurance and Quality Control

This chart shows a pattern called recurring cycles. These two identical curves might be caused by activities that occur at repeated times. Finding the root cause is again the key to preventing reoccurrence of the pattern.

Wild outliers

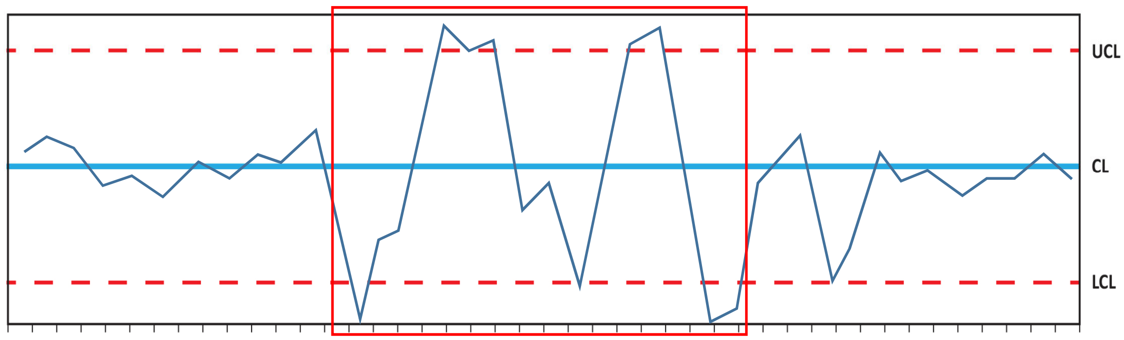


The list of errors may include mathematical calculation, plotting, sample size, sampling procedure, testing, sample contamination etc.

Quality Assurance and Quality Control

"Wild outlier" is another scenario. The list of errors causing a chart that looks like this might include mathematical calculation, plotting mistakes, sampling size mistakes, or testing errors. Do not overreact when an outlier is seen. Overreaction to an outlier problem might lead to the next chart, which we call excessive variability.

Excessive variability



- Over-adjustment due to one or two out-of-control points.

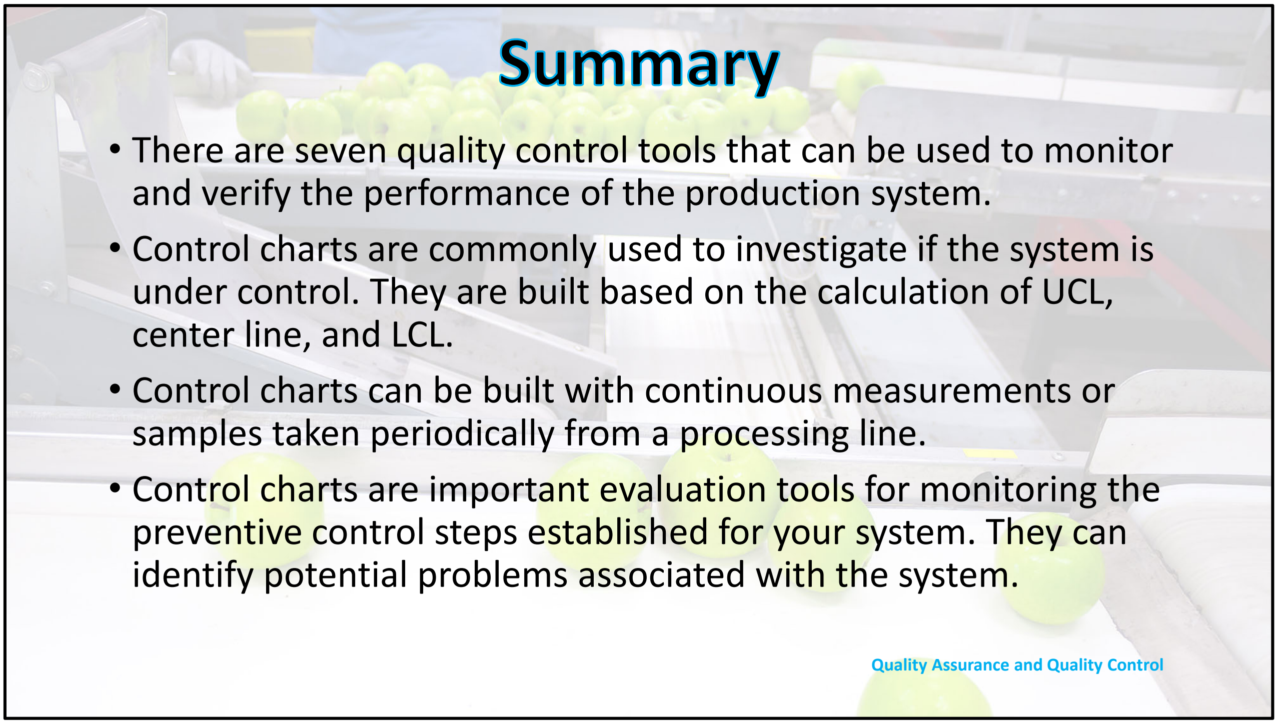
Quality Assurance and Quality Control

This is caused by over-adjustment of the system due to the overreacting to a couple of wild outliers. Identifying the root cause before adjust the processing line is important to avoid additional problems.

Potential signs of process problems

1. If the averages are out of limits but the variances are not, there might be serious problems with the process. This indicates that all of the observations in the subgroup are already out of control.
2. If the variances are out of limits but the averages are not, the process may be on the verge of developing an oscillation. It can be expected to soon drive the averages out-of-limits. It is likely that individual measurements are already close to or outside of the limits.
3. If both the averages and the variances are both out of limits, something drastic has occurred, and it can be expected to become worse unless immediate action is taken.

In general, you are building control charts to find potential signs of process problems. You need to use the information from both the individual charts and the charts monitoring the variations. Typically, if the averages are out of limits but the variances are not, this indicates serious problems with the process because all of the observations in the subgroup are already out of control. If the variances are out of limits but the averages are not, the process may be on the verge of developing an oscillation. It can be expected to soon drive the averages out-of-limits. It is likely that individual measurements are already close to or outside of the limits. If both the averages and the variances are out of limits, something drastic has occurred, and it can be expected to become worse unless immediate action is taken. A control chart can provide much information. Building control charts periodically for the processing system helps one to verify that the system works.



To give a summary, there are seven quality control tools that can be used. Among them, flowcharts, fishbone diagrams, and control charts are often used by the industry to identify key steps involved in the processing or critical factors that can contribute to processing failures or problems, as well as to verify if the system works or not.

To build a control chart, three key values need to be calculated. They are the upper control limit, the lower control limit, and the central line (typically the average of all measurements). Control charts can be built for continuous measurement of a system or for spot checking a system in which the production line is checked at different time points. Control charts are important evaluation tools for monitoring the preventive control steps established for your processing lines. You want to identify patterns, identify the reasons behind certain patterns, and prevent the formation of bigger problems.

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