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Introduction to Statistical Process Control

A Problem Solving Process Approach

Felix C. Veroya

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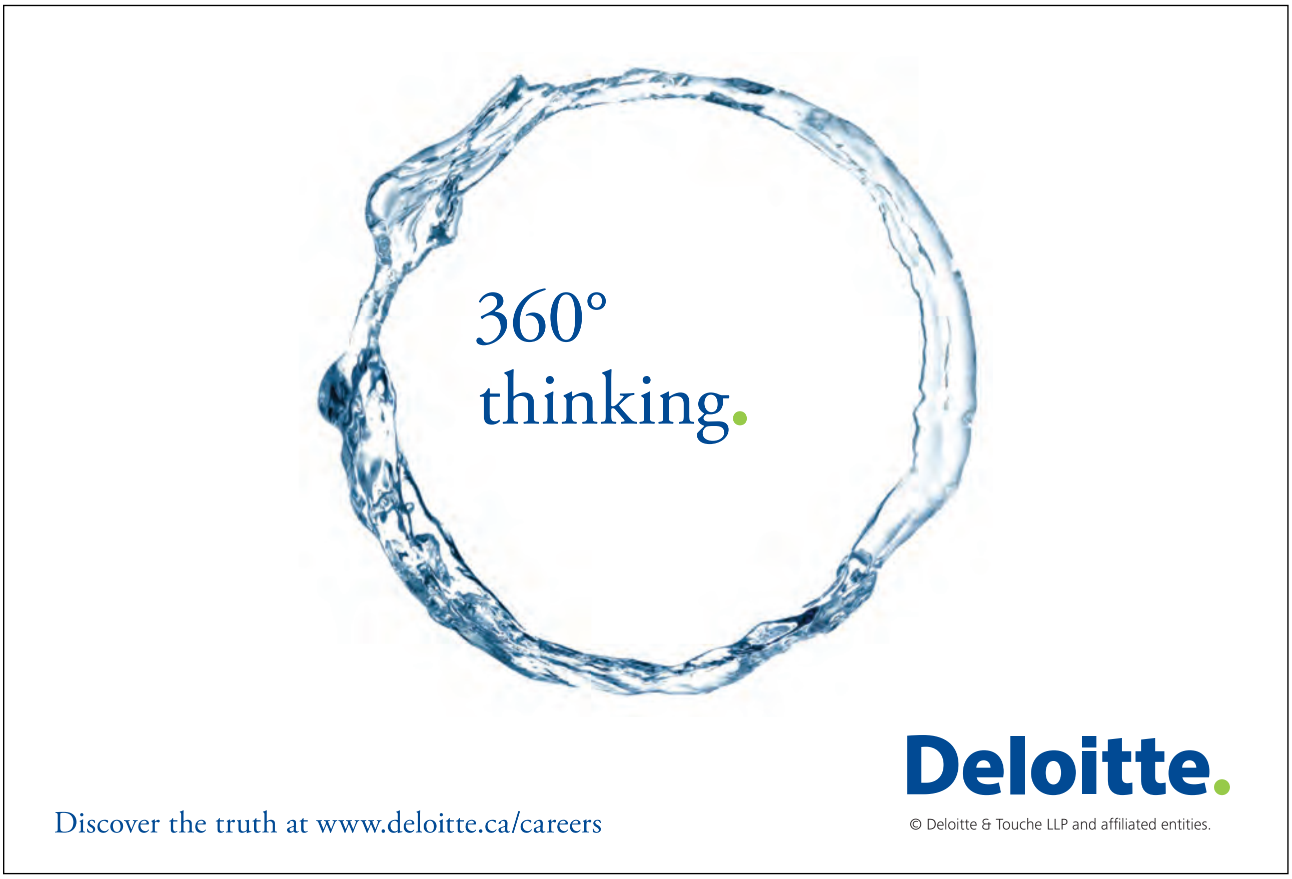

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1 Introduction

In this modern era of constraints on resources and costs of manufacturing products and rendering services, it becomes increasingly significant to make decisions based on facts and not just opinion. Consequently, data must be collected and analyzed. This is the role of Statistical Process Control Tools (SPC Tools). For more than eight (8) decades, industries have been continuously gathering the fruit of success the application of these tools have given them. SPC Tools aim to reduce the variability in aspects of the business concerned such as processes, products and services. These tools helped them in collecting data needed to be improved, analysis of how the data affects the processes, products and services, what are the causes of variations in the key input and output variables and improve those in order to attain controllability and sustain stability.

Businesses have two major objectives for their existence, to gain profit and to grow. By continually gaining maximized profit is the only way to translate growth in a progressive manner. Quality plays a significant role in attaining these two objectives. Quality is the realization of entitlement of value in terms of utility (form, fit and function), access (volume, location and timing) and worth (economic, emotional and intellectual). Therefore, whenever the quality of the process, products and/or services utilized and offered by the business are high, it is expected that potential to gain more and to continuously grow are high too.

1.1 Quality is the Responsibility of Everyone

Decisions must be data and fact driven. SPC Tools are not just a set of methodologies created by quality gurus for theoretical exercise. These tools aim to create consensus about a particular quality initiative by people who work and strive to improve themselves and their productivity every day. Decisions on what is to be improved, possible ways to improve and steps to maintain improvement after taking favorable results are all efforts made by humans and significantly based on their ability to utilize wisdom and gain experience. Therefore, everyone should be involved in the agenda of improving quality. SPC Tools is the best fit tool for this endeavor.

1.2 Costs as a Function of Quality

Using the basic model shown if Equation 1, profit can be maximized by either increasing revenue while holding total cost at current level or holding the revenue while decreasing the total cost. The latter condition is what you will consider in order to attain the optimal profit desired. Costs of quality for products and services are comprised of four major components, each parameter contributing significantly affecting the value of the processes, products and/or services. The higher the costs of quality, the lesser value is present.

Eq.1: **PROFIT (P) = REVENUE (R) – TOTAL COSTS (TC)**

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Where:

- Profit (P) – is a function of the revenue earned less the total costs incurred in producing/selling the products.
- Revenue (R) – is the earned value in the process of selling/rendering the products/services.
- Total Costs (TC) – a function of the total of fixed costs and variable costs utilized in the process of creating the products and services, i.e., TC = FC + VC.
- Variable Costs (VC) – a function of variable cost per unit and the number of units produced, sold and/or rendered.
- Fixed Costs (FC) – a function of the fixed cost incurred in producing, selling and and/ordering the units.

Example 1.2: Bakeshop Cupcakes

A particular bakeshop sells a cupcake for $0.5 each. It a month's time, the shop has been able to sell 2,000 cupcakes. With this units sold, the fixed cost incurred is $300 and variable cost per cupcake has been estimated to be $0.15. What is the profit earned by the bakeshop?

P = R – TC
P = ($0.5/cupcake*2,000 cupcakes) – ($300 + $0.15*2,000)
P = $1,000 - $600
P= $400 (The bakeshop has earned $400.)

Say the bakeshop has incurred quality related problems in the process of producing the cupcakes (2,000 units) resulting to an increase on the fixed cost by $100 and on variable cost per unit of $0.5. Selling cost for the cupcake for remained the same as to minimize the risk of losing customers due to sudden price increase. Problems associated with the increase in costs are yet still under observation and for correction. What will be the new profit with the given situation?

P = R – TC
P = ($0.5/cupcake*2,000 cupcakes) – ($400 + $0.2*2,000)
P = $1,000 - $800
P= $200 (The bakeshop has earned $200 yet a decrease of $200 has been observed due to increase in quality related problems.)

As illustrated, the profit for any given business is significantly affected by the quality it has and being maintained over time. If the quality related problems are to be addressed, the profit will be maximized and potential growth can be realized.

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2 The 7 Basic Statistical Process Control Tools

If a product is to meet or exceed customer expectations, it can be generalized that is produced by a process that is stable or repeatable. The process must be capable of operating with little variability around the target or nominal dimensions of the product's quality characteristics resulting to meet or exceed customer requirements. SPC Tools is a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability.

SPC is one of the greatest technological developments of the twentieth century because it is based on sound underlying principles. Advantages of using this set of tools are:

1) is easy to use
2) has significant impact, and
3) generally can be applied to any process.

The **toolbox' seven (7) major tools** are:

1) Histogram or stem-and-leaf plot
2) Check sheet
3) Pareto chart
4) Cause-and-effect diagram
5) Flow chart
6) Scatter diagram
7) Control chart

The proper deployment of the so called ***"magnificent seven"*** will help the organization to create a continuous improvement seeking environment in terms of quality and productivity. Development of this kind of environment requires the shared responsibility of the management thru providing necessary programs to educate the employees about the tools. On the other hand, employees have the responsibility to suitably apply and utilize the acquired tools. With this environment established, this will form part of their everyday living, the application of the tools, radiantly affecting the usual manner of doing business and achieving quality and productivity improvement objectives.

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2.1 Histogram

2.1.1 What is a Histogram?

A bar chart that displays the distribution of individual measurements taken on a part or process. Also called a frequency distribution because the frequency of occurrence of any given value is represented by the height of the bar. It also defined to be a more compact summary of data than a stem-and-leaf plot.

2.1.2 Why Use a Histogram?

- Allows a person to quickly visualize the center, variation (spread), and shape of the distribution of measurements.
- To observe patterns in the measurements.
- Provides clues to reducing variation and causes of problems.
- To observe the production consistency of a quality characteristic.
- To graphically show the relationship between the capability of the process and the engineering specifications.
- To visually assess whether a set of measurements is normally distributed.

2.1.3 When to Use a Histogram?

- Collecting measurements on a key characteristic or any process output.
- Capability studies are being performed.
- Analyzing the quality of incoming material and outgoing product.
- Analyzing the variation at each step in a series of steps where tolerance (variation) buildup is of concern.

2.1.4 How to Construct a Histogram?

1) Collect measurements (variable data) from a process or key characteristic. Thirty or more measurements are preferred.
2) Construct a check sheet to record the data.
3) Determine the range of the data by subtracting the smallest measurement from the largest, i.e., **Range = Xmax – Xmin.**
4) Select the proper number of class intervals into which the measurements should be grouped. *(Please see reminder below for the statistical explanation and calculations and/or refer to the Table 2.1.4 for recommended class intervals as calculated.)*

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5) Determine the width and limits of the class intervals. Class width is calculated by dividing the range by the number of classes. Set the class limits so that no data values fall on any one of the limits. This is done by adding the next logical decimal value to each limit. For instance, if you create intervals for data with limits of 0.5 to 5.5, 5.5 to 10.5, and so on, a value of 5.5 could go in either the first or second class. You can avoid this problem by setting the intervals at 0.51 to 5.50, 5.51 to 10.50, and so on, so that no data value falls on a class limit.
6) Construct a frequency table. Tally the number of observations found in each class.
7) Draw and label the histogram.

REMINDER: To construct a histogram for continuous data, we must divide the range of the data into intervals, which are usually called **class intervals, cells,** or **bins.** If possible, the bins should be of equal width to enhance the visual information in the histogram. Some judgment must be used in selecting the number of bins so that a reasonable display can be developed. The number of bins depends on the number of observations and the amount of scatter or dispersion in the data. A histogram that uses either too few or too many bins will not be informative. We usually find that between 5 and 20 bins is satisfactory in most cases and that the number of bins should increase with *n.* Choosing the number of bins approximately equal to the square root of the number of observations often works well in practice **(Bins = $\sqrt{n}$) – most applied method**. Some basic statistics suggest the use of other methodologies, one of those, the use of **Sturge's rule**, that is **Bins (h) = 1 + $\log_2 n$.**

Observations	Number of Class Intervals
25 to 50	5 to 8
51 to 100	6 to 11
101 to 250	9 to 13
Greater than 250	11 to 15

Table 2.1.4 Guide for Establishing the Number of Class Intervals

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2.1.5 Strengths and Weaknesses of Histogram

Given in Table 2.1.5 is the list of the advantages and disadvantages of using a Histogram.

Strengths	Weaknesses
Visual	Will not quantitatively assess process stability.
Simple and powerful.	Not time sensitive.
Quickly summarizes large amounts of data.	Generally takes large amounts of data before patterns can be seen.
May be used to show relationship of key characteristic variation to engineering specifications.	Tempting to over interpret.
	Shape can be somewhat subjective.

Table 2.1.5 Strengths and Weaknesses of Histogram

2.1.6 Interpretations

The histogram in Figure 2.1.6a resembles a normal distribution, but there are times that a histogram from a process does not follow a normal curve. Studying histogram patterns provides clues to causes of problems. Some common patterns, with their probable causes, are listed below (formal evaluation as to whether the data are from a normal distribution can be accomplished with various statistical tests).

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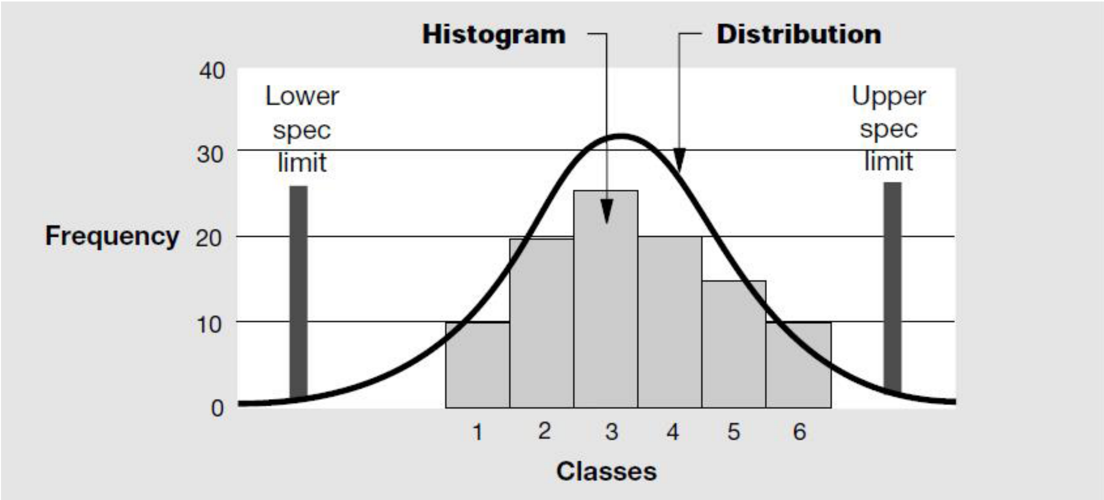

Figure 2.1.6a Histogram

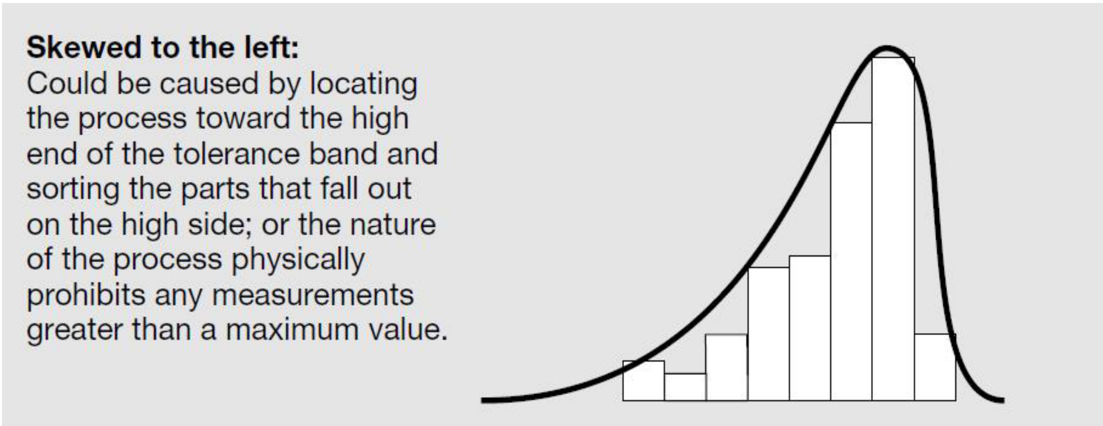

Figure 2.1.6b Skewed to the Left

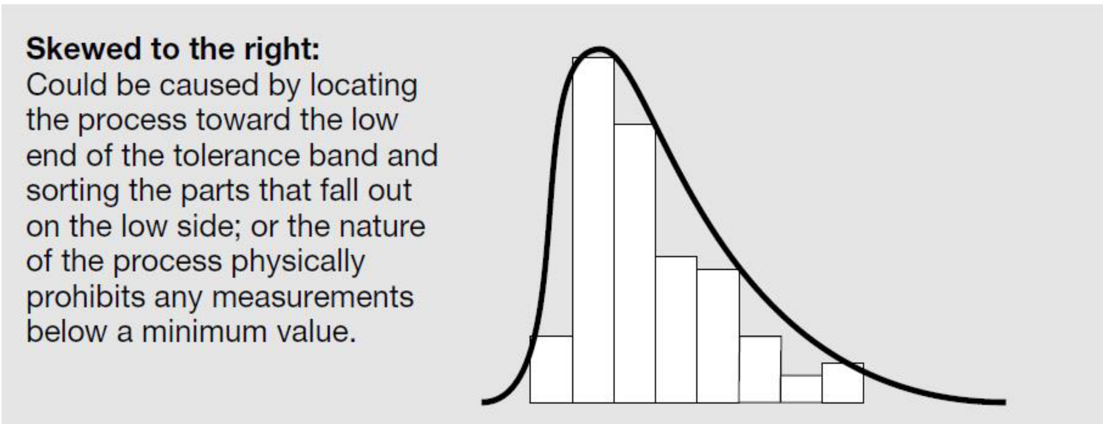

Figure 2.1.6c Skewed to the Right

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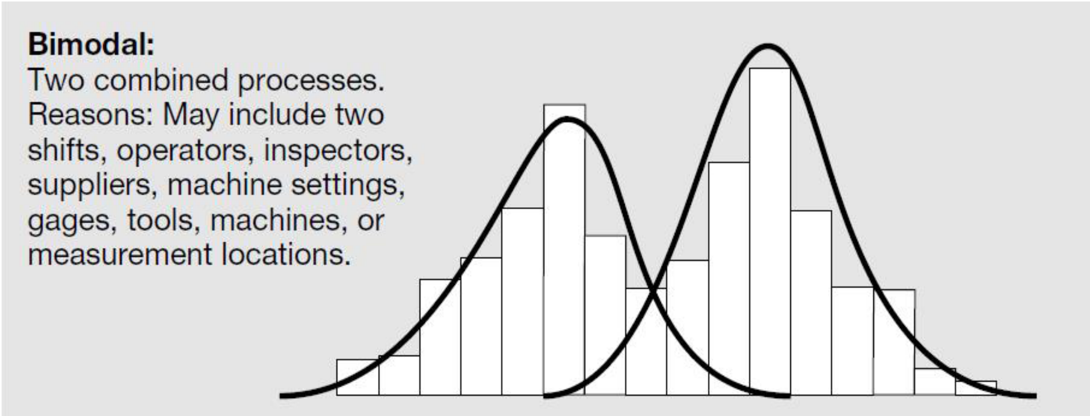

Figure 2.1.6d Bimodal

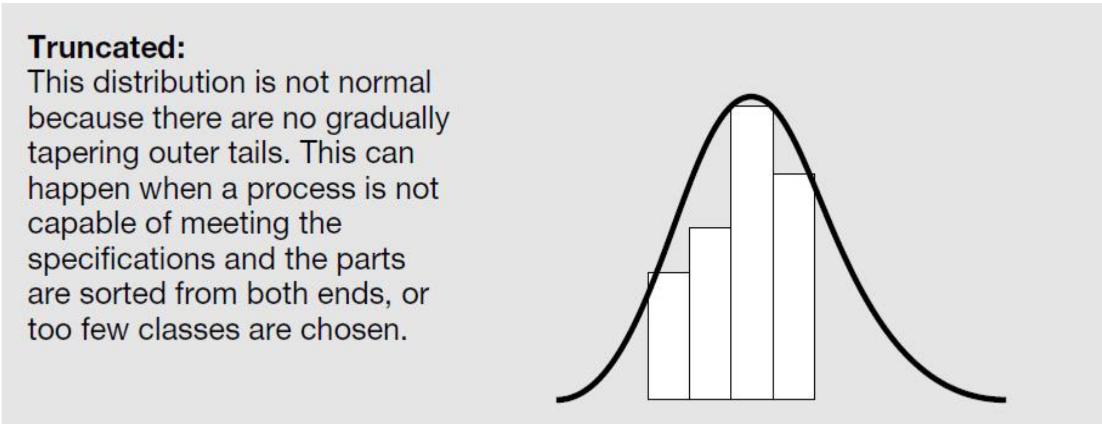

Figure 2.1.6e Truncated

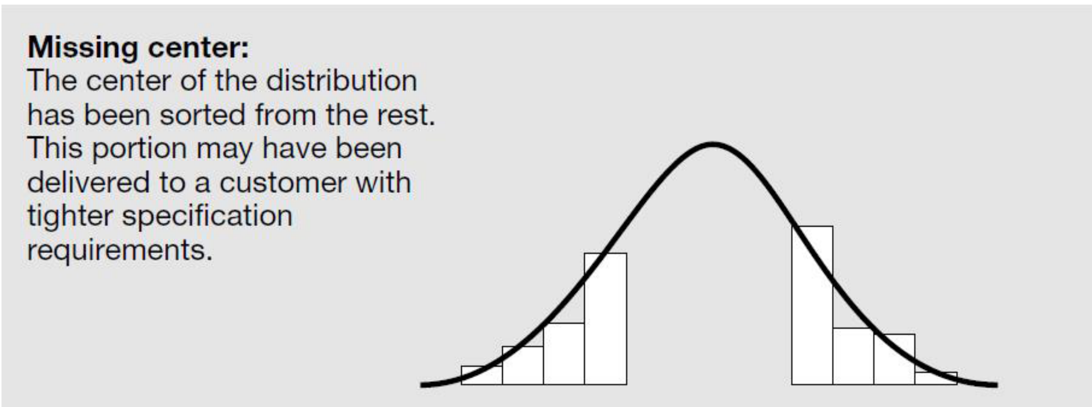

Figure 2.1.6f Missing Center

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Spikes at the tails:
The parts in the outer ends of the distribution are being reworked to bring the characteristic just within specifications, or measurements of out-of-specification parts are being recorded as in specification.

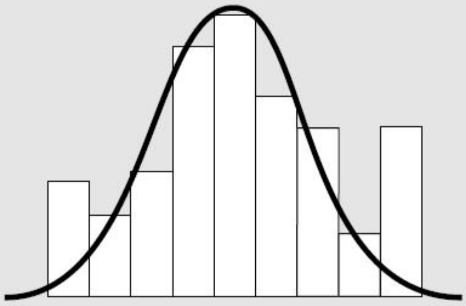


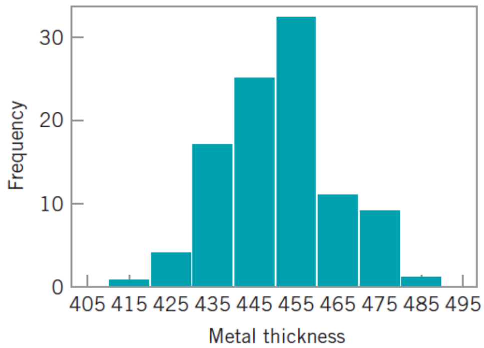
Figure 2.1.6g Spikes at the Tails

Example 2.1a Metal Thickness in Silicon Wafers

The table below presents the thickness of a metal layer on 100 silicon wafers resulting from a chemical vapor deposition (CVD) process in a semiconductor plant. Construct a histogram for these data.

438	450	487	451	452	441	444	461	432	471
413	450	430	437	465	444	471	453	431	458
444	450	446	444	466	458	471	452	455	445
468	459	450	453	473	454	458	438	447	463
445	466	456	434	471	437	459	445	454	423
472	470	433	454	464	443	449	435	435	451
474	457	455	448	478	465	462	454	425	440
454	441	459	435	446	435	460	428	449	442
455	450	423	432	459	444	445	454	449	441
449	445	455	441	464	457	437	434	452	439

Because the data set contains 100 observations and we suspect that about 10 bins will provide a satisfactory histogram. Below is a figure of the simulated histogram.



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Example 2.1b Defects in Automobile Hoods

The table below shows the number finish defects in the primer paint found by visual inspection of automobile hoods that were painted by a new experimental painting process. Construct a histogram for these data.

6	1	5	7	8	6	0	2	4	2
5	2	4	4	1	4	1	7	2	3
4	3	3	3	6	3	2	3	4	5
5	2	3	4	4	4	2	3	5	7
5	1	5	5	4	5	3	3	3	12

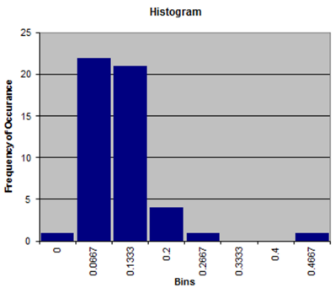

Figure 2.1b is the histogram of the defects. Notice that the number of defects is a discrete variable. From either the histogram or the tabulated data we can determine;

Proportions of hoods with at least 3 defect = 39 / 50 = .78 and proportions of hoods with between 0 and 2 defects = 11 / 50=0.22.

These proportions are examples of relative frequencies.

2.2 Check Sheets

2.2.1 What are Check Sheets?

- A basic tool for monitoring quality improvement processes.
- A data-collection form used to manually tally and record the number of observations or occurrences of certain events during a specified time period. The data collected can be either attribute (e.g., defects) or variable (e.g., measurements).
- Check sheets are simply charts for gathering data. When check sheets are designed clearly and cleanly, they assist in gathering accurate and pertinent data, and allow the data to be easily read and used. The design should make use of input from those who will actually be using the check sheets. This input can help make sure accurate data is collected and invites positive involvement from those who will be recording the data.
- Check sheets can be kept electronically, simplifying the eventual input of the data into several statistical software such as Statit, SPSS, Minitab, etc. Since most people have a spreadsheet program on their desktop PC, it might be easiest to design a check sheet in a spreadsheet format.
- Check sheets should be easy to understand. The requirements for getting the data into an electronic format from paper should be clear and easy to implement.

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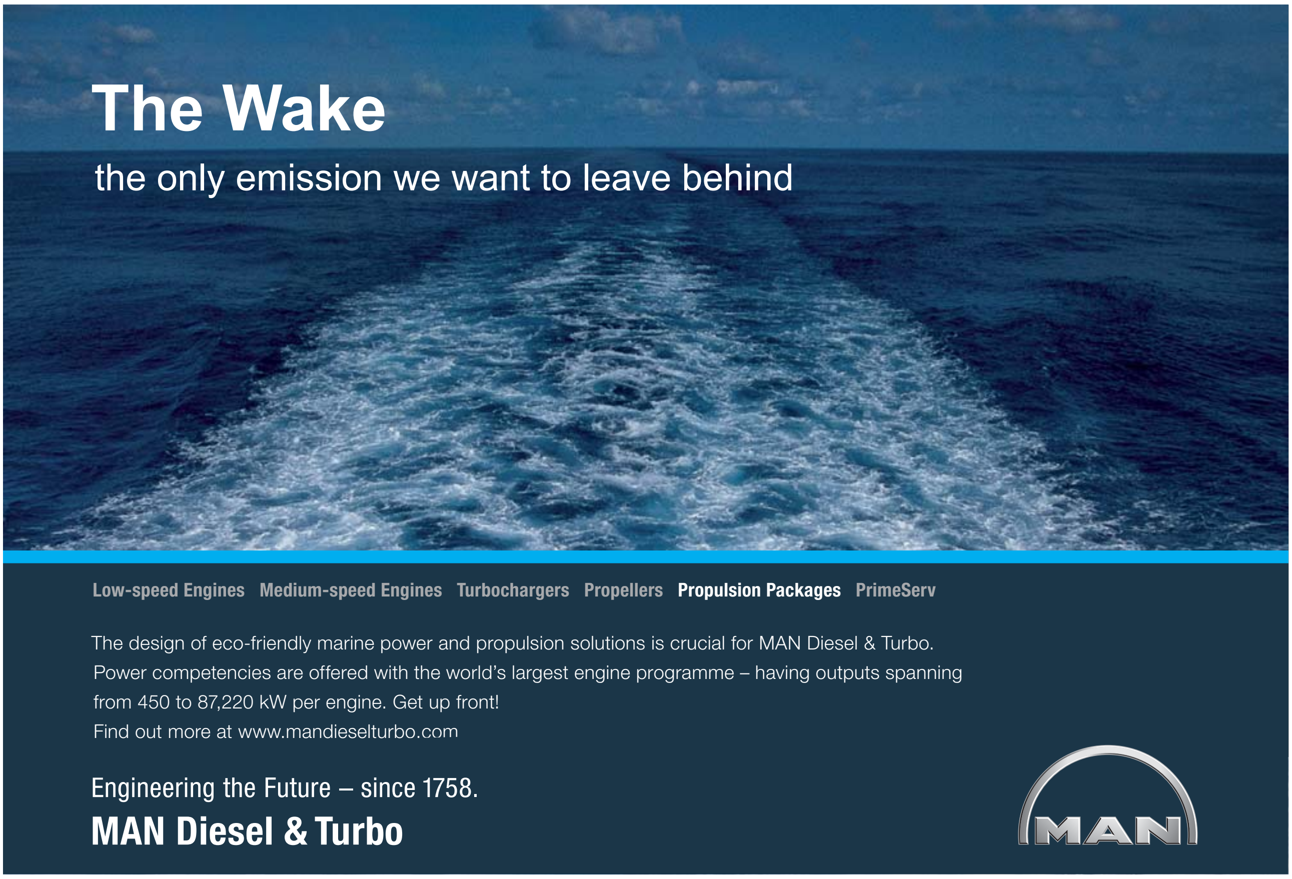
2.2.2 What are Common Types of Check Sheets?

a) **Distribution** – used to collect data in order to determine how a variable is dispersed within an area of possible occurrence.
b) **Location** – highlights the physical location of a problem/defect in order to improve quality. They may also utilize visual (schematic) drawings of areas in order to record where problems are occurring.
c) **Cause** – used to keep track of how often a problem happens or records the cause to a certain problem.
d) **Classification** – used to keep track of the frequency of major classifications involving the delivery of products or services.

2.2.3 Why Use Check Sheets?

- To collect and display data easily.
- To collect factual information about the process being studied.
- To answer the question,“How often are certain events happening?”
- To prioritize efforts where most problems occur.



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2.2.4 When to Use Check Sheets?

- Conducting a problem-solving exercise.
- Troubleshooting a process.
- Observing the behavior of a process.
- Building a histogram.
- Gathering data in order to detect patterns.

Week	Process Step						Total
	2	3A	3B	4	5	Insp.	
1	I		卌 III	卌 卌			19
2	卌	II	I	卌卌卌I	卌 卌 II	I	37
3	卌 I	卌 I		卌 I	卌 卌	II	30
4	卌 I	II		III	卌		16
Total	18	10	9	35	27	3	102

Figure 2.2.4a Distribution Check Sheets

Problem	Month			Total
	1	2	3	
A	III	II	I	6
B	I	II	I	4
C	卌	II	卌 I	13
Total	9	6	8	23

Paint defects	November				Total
	12	13	14	15	
Show through	卌 I	卌 卌	卌 III	II	26
Too heavy	II	IIII	I	III	10
Overspray	卌	I	II	I	9
Oil canning	卌卌 II	卌 IIII	卌 III	卌 III	37
Fish eyes	III		卌		8
Total	28	24	24	14	90

Figure 2.2.4b Cause Check Sheets

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2.2.5 How to Construct a Check Sheet?

1) The process to be observed is agreed upon by the team.
2) Decide on the time period during which data will be collected.
3) Decide whether data will be variable or attribute; define data categories.
4) Design a form that is clear and easy to use, making sure that all categories are clearly labeled and that there is enough space to enter the data.
5) Train the people who work in the process how to collect the data.
6) Collect the data by making a mark in the correct category for each observation, making sure that samples are as representative as possible.
7) Analyze the data for opportunities for process improvement.

CHECK SHEET
DEFECT DATA FOR 2002–2003 YTD

Part No.: TAX-41
Location: Bellevue
Study Date: 6/5/03
Analyst: TCB

	2002												2003					
Defect	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	Total
Parts damaged		1		3	1	2		1		10	3		2	2	7	2		34
Machining problems			3	3				1	8		3		8	3				29
Supplied parts rusted			1	1		2	9											13
Masking insufficient		3	6	4	3	1												17
Misaligned weld	2																	2
Processing out of order	2															2		4
Wrong part issued		1						2										3
Unfinished fairing			3															3
Adhesive failure				1							1		2			1	1	6
Powdery alodine					1													1
Paint out of limits						1								1				2
Paint damaged by etching			1															1
Film on parts						3		1	1									5
Primer cans damaged								1										1
Voids in casting									1	1								2
Delaminated composite										2								2
Incorrect dimensions											13	7	13	1		1	1	36
Improper test procedure										1								1
Salt-spray failure													4			2		4
TOTAL	4	5	14	12	5	9	9	6	10	14	20	7	29	7	7	6	2	166

Figure 2.2.5a Check sheets record defects on a tank used in an aerospace application.

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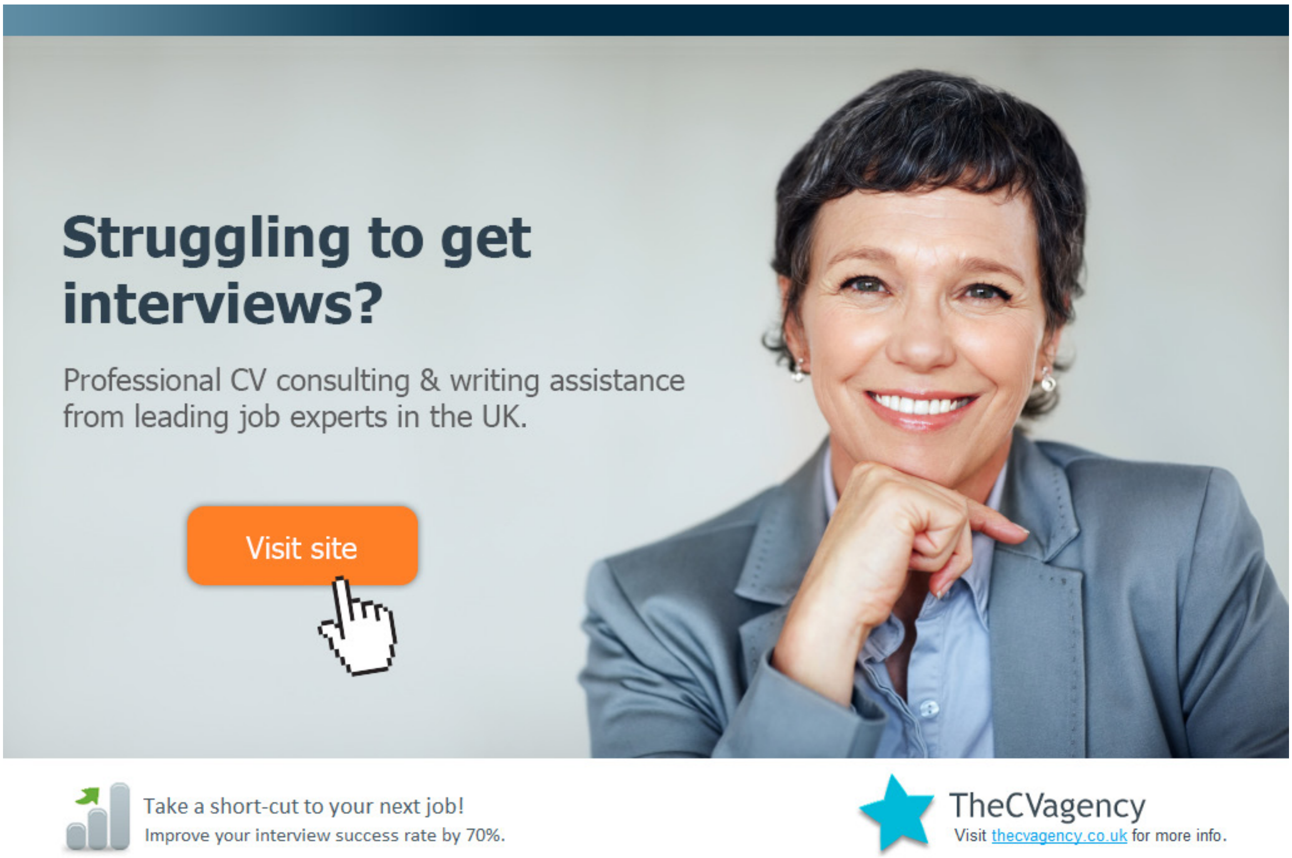
2.3 Pareto Chart

2.3.1 What is a Pareto Chart?

- A bar chart where the bars are arranged in descending order of magnitude. The bars may represent defect categories, locations, departments, and so on. The magnitude (length) of the bars may represent frequencies, percentages, costs, or times.
- A problem-solving tool that involves ranking all potential problem areas or sources of variation according to their contribution to cost or total variation. Typically, 80% of the effects come from 20% of the possible causes, so efforts are best spent on these "vital few" causes, temporarily ignoring the "trivial many" causes.
- There are often many different aspects of a process or system that can be improved, such as the number of defective products, time allocation or cost savings. Each aspect usually contains many smaller problems, making it difficult to determine how to approach the issue. A Pareto chart or diagram indicates which problem to tackle first by showing the proportion of the total problem that each of the smaller problems comprise.
- The name *Pareto chart* is derived from Italian economist Vilfredo Pareto (1848–1923), who theorized that in certain economies the majority of the wealth was held by a disproportionately small segment of the population. Quality engineers have observed that defects usually follow a similar Pareto distribution.



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2.3.2 Why Use Pareto Chart?

- To prioritize actions needed to solve complex problems.
- To sort out the "vital few" from the "trivial many."
- To break down a big problem into smaller pieces and identify biggest contributor.
- To separate important from unimportant causes contributing to a problem.
- To measure improvements after changes have been made.
- To allow better use of limited resources.
- To show where to focus efforts.

2.3.3 When to Use Pareto Chart?

- Prioritization of problems to be addressed or improvement to be deployed.
  - Process improvement efforts for increased unit readiness
  - Skills you want your division to have
  - Customer needs
  - Suppliers
  - Investment opportunities
- Many factors contribute to a problem.
- Attention needs to be directed only to the few factors that account for most of the problem.
- Analyzing the results of a risk analysis.
- Investigating on process that data are broken down into categories and you can count number of times each category occurs.

2.3.4 How to Construct a Pareto Chart?

1) Identify the problem and the time period for the study.
2) Define the types of data to be analyzed (e.g., defects, locations).
3) Define the form of measurement to be used (e.g., frequency, percentage).
4) Prepare a corresponding check sheet based on the determined parameters.
5) Collect representative data and categorize.
6) Count and arrange the data in descending order.
7) If possible, assign costs to each category, multiply frequency by cost, and reprioritize.
8) Make a bar chart of the data and clearly label categories.
   - Label the left-hand vertical axis. Make sure the labels are spaced in equal intervals from 0 to a round number equal to or just larger than the total of all counts. Provide a caption to describe the unit of measurement being used.
   - Label the horizontal axis. Make the widths of all of the bars the same and label the categories from largest to smallest. An "other" category can be used last to capture several smaller sets of data. Provide a caption to describe them. If the contributor names are long, label the axis A, B, C, etc. and provide a key.

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- Add a cumulative line. This is optional. Label the right axis from 0 to 100%, and line up the 100% with the grand total on the left axis. For each category, put a dot as high as the cumulative total and in line with the right edge of that category's bar. Connect all the dots with straight lines.

9) Analyze results and prepare improvement activities for "vital few."

Reasons for Rejected Crushed Core Panels

Type of errors	Percent of total errors
Resin starvation	58
Split core	23
Scrape	7
Discoloration	6
Warped	2
Broken	2
Other	2
Total	100

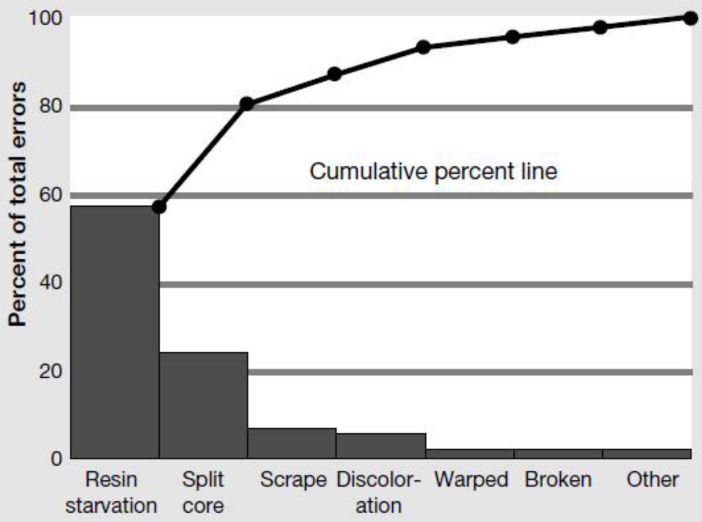

Figure 2.3.3a Pareto chart for the explored reasons for the rejected crushed core panels.

2.3.5 What is the Pareto Problem Solving Method?

- Pareto analysis is used to rank order the reasons for problems so that corrective action can be taken on the major causes of the problem. Pareto charts for a problem often lend themselves to further dissection.
- As a rule, start to work on one of the tallest bars (e.g., resin starvation) in Figure 2.3.3a. Construct a new Pareto to describe its components. Continue to break down the components until elementary levels are reached (see Fig. 2.3.4a). Working problems at the most elementary levels will result in improvement at the higher level.
- Once the causes for the tallest bar have been resolved, proceed to the next tallest. (If the tallest bar requires significant time and a resource to work and the team is new, it may be of value to tackle a shorter, faster bar first.)
- Continue this process until the root causes have been eliminated, or reduced to a satisfactory level.

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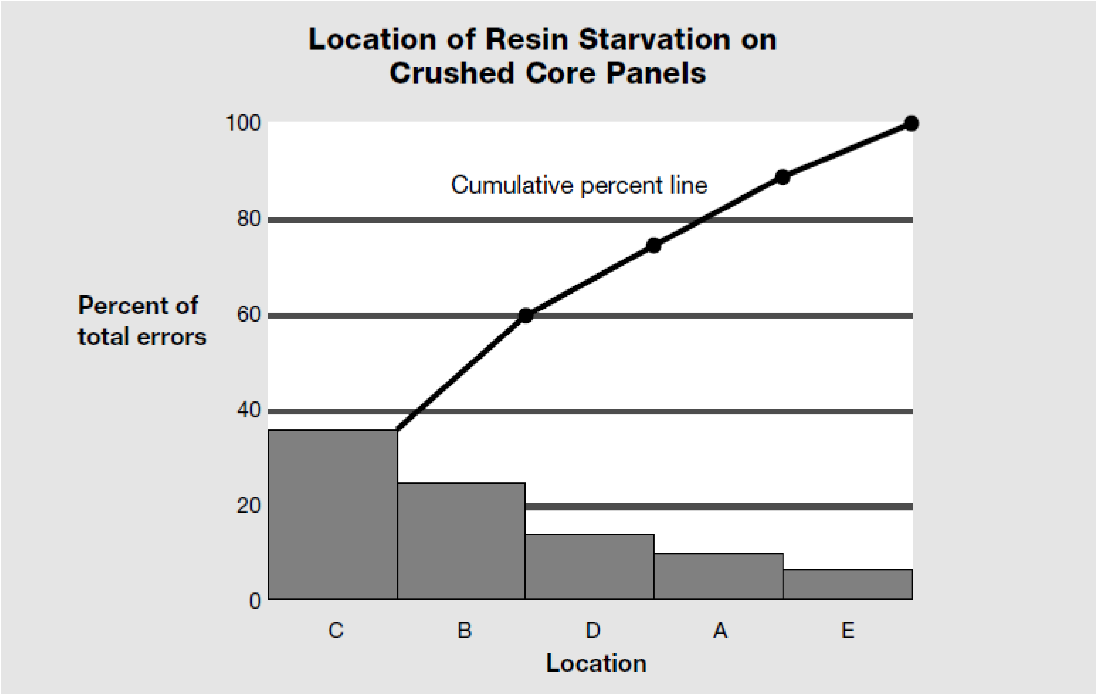
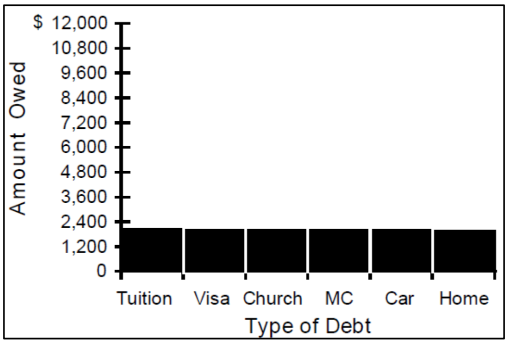


Figure 2.3.4b Pareto chart for the locations of resin starvation.

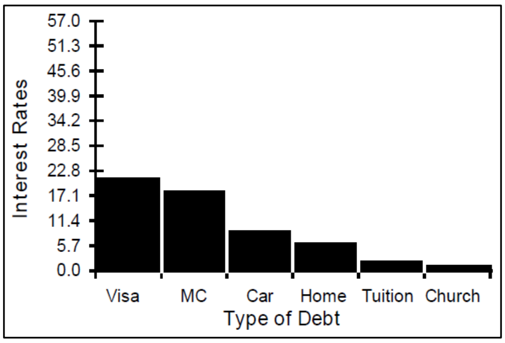
Example 2.3a $10.000 Inheritance

You recently inherited $10,000 and would like to apply it to some of your outstanding bills. Here is what you owe:

Category	Amount ($)
School tuition (monthly installments)	2,030
Visa	2,007
Church pledge (monthly installments)	2,000
Mastercard	1,983
Balance of car loan	1,971
Home improvement loan balance	1,956
Total	11,947



Category	Int. Rate (%)
Visa	21
Mastercard	18
Balance of car loan	9
Home improvement loan balance	6
School tuition (monthly installments)	2
Church pledge (monthly installments)	1



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Example 2.3a: You probably noticed that no single bar is dramatically different from the others. Looking at your outstanding debts in this way isn't much help. Is there a different way the data could be categorized to make it more meaningful? What if you were to consider the interest rates on your outstanding debts?

REMINDER: The ***significant few-trivial many*** principle does not always hold. No matter how many data are categorized, they can be ranked and made into a Pareto diagram. But sometimes no single bar is dramatically different from the others, and the Pareto Chart looks flat or gently sloping. To attack the tall bar in that situation is no help. You need to look for another way to categorize the data.

2.3.6 Additional Tips for the Analysis of a Pareto Chart

When you look at a Pareto Chart, you can see break points in the heights of the bars which indicate the most important categories. This information is useful when you are establishing priorities.

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As you can see in the example we've just looked at, you can detect two big breaks in the heights of the bars when you categorize the data in a different way:

1) The first break point is between the second and third bars. The difference between these two bars is much more noticeable than the other differences. This shows the relative importance of the first two bars in relation to the others.
2) The other break point occurs after the fourth bar. Addressing the third and fourth bars will give a higher payoff than addressing the last two bars.

You will have an opportunity to develop your interpretation skills when you do the practice continuous exercising of this powerful tool.

2.4 Cause and Effect Diagram

2.4.1 What is a Cause and Effect Diagram?

- A tool used to graphically display the relationship between an effect (e.g., a problem or key characteristic) and the causes that influence it.
- A tool used to analyze cause and effect relationship. It is also called Ishikawa diagram/analysis because Kaoru Ishikawa developed it in 1943. It is also called fishbone diagram since it resembles one with the long spine and various connecting branches.
- The fishbone chart organizes and displays the relationships between different causes for the effect that is being examined. This chart helps organize the brainstorming process. The major categories of causes are put on major branches connecting to the backbone, and various sub-causes are attached to the branches. A tree-like structure results, showing the many facets of the problem.
- The method for using this chart is to put the problem to be solved at the head, then fill in the major branches. Man, machine, method and materials are commonly identified causes.
- This is another tool that can be used in focused brainstorming sessions to determine possible reasons for the target problem. The brainstorming team should be diverse and have experience in the problem area. A lot of good information can be discovered and displayed using this tool.

2.4.2 Why Use a Cause and Effect Diagram?

- Helps identify lower level key characteristics and key process parameters affecting key characteristics.
- Helps identify the various causes affecting a process problem.
- Helps a group reach a common understanding of a problem.
- Exposes gaps in existing knowledge of a problem.
- Helps reduce the incidence of uninformed decision making.
- Helps determine the root causes of a problem or quality characteristic using a structured approach.

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- Encourages group participation and utilizes group knowledge of the process.
- Uses an orderly, easy-to-read format to diagram cause-and-effect relationships.
- Indicates possible causes of variation in a process.
- Increases knowledge of the process by helping everyone to learn more about the factors at work and how they relate.
- Identifies areas where data should be collected for further study.

2.4.3 When to Use the Cause and Effect Diagram / Analysis?

- Performing key characteristic flow down.
- Looking for all potential causes of a problem.
- Organizing brainstorming lists into causes and effects.
- Sorting out and relate some of the interactions among the factors affecting a particular process or effect.
- Identifying sources of process variation.
- Identify the possible root causes, the basic reasons, for a specific effect, problem, or condition.
- Analyzing existing problems so that corrective action can be taken.
- Linking process output to process parameters.
- Performing a DOE.

2.4.4 How to Construct a Cause and Effect Diagram?

1. Decide on the effect to be examined. Effects are stated as particular quality characteristics, problems resulting from work, planning objectives, and the like.
    - Use Operational Definitions. Develop an Operational Definition of the effect to ensure that it is clearly understood.
2. Generate potential causes of a problem (or effect) through structured brainstorming.
    - Remember, an effect may be positive (an objective) or negative (a problem), depending upon the issue that's being discussed. You must decide which approach will work best with your group.

      Using a **positive effect** which focuses on a desired outcome tends to foster pride and ownership over productive areas. This may lead to an upbeat atmosphere that encourages the participation of the group. When possible, it is preferable to phrase the effect in positive terms.

      Focusing on a **negative effect** can sidetrack the team into justifying why the problem occurred and placing blame. However, it is sometimes easier for a team to focus on what causes a problem than what causes an excellent outcome. While you should be cautious about the fallout that can result from focusing on a negative effect, getting a team to concentrate on things that can go wrong may foster a more relaxed atmosphere and sometimes enhances group participation.

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3. Draw a horizontal arrow pointing to the right. This is the ***spine***.
   - To the right of the arrow, write the brief description of the effect or outcome which results from the process. Draw a box around the description of the effect. If a problem statement or objective has been determined, you can write it instead.
4. Decide upon the major cause categories of the event, problem, or key characteristics. You should use category labels that make sense for the diagram you are creating. Here are some commonly used categories:
   - 4Ms – methods, materials, machinery, and man
   - 4Ps – policies, procedures, people and plant
   - Milieu – environment, a possible additional category.
5. Write the major cause categories on the left-hand side of paper and draw lines to them off the main horizontal line. Arrow heads must be drawn towards the spine so to reflect causal relationship between the brainstormed causes and the effect being discussed.
6. When evaluating for causes, all the major potential sources should be reviewed: machines, methods, materials, people, measurements, and environment.
7. Place the brainstormed ideas under the appropriate major cause category. Add any newly identified causes.
8. For each cause, ask, “Why does it happen?” And list responses as branches off the major cause branches. Identifying causes can be continuously done to attain more levels by asking a series of why questions or what we call **“Why – Why”** or **“5Y” Analysis**.

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9. Continue this process to the root-cause level.
10. Identify the most influential causes and focus activities on them. Analyze the diagram. Analysis helps you identify causes that warrant further investigation. Since Cause-and-Effect Diagrams identify only possible causes, you may want to use a Pareto Chart to help your team determine the cause to focus on first.
11. Look at the **"balance"** of your diagram, checking for comparable levels of detail for most of the categories.
    - A thick cluster of items in one area may indicate a need for further study.
    - A main category having only a few specific causes may indicate a need for further identification of causes.
    - If several major branches have only a few sub branches, you may need to combine them under a single category
12. Look for causes that appear repeatedly. These may represent root causes. Look for what you can measure in each cause so you can quantify the effects of any changes you make. **Most importantly, identify and circle the causes that you can take action to.**

REMINDER: You may need to break your diagram into smaller diagrams if one branch has too many sub branches. Any main cause (4Ms, 4Ps, or a category you have named) can be reworded into an effect.

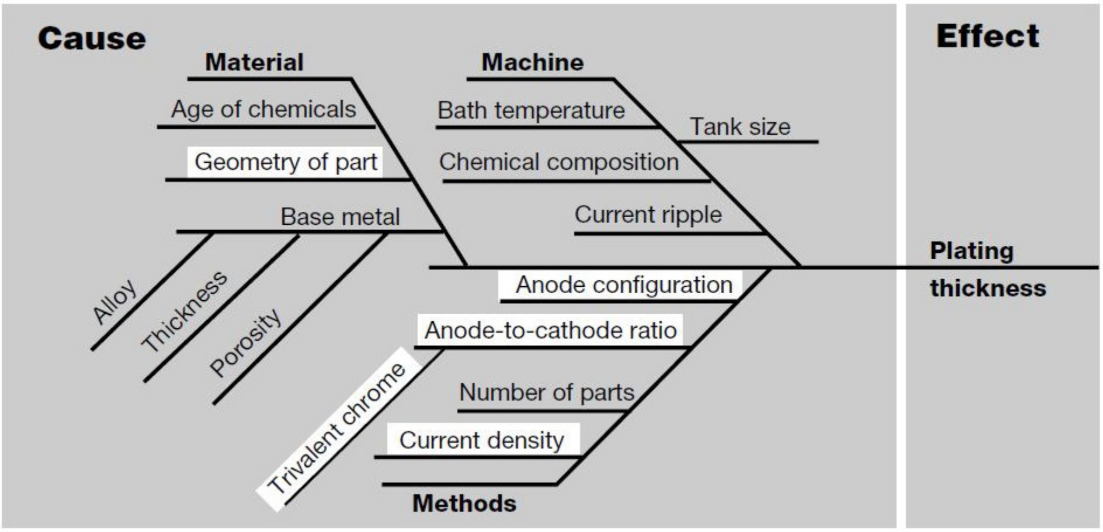

Figure 2.4.1a Cause and Effect Diagram on the Plating Thickness Problems

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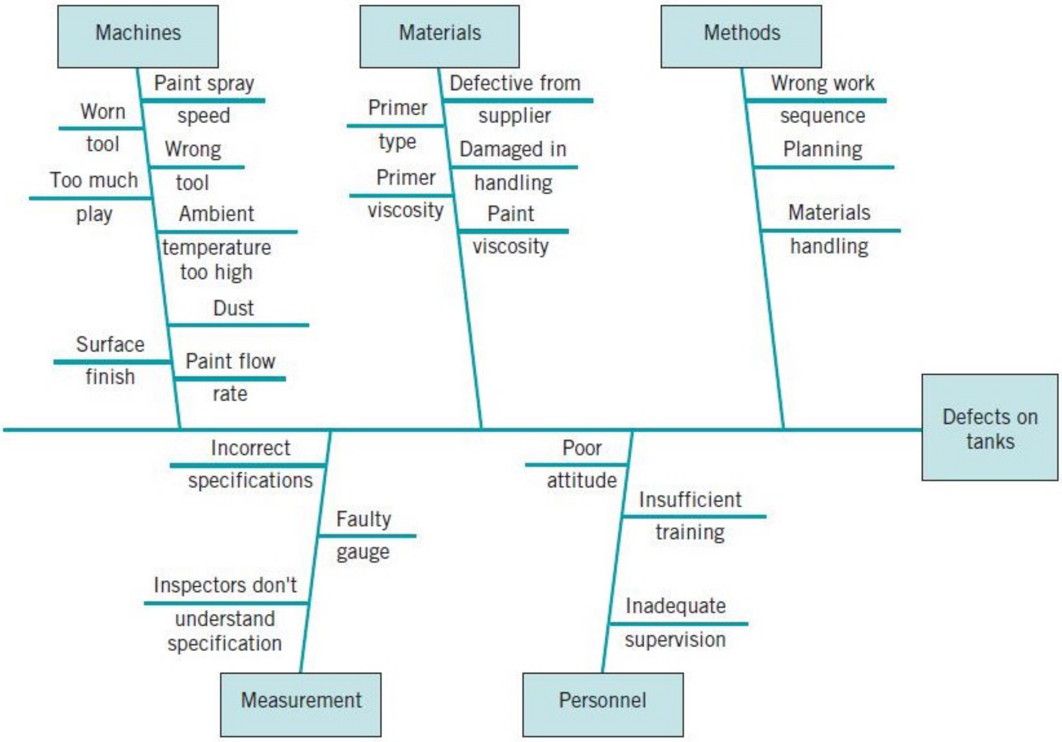

Figure 2.4.1b Cause and Effect Diagram on the Tank Defect Problem

2.5 Flow Chart

2.5.1 What is a Flow Chart?

- A flowchart is a diagram that uses graphic symbols to depict the nature and flow of the steps in a process. Another name for this tool is "flow diagram."
- Shows customer and supplier boundaries and relationships.
- Shows inputs, tasks/actions and outputs of a process.
- It can be used for business processes as well as production processes.
- After a process has been identified for improvement and given high priority, it should then be broken down into specific steps and put on paper in a flowchart. This procedure alone can uncover some of the reasons a process is not working correctly. Other problems and hidden traps are often uncovered when working through this process.
- Flowcharting also breaks the process down into its many sub-processes. Analyzing each of these separately minimizes the number of factors that contribute to the variation in the process.

2.5.2 Why Use a Flow Chart?

- Provides way to map the activities for a given process, product and/or service.
- Promotes and enhances process understanding.
- Helps to identify key measure points.

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- Standardizes and documents reliable processes.
- Provides tool for training.
- Identifies bottlenecks.
- Identifies problems areas and improvement opportunities as well as variation sources.
- Depicts customer – supplier relationships.
- Gives a tool to determine value and non – value adding activities.
- Helps the team to get involved in the understanding of how a process works.

2.5.3 When to Use a Flow Chart?

- Performing process analysis.
- Establishing any new process, such as the design and manufacture of a new part.
- Documenting the "as-is" process.
- Describing the ideal process.
- Looking for key measurement points.
- Promoting the understanding of a process thru explanation of the steps pictorially. People may have different perspectives about how a process works. A flowchart can help an individual gain agreement about the sequence of process steps. Flowcharts promote understanding in a way that written procedures cannot do. One good flowchart can replace pages of words.

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- Providing a tool for training for employees. Because of the way they visually layout the sequence of process steps, these can be useful in training employees to perform the process according to standardized procedures.
- Identifying problem areas and opportunities for process improvement. Once you break down the process steps and diagrams, problem areas become more visible. It is easy to spot opportunities for simplifying and refining your process by analyzing decision points, redundant steps and rework loops.
- Depicting customer – supplier relationships.

2.5.4 What Symbols are used in Flowcharts?

The symbols that are commonly used in Flowcharts have specific meanings and are connected by arrows indicating the flow from one step to another:

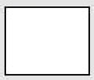
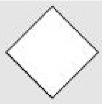
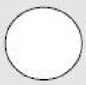
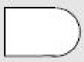
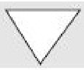
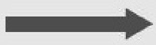
Symbol	Meaning	Example
	Operation	• Drill hole • Fill out form • Design a part
	Decision point	• Make or buy? • Send to operation A or operation B?
	Inspection	• Part tested by QA • Forms audited • Buyoff
	Delay	• For signature • To be filed • From supplier • From stores
	Storage	• Filed documents • In stores
	Direction of flow	• Move a part to next location • Deliver a document • Process output • Process input
	Transmission	• Data transmission

Figure 2.5.4a Flow Chart Symbols

2.5.5 What are the Levels of Flow Chart Detail?

When you are developing a Flowchart, consider how it will be used and the amount and kind of information needed by the people who will use it. This will help you determine the level of detail to include. Figure 2.5.5a compares the levels described using the process for producing the Plan of the Day (POD).

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Macro Level. The top leadership may not need the amount of detail required by the workers in a process. A "big picture," or macro-level, view of the process may be enough for their purposes. Generally, a macro-level Flowchart has fewer than six steps. Think of it as a view of the ground from an airplane flying at 30,000 feet.

Mini Level. The term "mini" or "midi" is used for a Flowchart that falls between the big picture of the macro level and the fine detail of the micro level. Typically, it focuses on only a part of the macro-level Flowchart. Using the airplane analogy, you see the level of detail as if looking at the ground from 10,000 feet.

Micro Level. People trying to improve the way a job is done need a detailed depiction of process steps. The micro-level, or ground-level, view provides a very detailed picture of a specific portion of the process by documenting every action and decision. It is commonly used to chart how a particular task is performed.

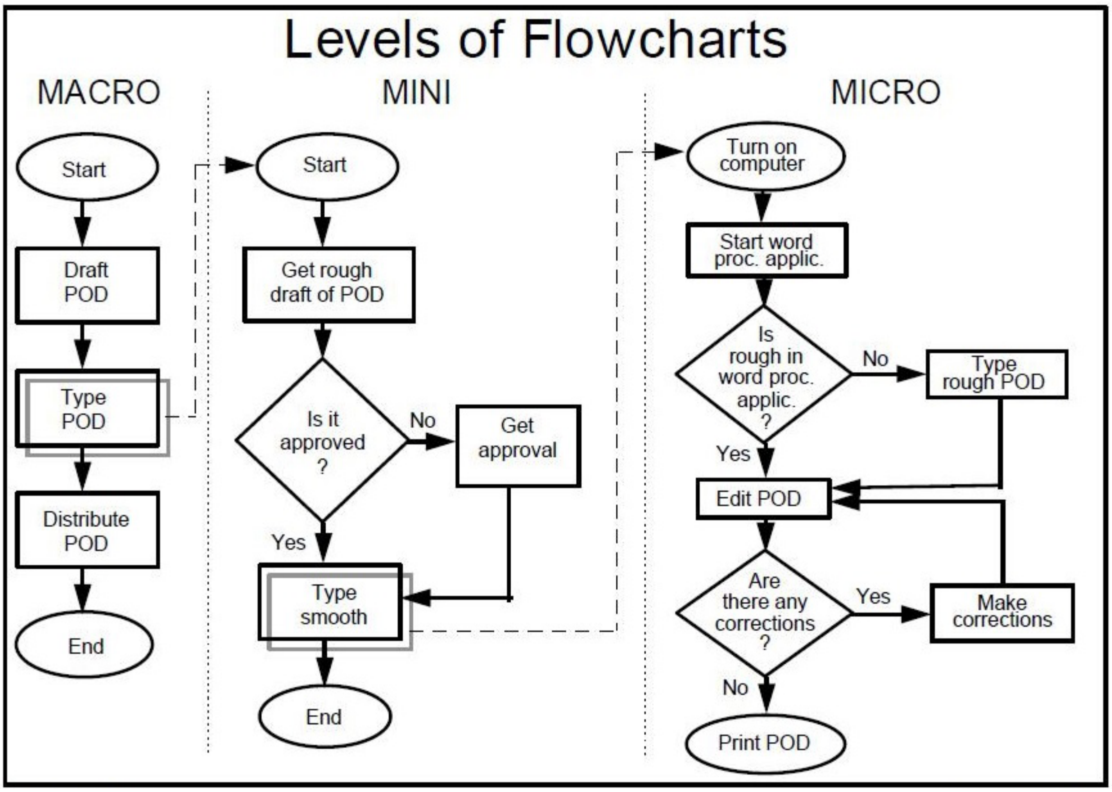

Figure 2.5.5a Levels of a Flow Chart Details

2.5.6 What are the Types of Flow Charts?

Besides the three levels of detail used to categorize Flowcharts, there are three main types of Flowcharts – Linear, Deployment, and Opportunity. The level of detail can be depicted as macro, mini, or micro for each of these types.

The succeeding figures show how one process, Producing the Plan of the Day (POD), might be depicted using each of the three Flowchart types.

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Linear Flowchart. A Linear Flowchart (Figure 2.5.6a) is a diagram that displays the sequence of work steps that make up a process. This tool can help identify rework and redundant or unnecessary steps within a process.

Deployment Flowchart. A Deployment Flowchart shows the actual process flow and identifies the people or groups involved at each step (Figure 2.5.6b). Horizontal lines define customer-supplier relationships. This type of chart shows where the people or groups fit into the process sequence, and how they relate to one another throughout the process.

Opportunity Flowchart. An Opportunity Flowchart – a variation of the basic linear type – differentiates process activities that add value from those that add cost only (Figure 2.5.6c).

- **Value-added** steps **(VA)** are essential for producing the required product or service. In other words, the output cannot be produced without them.
- **Cost-added-only** steps **(CAO)** are not essential for producing the required product or service. They may be added to a process in anticipation of something that might go wrong, or because of something that has gone wrong. For example, end-of-process inspection might be instituted because of defects, errors, or omissions that occurred in the past. Other CAO steps may depend on actions in supplier processes – waiting for approvals or the availability of equipment, for example.

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2.5.7 How to Construct a Linear Flow Chart?

1) Define the process to be flowcharted, and the purpose for flowcharting it.
2) Assemble the right people to develop the Flowchart – those operators, technicians, or office workers who are actually involved in the process.
3) Establish process boundaries – the starting and ending points.
   - Identify the major activities or sub processes that are included in the process.
   - Determine what is not included in the scope of the process to remove any doubt or confusion about the boundaries. This may also help establish the scope of related processes.
4) List the steps, activities and decisions to be charted. If your team is not sure about a step, mark it to be investigated later.
5) Put the steps in chronological order. Sometimes, it is easier to start with the last step and work back to the first step.
6) Assign flowchart symbols such as boxes, diamonds and triangles.
7) Review and title the chart.

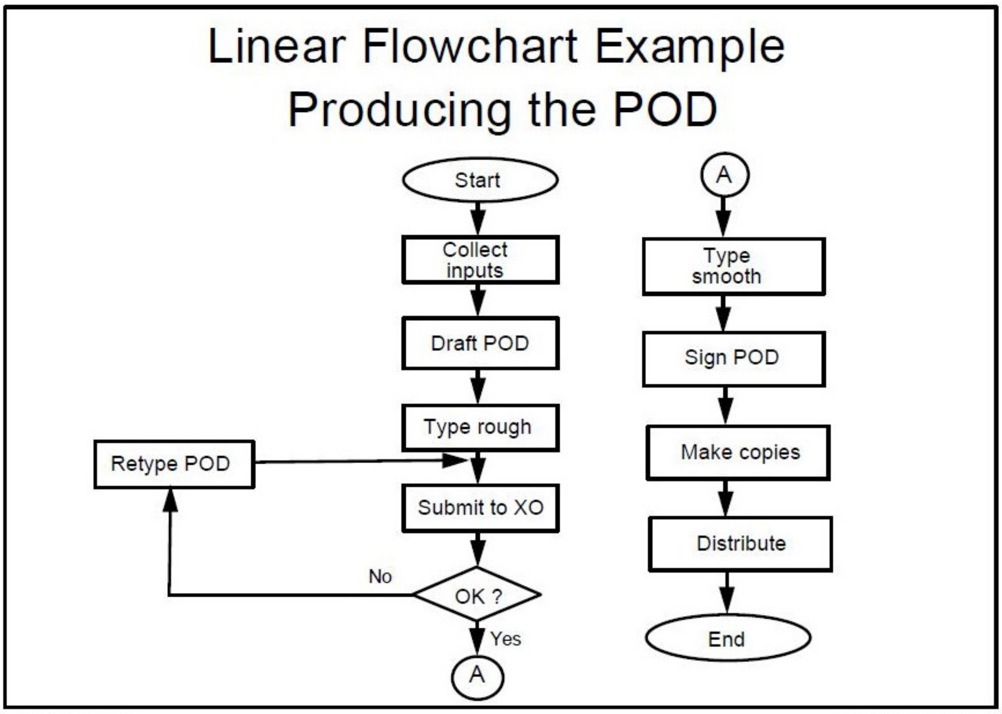

Figure 2.5.6a Example of a Linear Flow Chart

2.5.8 How to Construct a Deployment Flow Chart?

1) List the major steps of the process vertically on the left side of a sheet of paper.
2) List the responsible process workers across the top, each in a separate column.
3) Place each step in the appropriate column under the responsible process worker's name.
4) Connect the steps in the order in which they relate to each other.

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REMINDER: Every horizontal line in a Deployment Flowchart identifies a customer supplier relationship. This resembles a **SIPOC** (**S**uppliers-**I**nputs-**P**rocess-**O**utputs-**C**ustomers) Diagram.

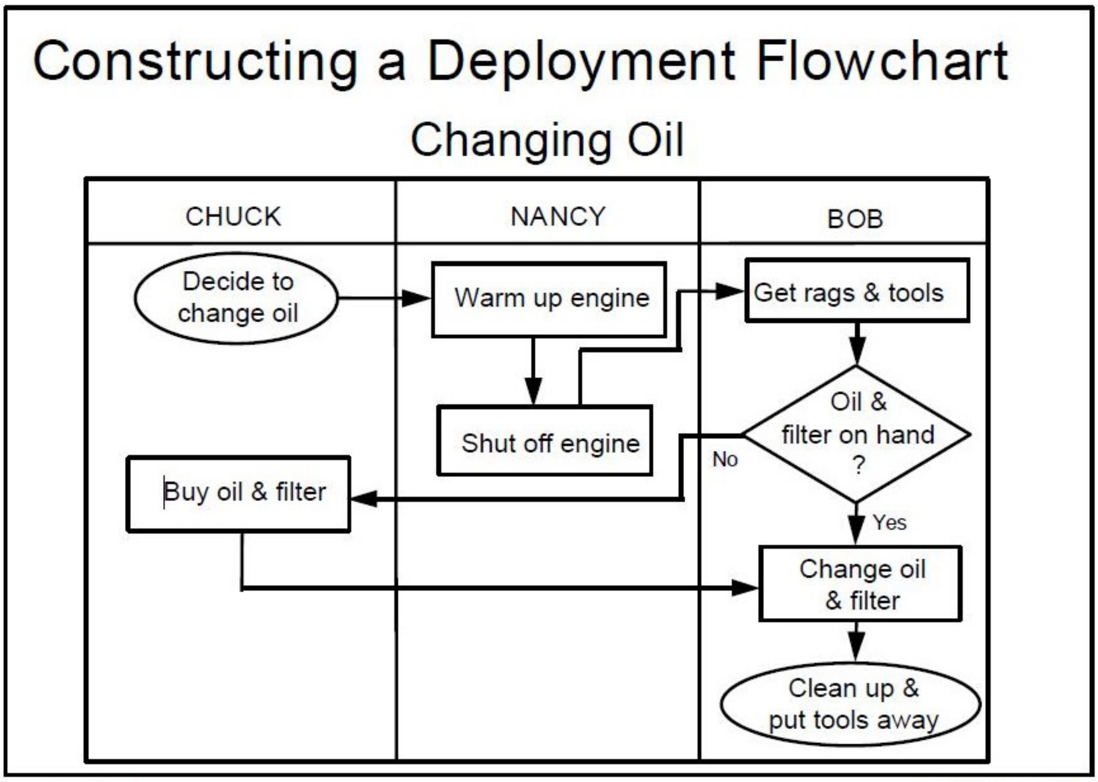

Figure 2.5.6b Example of a Deployment Flow Chart

2.5.9 How to Construct an Opportunity Flow Chart?

To construct an Opportunity Flowchart, you need to distinguish value-added from cost-added-only steps. You may want to review how to differentiate these steps under the description of Opportunity Flowcharts that precedes this discussion.

1) Starting with your Linear Flowchart, evaluate each step before placing it in the Opportunity format.
2) Divide your paper into two columns headed Value Added (VA) and Cost Added Only (CAO).
3) List the steps in the process in these columns vertically, all VA steps in one column and all CAO steps in the other.
4) Connect the steps.

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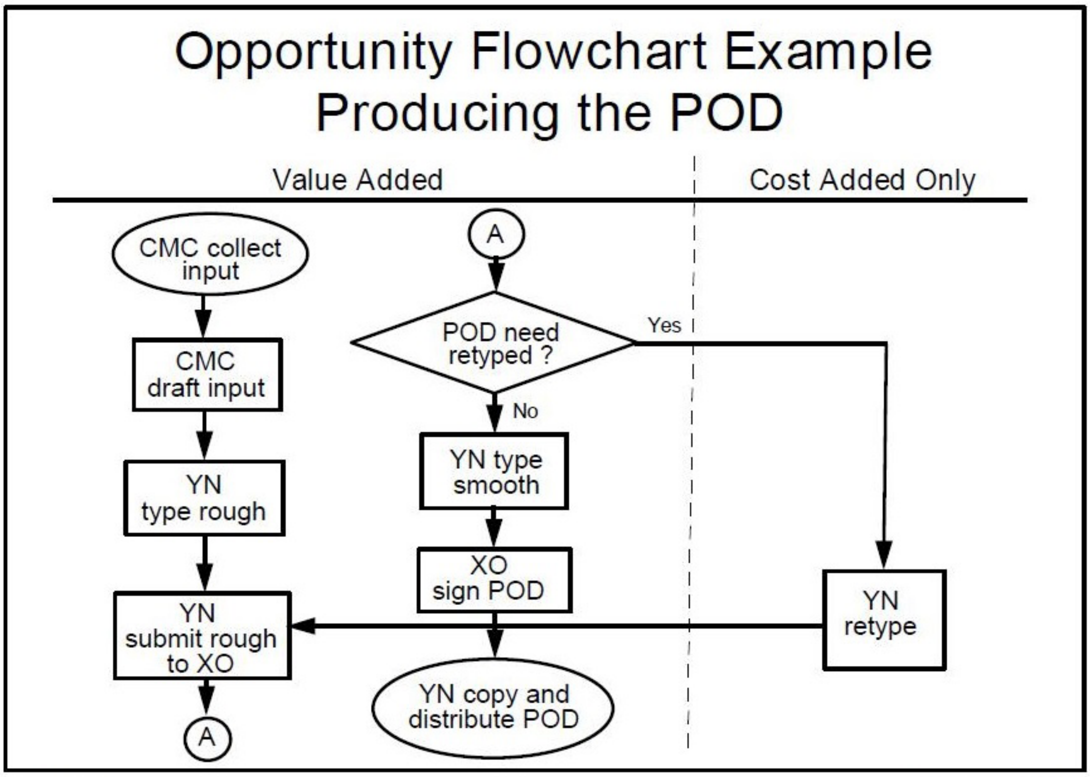

Figure 2.5.6c Example of an Opportunity Flow Chart

2.5.10 How to Interpret a Flow Chart?

A Flowchart will help you understand your process and discover ways to improve it only if and only if you use it to analyze what is happening. Interpreting your Flowchart will help you to:

- Determine who are the entities involved in a particular process (suppliers, inputs, processes, outputs and customers).
- Form theories and collect information about root causes.
- Identify ways to streamline the process like what a Value Stream Mapping (VSM) does. By streamlining a business process only means finding ways to be more productive while maintaining cost effectiveness.
- Determine how to implement changes to the process.
- Locate non – value added (NVA) steps or those cost-added-only steps (COA).
- Provide training on how the process works or should work.

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Here is a set of recommended steps on how to do an effective Flow Chart Analysis.

1) Examine each processes in the chart following the conditions of the processes that need to be improved.

   Bottlenecks. These points in the process where it slows down may be caused by redundant or unnecessary steps, rework, lack of capacity, or other factors. In the Fire Drill for example, the phrase "Monitors go to Log Room to get red hats…" step indicates a potential bottleneck.

   Another illustration is when you have three (3) processes, Process 1 can produce 100 units, Process 2 can accommodate 90 units and the last process, Process 3, can work on 100 units. It can be observed that there is a lack of capacity in Process 2 that can consequently bring delays in the three process activity.

   Weak links. These are steps where problems occur because of inadequate training of process workers, equipment that needs to be repaired or replaced, or insufficient technical documentation. "We cannot continue this process due to a machine breakdown" is one of the phrases that manifest weak link.

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Poorly defined steps. Steps which are not well-defined and oriented may be interpreted, perceived and performed in a different way by each person involved, leading to process variation. This is greatly affected by a common psychological factor of individual perception. "Improvise" is a poorly defined step and manifest a weak link.

Cost-added-only steps. Such steps add no value to the output of the process and should be subjected for elimination. Steps that are NVAs or COAs may contain the words Hold, Pre – Position, Position, Search and Select. This is based on the Therbligs invented by Frank Gilbreth.

2) Examine each decision symbol. You may want to collect data on how a decision is being executed, on what is the frequency of "Yes" or "No" and "Go" or "No Go". If the answers in any decision point go one way rather than the other, you may opt to remove the decision point.
3) Examine each rework loop. Processes with numerous checks generate rework and waste. Examine the activities preceding the rework loop and identify those that need to be improved. Minimize the loop of rework and if possible, eliminate the loop.
4) Examine each activity symbol. If the activities do not build value, eliminate those. This is one base principle of Lean Thinking, i.e., Build Value, Nothing but Value.

2.5.11 What are the Pitfalls in using a Flow Chart?

- The user of the chart may be unconsciously bias in a way that he drawn the chart as they envision the process, not as it is.
- They may be reluctant to show the obviously illogical parts of the process for fear they will be called upon to explain why they allowed it to happen.
- Rework loops are often overlooked due to the thinking that these are small activities only and they think that those are insignificant.
- People drawing the chart are not process owners or do not have full comprehension of the process.

2.6 Scatter Diagram

2.6.1 What is a Scatter Diagram?

- A plot of one measured variable against another. Paired measurements are taken on each item and plotted on a standard X-Y graph.
- It is a problem solving tool and is also known as the correlation diagram.
- It is used to uncover possible cause-and-effect relationships.
- It cannot prove that one variable causes another, but it does show how a pair of variables is related and the strength of that relationship. Statistical tests quantify the degree of correlation between the variables.
- It is a tool used in regression modelling or predicting a close estimate of the dependent variable given a value of the independent variable by the factor of relationship present between the two.

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2.6.2 Why Use a Scatter Diagram?

- To study the possible causal relationship between one variable and another.

REMINDER: It will be a pitfall to think that **correlation** is the same thing as the **causality**. The scatter diagram is used to determine possible causal relationship between two variables. The effect of causation may be accounted to a third variable that is why only correlation is being supplied by a scatter diagram not an exact causal relationship.

2.6.3 When to Use a Scatter Diagram?

- There is a need to display what happens to one variable when another one changes (i.e., in order to determine whether two variables are related).
- Performing a DOE (Design of Experiments).
- Looking for a root cause to an out-of-control point during the use of multivariate SPC.
- Confirming relationships identified in a cause and effect diagram.
- Performing data analysis during the Product, Process, and Problem Analysis.

2.6.4 How to Construct a Scatter Diagram?

1) Collect twenty (2) or more paired samples of data believed to be related. The data can be discrete or continuous or combination of the two. Say, the first variable is said to be the measurement of a part (continuous) in relation to the second variable, number of rejected units with those measurements (discrete).
2) Make a tabular form of the data such data for every sample taken there is corresponding paired value.
3) Draw the horizontal and vertical axes of the scatter diagram. The values marked on the axis should get larger as you move up or right on each axis.
4) Label the axes. The variable that is believed to be the cause will be on the x-axis while the variable that is believed to be the effect on the y-axis.
5) Plot the paired data. After plotting all paired data, you can draw a straight line in the cluster of points in order to see the possible relationship.
6) Analyze what relationship is being described of the paired data. For analysis reference, please see succeeding paragraphs.

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2.6.5 How to Interpret a Scatter Diagram Using Patterns?

The direction and "tightness" of the cluster gives a clue as to the type and the strength of the relationship between the two variables. The more this cluster resembles a straight line, the stronger the correlation between the variables. Again, it should be kept in mind that A strong correlation does not necessarily mean that one variable caused the other. In particular, there could be a third variable that is the cause for changes in both of the plotted variables, and it is the causal relationships involving this third variable that result in a clustered pattern in the scatter diagram.

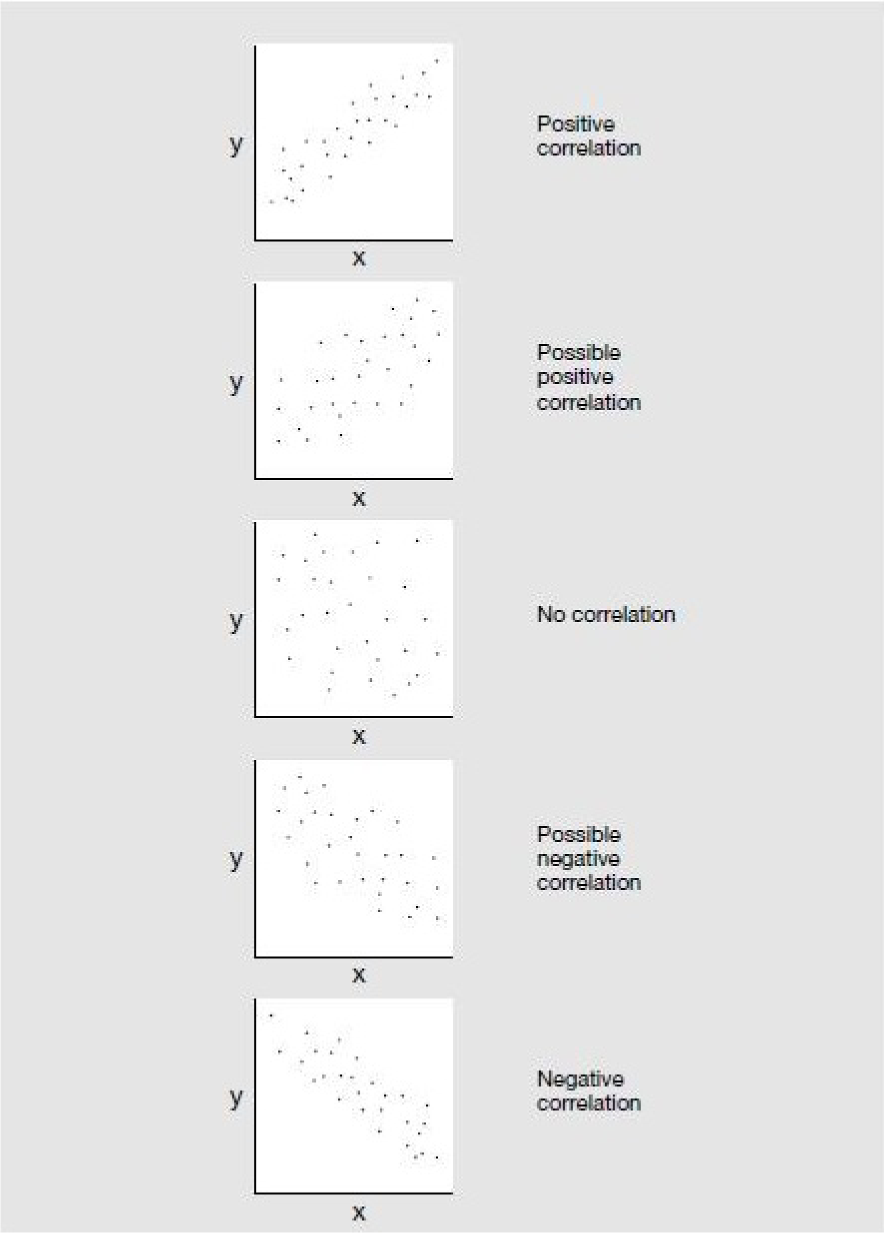

Figure 2.6.5a Scatter Diagram Patterns and Interpretations

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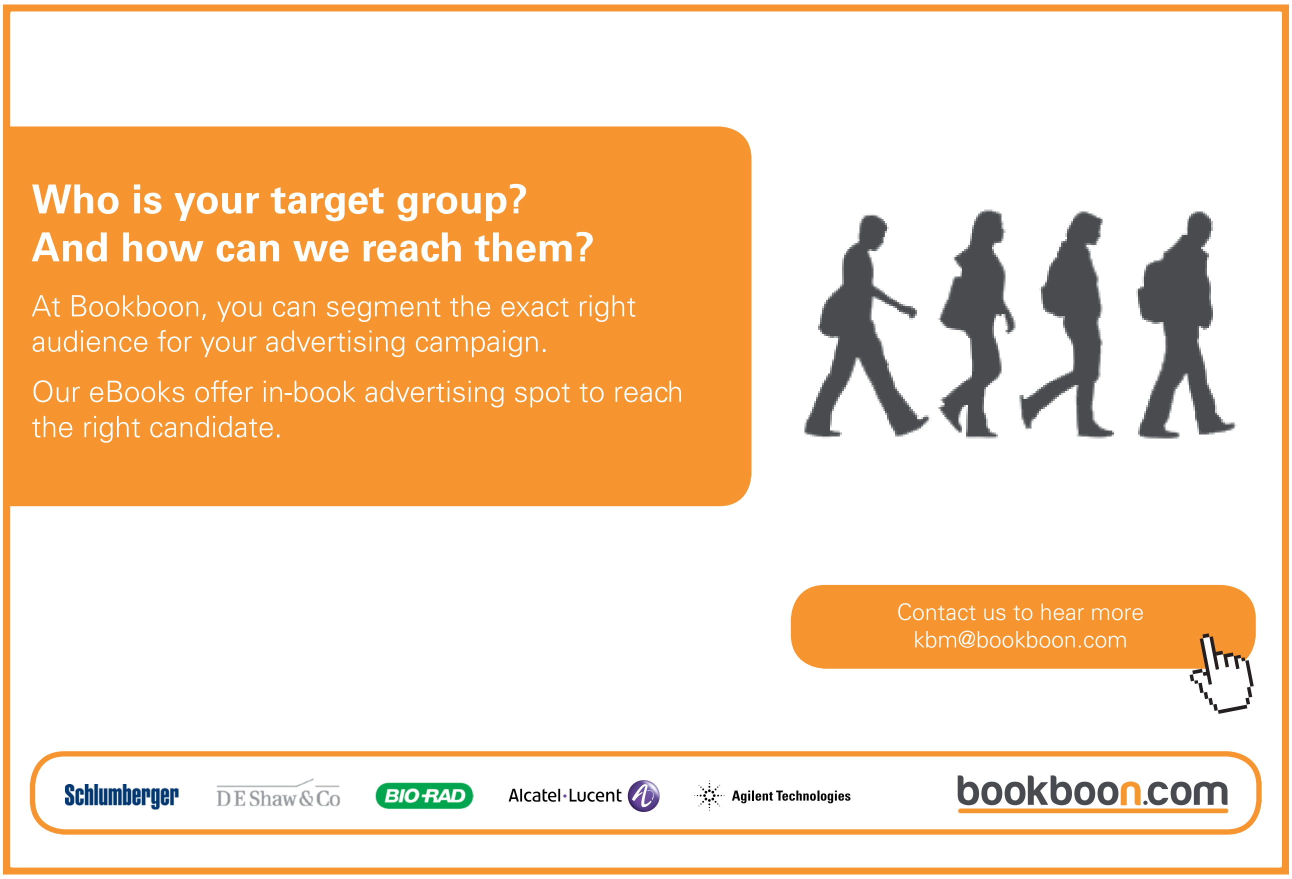
Figure 2.6.5a shows five (5) patterns namely, positive correlation, possible positive correlation, no correlation, possible negative correlation and negative correlation. Basically, there are three (3) types of correlation.

The first one is the **positive correlation** wherein when a variable changes, the other variable tends to change directly proportional to the former. If the x increases, y increases too and if x decreases, y decreases too.

The second pattern is the **negative correlation** wherein when a variable changes, the other variable tends to change indirectly or inversely in reference to the former. Say, when x increase, the value of y decreases and when the value of x decreases, the value of y increases.

The third pattern is the **no correlation** wherein it said that the first variable has no correlation or relationship with the second variable.



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2.6.6 How to Interpret a Scatter Diagram Using Correlation Coefficient

There is no problem in using the scatter diagram to check the relation between two variables but for the sake of argument, what if an individual uses a different scale for the same set of data, the depicted pattern might have been different. To assure correct interpretation we can use the **Linear Correlation Coefficient *(r)*.** It is a measure of how strong is the linear relationship between two variables. You can use the mathematical equation below to calculate ***r***.

$$\boldsymbol{r = \frac{\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}}{\sqrt{\sum_{i=1}^{n} {x_i}^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}}\sqrt{\sum_{i=1}^{n} {y_i}^2 - \frac{(\sum_{i=1}^{n} y_i)^2}{n}}}}$$

Given this equation, we can evaluate the relationship by analyzing the calculated ***r*** based on the properties given below.

1) Remember, ***r*** is always between -1 and 1, inclusive, i.e., -1≤ ***r*** ≤ 1.
2) If ***r*** = 1, there is a perfect positive correlation between the two variables.
3) If ***r*** = -1, there is a perfect negative correlation between the two variables.
4) The closer ***r*** to 1, the stronger is the evidence of positive correlation between the two variables.
5) The closer ***r*** to -1, the stronger is the evidence of negative correlation between the two variables.
6) The closer ***r*** to 0, the stronger is the evidence of no linear correlation between the two variables.

Consequently, when there is an evident correlation coefficient calculated, we can use the x variable to predict the possible value of the y variable. This is with the use of the **regression analysis**. The term **regression** can be tracked in the works of Sir Francis Galton. He noted that the sons of very tall fathers tended to be tall, but not quite as tall as their fathers. Also, sons of very short fathers tended to be short, but not quite as short as their fathers. He called this tendency, **regression**.

Given below is the mathematical equation of the regression model:

$$\boldsymbol{y = a + bx}$$

Where:

y = the value of the dependent variable we want to predict
a = is the y intercept
b = is the x intercept
x = is the independent variable we will use to estimate the corresponding y value

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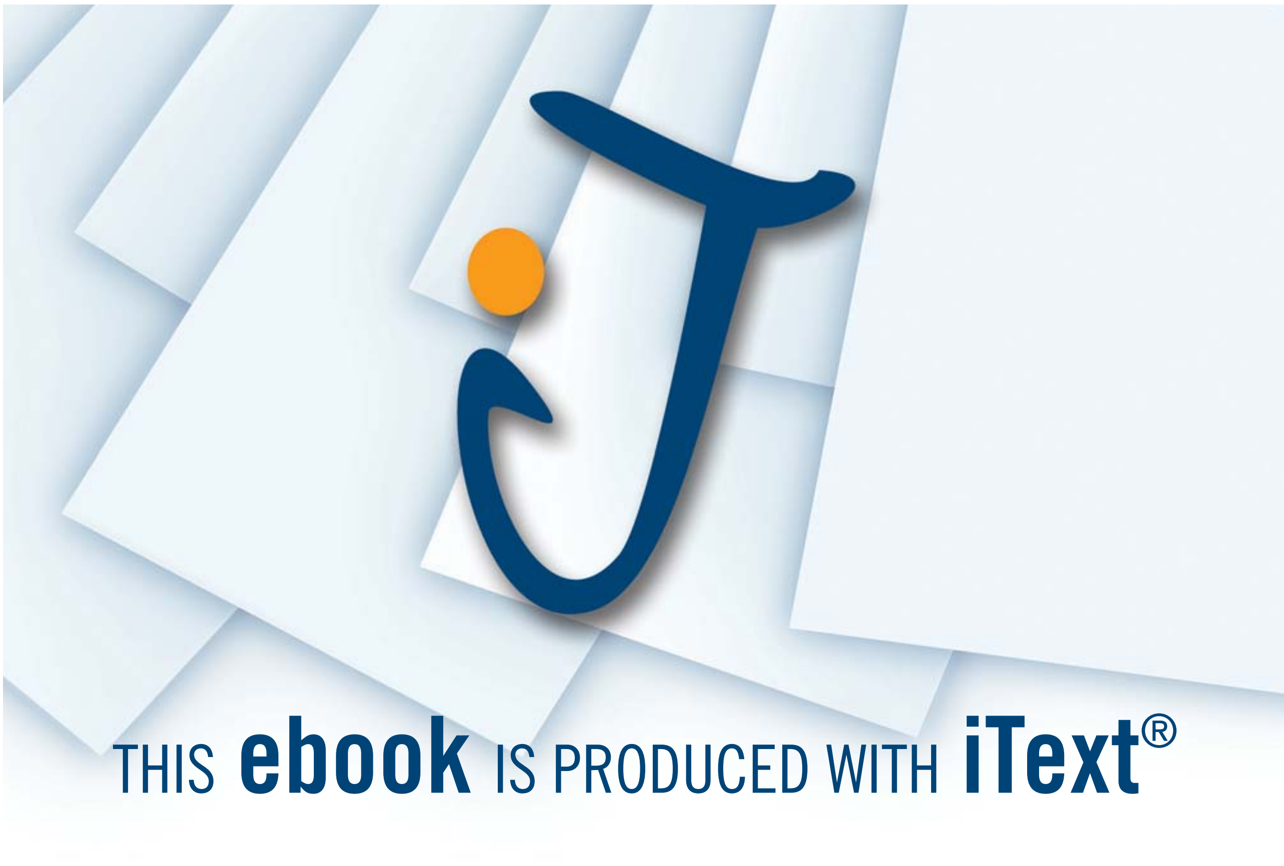
In order to calculate for the values of a, b and x, we can use the equations below.

$$b = \frac{\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}}{\sqrt{\sum_{i=1}^{n} {x_i}^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}}}$$

$$a = \bar{y} - b\bar{x}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$



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Example 2.6a Specific Heat

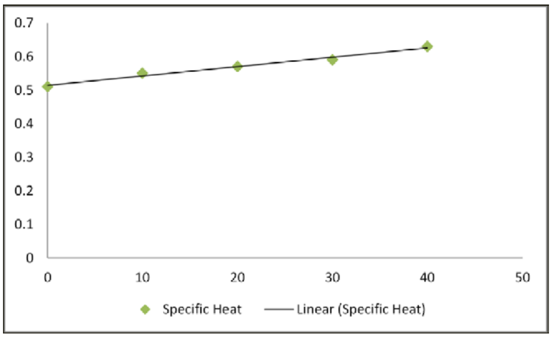
An analyst had collected measurements of the specific heat of a certain were made in order to investigate the variation in specific heat with the specific heat.

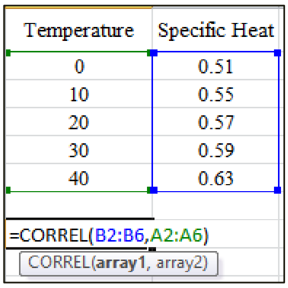
Temperature (Celsius)	0	10	20	30	40
Specific Heat	0.51	0.55	0.57	0.59	0.63

a) What can you say about the relationship of the two variables? Value of r?
b) What is the regression equation?
c) What is the value of the specific heat if the temperature is 25 degrees Celsius?

Solutions:

a) By plotting paired points, we can say that there is a positive correlation between the variables. The value of r using MS Excel with function CORREL is 0.9899 which is close to 1.0 depicting a positive correlation too.





Temperature	Specific Heat
0	0.51
10	0.55
20	0.57
30	0.59
40	0.63

=CORREL(B2:B6,A2:A6)
CORREL(array1, array2)

Sample	Temperature (x)	Specific Heat	xy	x^2	y^2
1	0	0.51	0.00	0	0.26
2	10	0.55	5.50	100	0.30
3	20	0.57	11.40	400	0.32
4	30	0.59	17.70	900	0.35
5	40	0.63	25.20	1600	0.40
Total	100	2.85	59.80	3000	1.63

b) Using the equations for regression;

$$b = \frac{59.8 - \frac{2.85x100}{55}}{\sqrt{3{,}000 - \frac{100^2}{5}}} = 0.0028$$

$$a = 0.57 - 0.00028 * 20.0 = 0.514$$

Therefore, the equation is y = 0.514 + 0.0028x

c) The value of y when x = 25 will be, y = 0.514 + 0.0028*25 = **0.584.**

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2.7 Control Charts

2.7.1 What is a Control Chart?

- A statistical control chart is a line graph of the measurements of a product or process over time that has statistically based control limits placed on it.
- The points that are plotted on a control chart may be the actual measurements of a part characteristic or summary statistics from samples (subgroups) of parts taken as they are produced over time.
- A control chart has control limits based upon process variation and a centerline representing the average of all the measurements used to construct the control chart.
- The statistical control limits define the boundaries of the expected variation of the process when only common-cause variation is operating, and are placed three standard deviations above and below the centerline.
- Summary statistics often plotted include the subgroup average, subgroup range, subgroup standard deviation, percent defective, average number of defects per unit, and so on.
- Key characteristics are examples of process output that can be monitored by statistical control charts.
- All processes have and exhibit variation. Variation makes defects and poor quality possible – not something we want. Statistical control charts monitor and display the variation in process output and can be an important tool for product and process improvement.

2.7.2 Why Use a Control Chart?

- To display and manage variation in process output over time.
- To identify when a process changes.
- To provide a basis for improvement.
- To identify the causes of variation and process capability.
- To distinguish special from common causes of variation (that is, when to correct sporadic problems or when to change the process).
- To help assign causes of variation.
- To identify process problems on an ongoing basis.
- To tell the operator when not to take action and just let the system run.
- To control upstream processes contributing to the production of a product.
- To reduce process variation and prevent defective output from being produced.
- To eliminate waste and reduce loss.

2.7.3 When to Use a Control Chart?

- Measuring key characteristics of a product or process.
- Moving from an inspection-based system to a prevention-based system.
- Stabilizing a process to make it more predictable.
- Improving the capability of a process early on.
- Assessing and verifying the effectiveness of design or process changes.

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2.7.4 How to Construct a Control Chart?

1. Define the key characteristic or quality characteristic to be measured.
2. Define where in the process the key characteristic will be measured. It should be at the earliest possible point in the manufacturing process where the characteristic can be measured.
3. Select which control charts to use.
4. Determine subgroup size and frequency of measurement.
5. Take measurements.
6. Plot measurements or summary statistics on the chart.
7. Connect the plot points.
8. After at least 20 plot points, calculate the centerline and control limits (the actual number of plot points depends upon the circumstances).
9. Identify any out-of-control points.
10. Analyze for special causes of variation and remove them.
11. Remove subgroup data corresponding to any out-of-control points from the calculation of the control limits.
12. Add a corresponding number of plot points and recalculate the control limits using data from all in-control plot points.
13. Extend the control limits into the future. Do not recalculate the control limits until significant and identifiable process changes occur. Do not change the control limits continually as new data is added.

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2.7.5 How Select a Control Chart?

In selecting a control chart to be used, the first to do is to identify whether the data to be collected and studied is **variable (continuous data)**, there are measurable data like length, weight, diameter, thickness or **attribute (discrete data),** these are countable data such as number of defects or defective in a lot or average number of defects per unit.

When using variable data, both average and variability of the process must be monitored. **The control limits must be based on the natural variability of the process (not specification limits).**

Data	Chart	Conditions	Subgroup Size
Variable	Traditional X Bar and R	One Part Number High volume production rate One characteristic charted	2 to 8, 3 to 5 preferred
	Traditional X Bar and S	Same as X bar and R	2 or more
	Individual X – Moving Range (IX-MR)	One part number One characteristic charted Low volume production rate	One
	a) Target X Bar and R b) X Bar and S c) IX – MR	Short run applications Multiple part numbers charted One characteristic per part Similar variability on all parts	a) 2 to 8 b) 2 or more c) One
Attribute	p (proportion defective)	Very high volume production rate One type of unit Constant or varying subgroup size	At least 30 but can vary
	np (number defective)	Very high volume production rate One type of unit Constant subgroup size	At least 30 but constant
	c (counting defects on a unit)	Many types of defects possible One type of unit Constant subgroup size	One more unit or more, but constant
	u (average number of defects per unit)	Many types of defects possible One type of unit Constant or varying subgroup size	One more unit or more, but constant

Table 2.7.4a Chart Selection Guide

It is very important to select the appropriate chart so as to bear a favorable result. With precision and accuracy of the choice made, a better understanding of the process and the sources of its variations can be strongly established.

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2.7.6 How to Analyze a Control Chart?

With the use of a control charts with all data plotted on it, we can analyze the behavior of the process and determine the current condition of it thru the use of the **Sensitizing Rules for Control Charts.** The Western Electric Handbook (1956) suggests a set of decision rules for detecting nonrandom patterns on control charts. These rules are those in numbers 1 to 4 and eventually integrated to the general Sensitizing Rules for Control Charts. Figure 2.7.5a shows the zones used in interpreting and analyzing a control chart. **Whenever one of these rules had been evident in the control chart being created, we can say that the process has a higher chance to produce out of control units.**

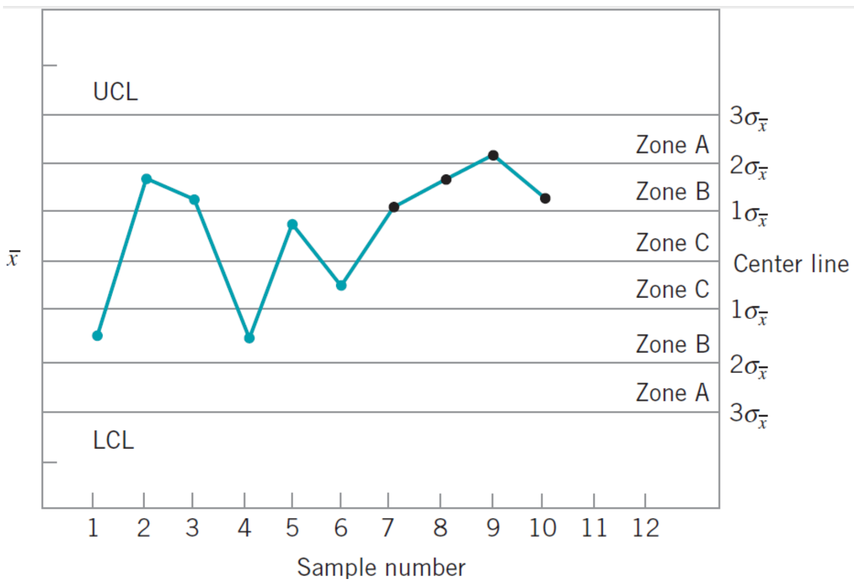

Figure 2.7.5a Zones for Control Chart Analysis

Sensitizing Rules for Control Charts

1. One or more points outside of the control limits.
2. Two of three consecutive points outside the two sigma warning limits still inside the control limits.
3. Four of five consecutive points beyond the one sigma limits.
4. A run of eight consecutive points on one side of the center line.
5. Six points in a row steadily increasing or decreasing.
6. Fifteen points in a row in Zone C (both above and below the center line).
7. Fourteen points in a row alternating up and down.
8. Eight points in a row on both sides of the center line with none in Zone C.
9. An unusual or non-random pattern in the data.
10. One or more points near a warning or control limit.

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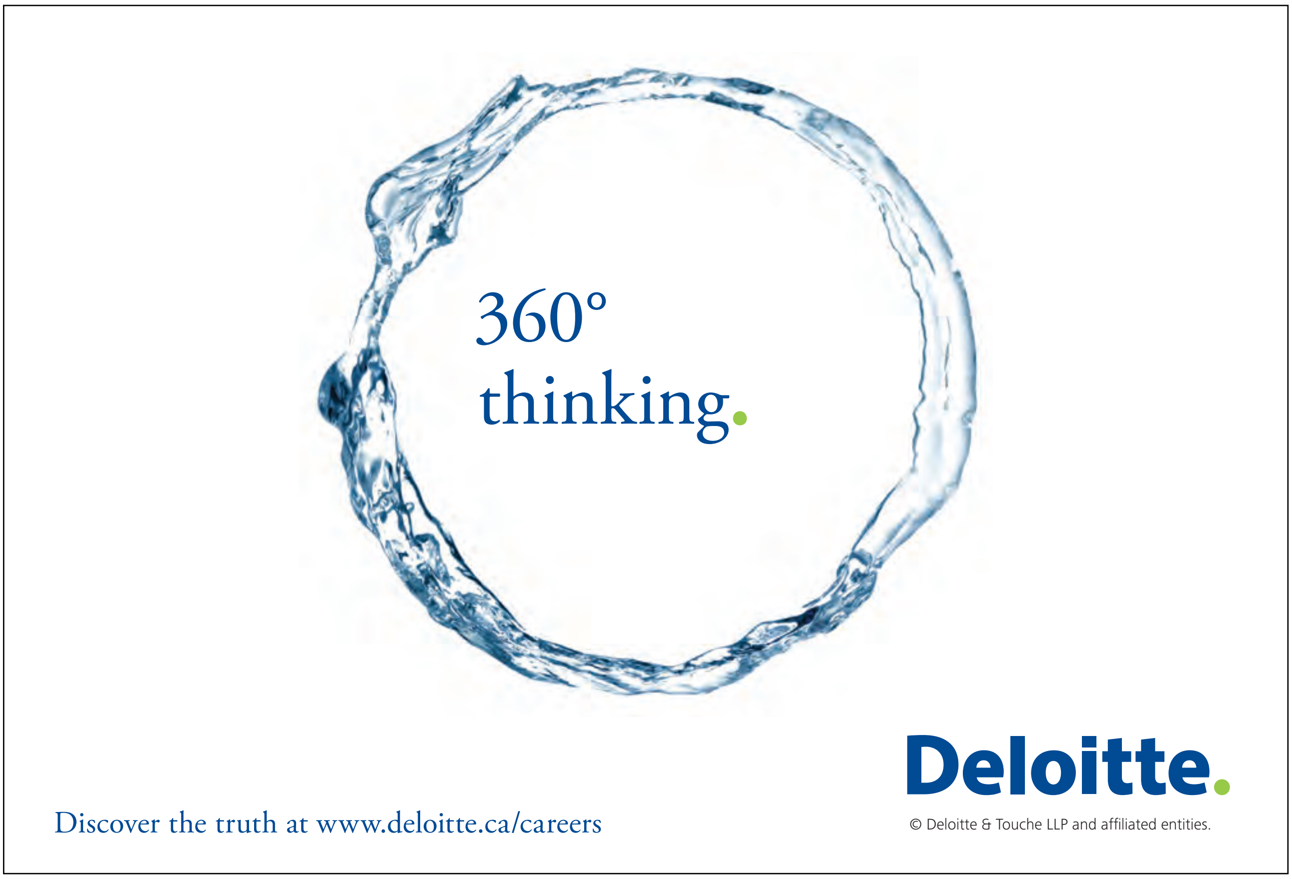
2.7.7 X Bar and R Charts

Control charts for variable data used to monitor the behavior of the process average and the range of single measureable characteristic.

In order to construct a X Bar and R Chart, we must plot averages and ranges on separate charts and adding the centerline and control limits to each part.

The following conditions must be met in order to use this chart:

- Subgroup size is greater than 1.
- One part number.
- One characteristic per chart.
- Product is produced frequently.
- Should have at least 20 subgroups before calculation of control limits.
- Engineering specification limits must not be drawn on the X Bar chart.



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To calculate Plot Points, Central and Control Limits:

Chart	Control Limits	Centerlines	Plot Points	Subgroup Size
X Bar	$UCL = \bar{\bar{x}} + A_2\bar{R}$ $LCL = \bar{\bar{x}} - A_2\bar{R}$	$\bar{\bar{x}} = \frac{\sum \bar{x}}{k}$ k = number of subgroups	$\bar{x} = \frac{\sum x}{n}$	n = 2 to 9 but 3 to 5 preferred. Subgroup sizes can vary, but constant is easier.
R	$UCL = D_4\bar{R}$ $LCL = D_3\bar{R}$	$\bar{R} = \frac{\sum R}{k}$	R = Range of subgroup = Xmax - Xmin	

Table 2.7.6a X Bar and R Chart Limits

For values of the constant such as A_2, D_4 and D_3, please refer to the table below.

Observations in Sample, n	Chart for Averages					Chart for Standard Deviations						Chart for Ranges				
	Factors for Control Limits			Factors for Center Line		Factors for Control Limits				Factors for Center Line		Factors for Control Limits				
	A	A_2	A_3	c_4	$1/c_4$	B_3	B_4	B_5	B_6	d_2	$1/d_2$	d_3	D_1	D_2	D_3	D_4
2	2.121	1.880	2.659	0.7979	1.2533	0	3.267	0	2.606	1.128	0.8865	0.853	0	3.686	0	3.267
3	1.732	1.023	1.954	0.8862	1.1284	0	2.568	0	2.276	1.693	0.5907	0.888	0	4.358	0	2.574
4	1.500	0.729	1.628	0.9213	1.0854	0	2.266	0	2.088	2.059	0.4857	0.880	0	4.698	0	2.282
5	1.342	0.577	1.427	0.9400	1.0638	0	2.089	0	1.964	2.326	0.4299	0.864	0	4.918	0	2.114
6	1.225	0.483	1.287	0.9515	1.0510	0.030	1.970	0.029	1.874	2.534	0.3946	0.848	0	5.078	0	2.004
7	1.134	0.419	1.182	0.9594	1.0423	0.118	1.882	0.113	1.806	2.704	0.3698	0.833	0.204	5.204	0.076	1.924
8	1.061	0.373	1.099	0.9650	1.0363	0.185	1.815	0.179	1.751	2.847	0.3512	0.820	0.388	5.306	0.136	1.864
9	1.000	0.337	1.032	0.9693	1.0317	0.239	1.761	0.232	1.707	2.970	0.3367	0.808	0.547	5.393	0.184	1.816
10	0.949	0.308	0.975	0.9727	1.0281	0.284	1.716	0.276	1.669	3.078	0.3249	0.797	0.687	5.469	0.223	1.777
11	0.905	0.285	0.927	0.9754	1.0252	0.321	1.679	0.313	1.637	3.173	0.3152	0.787	0.811	5.535	0.256	1.744
12	0.866	0.266	0.886	0.9776	1.0229	0.354	1.646	0.346	1.610	3.258	0.3069	0.778	0.922	5.594	0.283	1.717
13	0.832	0.249	0.850	0.9794	1.0210	0.382	1.618	0.374	1.585	3.336	0.2998	0.770	1.025	5.647	0.307	1.693
14	0.802	0.235	0.817	0.9810	1.0194	0.406	1.594	0.399	1.563	3.407	0.2935	0.763	1.118	5.696	0.328	1.672
15	0.775	0.223	0.789	0.9823	1.0180	0.428	1.572	0.421	1.544	3.472	0.2880	0.756	1.203	5.741	0.347	1.653
16	0.750	0.212	0.763	0.9835	1.0168	0.448	1.552	0.440	1.526	3.532	0.2831	0.750	1.282	5.782	0.363	1.637
17	0.728	0.203	0.739	0.9845	1.0157	0.466	1.534	0.458	1.511	3.588	0.2787	0.744	1.356	5.820	0.378	1.622
18	0.707	0.194	0.718	0.9854	1.0148	0.482	1.518	0.475	1.496	3.640	0.2747	0.739	1.424	5.856	0.391	1.608
19	0.688	0.187	0.698	0.9862	1.0140	0.497	1.503	0.490	1.483	3.689	0.2711	0.734	1.487	5.891	0.403	1.597
20	0.671	0.180	0.680	0.9869	1.0133	0.510	1.490	0.504	1.470	3.735	0.2677	0.729	1.549	5.921	0.415	1.585
21	0.655	0.173	0.663	0.9876	1.0126	0.523	1.477	0.516	1.459	3.778	0.2647	0.724	1.605	5.951	0.425	1.575
22	0.640	0.167	0.647	0.9882	1.0119	0.534	1.466	0.528	1.448	3.819	0.2618	0.720	1.659	5.979	0.434	1.566
23	0.626	0.162	0.633	0.9887	1.0114	0.545	1.455	0.539	1.438	3.858	0.2592	0.716	1.710	6.006	0.443	1.557
24	0.612	0.157	0.619	0.9892	1.0109	0.555	1.445	0.549	1.429	3.895	0.2567	0.712	1.759	6.031	0.451	1.548
25	0.600	0.153	0.606	0.9896	1.0105	0.565	1.435	0.559	1.420	3.931	0.2544	0.708	1.806	6.056	0.459	1.541

Table 2.7.1a Factors in Constructing Control Charts

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2.7.8 Process Capability Analysis Using Control Charts

For Control Charts results, it is possible to estimate the process capability using the collected and plotted data. The chart provides information about the **process capability** thru the estimation using the equation, that is,

$$\hat{\sigma} = \frac{\bar{R}}{d_2}$$

where the value of d_2 can be derived from **Table 2.7.1a Factors in Constructing Control Charts.** Using the equation above, we can say that **process capability** (C_p) (is equal to:

$$C_p = \frac{USL - LSL}{6\hat{\sigma}}$$

Process capability compares the spread of the **allowable specification limits** to the spread of the process thru the **allowable natural tolerance limits**. Remember that, **there is no mathematical or statistical relationship between specifications and control limits**. It also depicts the ratio of how much of the tolerance limits is used up.

$$P = (\frac{1}{C_p})100\%$$

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The resulting ratio C_p can be used to analyze the probability of producing out of control or non-conforming units. The numerator of the equation refers to the width of the **specification limits.** These limits are set by the management or the customers while the denominator.

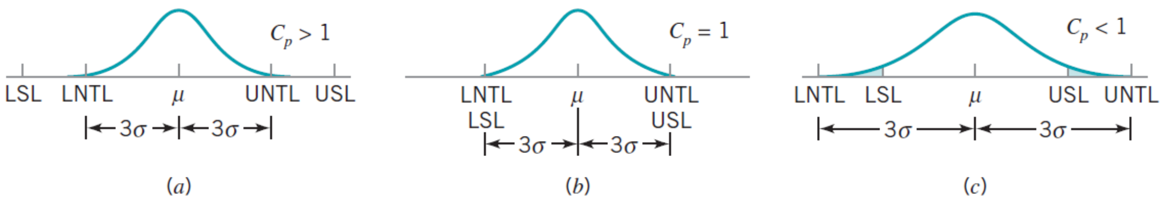

Figure 2.7.8a Process Capability Ratios

In **Figure 2.7.8a Process Capability Ratios**, three major ratios are presented. In **Figure a**, the **process capability is greater than unity or 1.0**. This means that the process much less than 100% of the tolerance band. Any slight change or shift in the process can be absorbed by the remaining unused tolerance band. With this situation, the number of non-conforming units will be relatively few.

In **Figure b**, the **process capability is equal to unity**. This means that the process used up 100% of the tolerance band. For a normal distribution, it will imply about 0.27% or 2,700 ppm (parts per million) non-conforming units produced. This is due to no tolerance can absorb the shift whenever it occurs.

In **Figure c,** the **process capability is greater than the unity**. This means that the process used up greater than 100% of the tolerance band. With this a large number of non-conforming units will be produced.

2.7.9 Revisions of Center and Control Limits

The effective use of any control chart will require periodic revision of the control limits and center lines. For practicing professionals in the field, this is done weekly, monthly, quarterly or in a lot by lot model such as every 25, 50 or 100 samples.

At times, the x bar will be replaced by a target value to attain controllability. **If the R chart exhibit control**, this can be helpful in shifting the process average to the desired value, that is, by a fairly simple adjustment of a manipulatable variable in the process.

If the R chart has out of control points, we often eliminate the out of control points and recompute a revised value of R bar. This value is then used to determine the new limits and the center line of the R chart and the new limits of the x bar charts. With this action, the limits will be tightened on both charts due to the revision made.

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For X Bar and R Chart, the revised center line and control limits can be computed as:

Chart	Control Limits	Centerlines	Plot Points	Subgroup Size
X Bar	$UCL = \bar{\bar{x}} + A_2 \left[\frac{d_2(new)}{d_2(old)}\right] \bar{R}_{old}$ $LCL = \bar{\bar{x}} - A_2 \left[\frac{d_2(new)}{d_2(old)}\right] \bar{R}_{old}$	$\bar{\bar{x}} = \frac{\sum \bar{x}}{k}$ k = number of subgroups	$\bar{x} = \frac{\sum x}{n}$	Usually subgroup size if reduced to tighten limits, say from 5 to 3. A_2 used is from the new sample size.
R	$UCL = D_4 \left[\frac{d_2(new)}{d_2(old)}\right] \bar{R}_{old}$ $LCL = max\left\{0, D_3 \left[\frac{d_2(new)}{d_2(old)}\right] \bar{R}_{old}\right\}$	$CL = \bar{R}_{new}$ $= \left[\frac{d_2(new)}{d_2(old)}\right] \bar{R}_{old}$	R = Range of subgroup = Xmax - Xmin	

Table 2.7.9a Revised Control Limits for X Bar and R

REMINDER: By changing the sample size, say from 5 to 3, we are increasing the width of the limits of the x bar chart that is because of the estimator of the process standard deviation which is σ / square root of n. When n = 5, it is smaller than when n = 3. By doing this, we are able to lower the center line and upper control limit on the R chart because the expected range from a sample of 3 is smaller compared to n n = 5.

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Example 2.7.7a Wafer Thickness in microns

Establish control charts for this set of data. Revise control limits if needed.

Sample Number	1	2	3	4	5	X bar	R
1	1.3235	1.4128	1.6744	1.4573	1.6914	1.5119	0.3679
2	1.4314	1.3592	1.6075	1.4666	1.6109	1.4951	0.2517
3	1.4284	1.4871	1.4932	1.4324	1.5674	1.4817	0.1390
4	1.5028	1.6352	1.3841	1.2831	1.5507	1.4712	0.3521
5	1.5604	1.2735	1.5265	1.4363	1.6441	1.4882	0.3706
6	1.5955	1.5451	1.3574	1.3281	1.4198	1.4492	0.2674
7	1.6274	1.5064	1.8366	1.4177	1.5144	1.5805	0.4189
8	1.4190	1.4303	1.6637	1.6067	1.5519	1.5343	0.2447
9	1.3884	1.7277	1.5355	1.5176	1.3688	1.5076	0.3589
10	1.4039	1.6697	1.5089	1.4627	1.5220	1.5134	0.2658
11	1.4158	1.7667	1.4278	1.5928	1.4181	1.5242	0.3509
12	1.5821	1.3355	1.5777	1.3908	1.7559	1.5284	0.4204
13	1.2856	1.4106	1.4447	1.6398	1.1928	1.3947	0.4470
14	1.4951	1.4036	1.5893	1.6458	1.4969	1.5261	0.2422
15	1.3589	1.2863	1.5996	1.2497	1.5471	1.4083	0.3499
16	1.5747	1.5301	1.5171	1.1839	1.8662	1.5344	0.6823
17	1.3680	1.7269	1.3957	1.5014	1.4449	1.4874	0.3589
18	1.4163	1.3864	1.3057	1.6210	1.5573	1.4573	0.3153
19	1.5796	1.4185	1.6541	1.5116	1.7247	1.5777	0.3062
20	1.7106	1.4412	1.2361	1.3820	1.7601	1.5060	0.5240
21	1.4371	1.5051	1.3485	1.5670	1.4880	1.4691	0.2185
22	1.4738	1.5936	1.6583	1.4973	1.4720	1.5390	0.1863
23	1.5917	1.4333	1.5551	1.5295	1.6866	1.5592	0.2533
24	1.6399	1.5243	1.5705	1.5563	1.5530	1.5688	0.1156
25	1.5797	1.3663	1.6240	1.3732	1.6887	1.5264	0.3224

We can compute for the grand mean by adding the 25 individual mean and divide it by 25, $\bar{\bar{x}}$ = 1.5056 and R bar is 0.32521. Factors has been derived from the Table of Factors

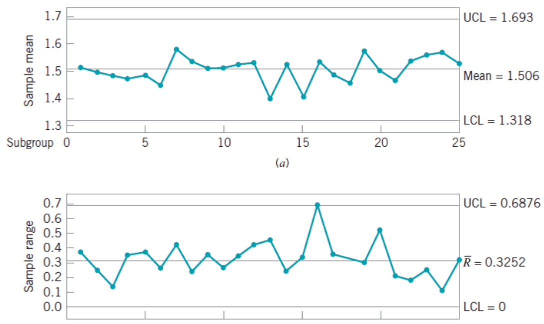
Limits for the X Bar Chart are:

$$UCL = \bar{\bar{x}} + A_2\bar{R} = 1.5056 + (0.577)(0.32521) = 1.6325$$
$$LCL = \bar{\bar{x}} - A_2\bar{R} = 1.5056 - (0.577)(0.32521) = 1.31795$$

Limits fir the R Chart are:

$$LCL = D_3\bar{R} = (0)(0.32521) = 0$$
$$UCL = D_4\bar{R} = (2.114)(0.32521) = 0.68749$$

We can see that there is no out of control points in both charts, but if we want a better estimation of the limits, it is expected to reduce the number of samples from 5 to 3.



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Example 2.7.7a Wafer Thickness in microns

Establish a better set of control limits by using a smaller sample size of 3 from 5. We will used factors under n = 3.

For X Bar Chart New Limits:

$$UCL = 1.5056 + (1.023)\left[\frac{1.693}{2.326}\right](0.32521) = 1.7478$$

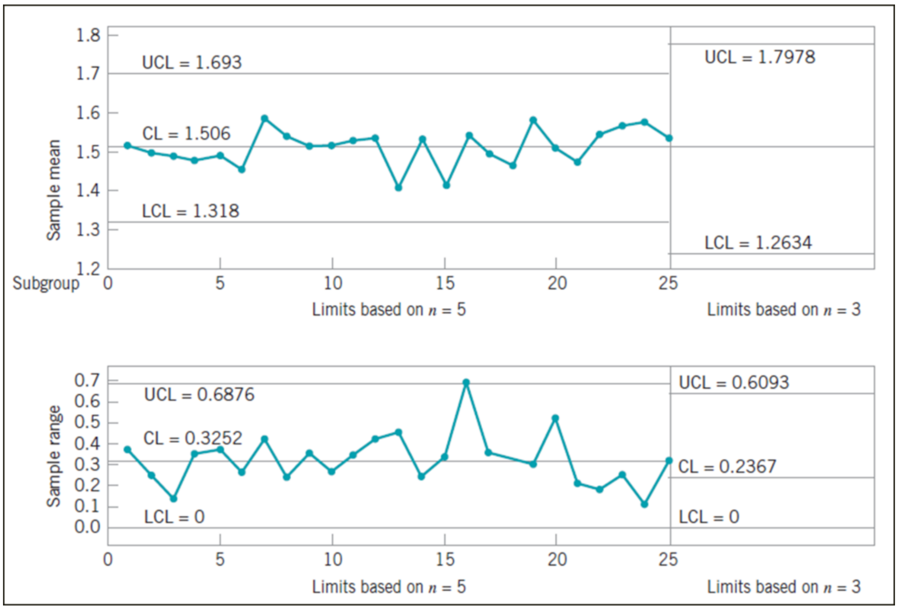
$$LCL = 1.5056 - (1.023)\left[\frac{1.693}{2.326}\right](0.32521) = 1.2634$$

For R Chart New Limits:

$$UCL = (2.574)\left[\frac{1.693}{2.326}\right](0.32521) = 0.6093$$

$$CL = \bar{R}_{new} = \left[\frac{1.693}{2.326}\right](0.32521) = 0.2367$$

$$LCL = \max((0, (0)\left[\frac{1.693}{2.326}\right](0.32521)) = 0$$



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2.7.10 X Bar and S Chart

It is a control chart for variable data used to monitor the behavior of process average and standard deviation of a single measurable characteristic produced frequently. Compared to the R chart, this chart offers greater precision.

This chart is commonly used when parts are produced frequently and in high volume. Subgroup sizes are greater than 1 and certainly used when subgroup sizes are 10 or larger.

In order to use this chart, the following conditions must be met:

- Subgroup size is greater than 1.
- One part number.
- Can be used when the original measurements are not normally distributed since averages tend toward normality.
- One characteristic per chart.
- Product is produced frequently.
- Should have at least 20 subgroups before calculating control limits.
- Engineering specification limits are not drawn on the x bar chart.

To Calculate Plot Points, Center and Control Limits:

<table>
<tr><th>Chart</th><th>Control Limits</th><th>Centerlines</th><th>Plot Points</th><th>Subgroup Size</th></tr>
<tr><td>X Bar</td><td>$UCL = \bar{\bar{x}} + A_3\bar{S}$
$LCL = \bar{\bar{x}} - A_3\bar{S}$</td><td>$\bar{\bar{x}} = \frac{\sum \bar{x}}{k}$
k = number of subgroups</td><td>$\bar{x} = \frac{\sum x}{n}$</td><td rowspan="2">n = 2 or greater but 3 to 5 preferred.

Subgroup sizes can vary, but constant is easier.</td></tr>
<tr><td>S</td><td>$UCL = B_4\bar{S}$
$LCL = B_3\bar{S}$</td><td>$\bar{S} = \frac{\sum S}{k}$</td><td>$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n - 1}}$</td></tr>
</table>

For values of the constant such as A_2, D_4 and D_3, please refer to the **Table 2.7.1a Factors in Constructing Control Charts.**

For the **process capability** estimate, the equation is:

$$\hat{\boldsymbol{\sigma}} = \frac{\bar{\boldsymbol{S}}}{\boldsymbol{c_4}}$$

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Where $\bar{S}$ is computed as the summation of all sample standard deviations over the total number subgroup and c_4 is a constant factor from the table.

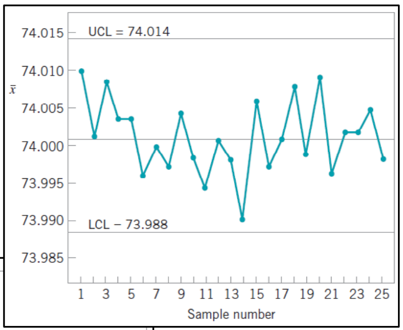
Example 2.7.10a Piston Ring Inside Diameter (mm)

Number	Observations					$\bar{x}_i$	s_i
1	74.030	74.002	74.019	73.992	74.008	74.010	0.0148
2	73.995	73.992	74.001	74.011	74.004	74.001	0.0075
3	73.988	74.024	74.021	74.005	74.002	74.008	0.0147
4	74.002	73.996	73.993	74.015	74.009	74.003	0.0091
5	73.992	74.007	74.015	73.989	74.014	74.003	0.0122
6	74.009	73.994	73.997	73.985	73.993	73.996	0.0087
7	73.995	74.006	73.994	74.000	74.005	74.000	0.0055
8	73.985	74.003	73.993	74.015	73.988	73.997	0.0123
9	74.008	73.995	74.009	74.005	74.004	74.004	0.0055
10	73.998	74.000	73.990	74.007	73.995	73.998	0.0063
11	73.994	73.998	73.994	73.995	73.990	73.994	0.0029
12	74.004	74.000	74.007	74.000	73.996	74.001	0.0042
13	73.983	74.002	73.998	73.997	74.012	73.998	0.0105
14	74.006	73.967	73.994	74.000	73.984	73.990	0.0153
15	74.012	74.014	73.998	73.999	74.007	74.006	0.0073
16	74.000	73.984	74.005	73.998	73.996	73.997	0.0078
17	73.994	74.012	73.986	74.005	74.007	74.001	0.0106
18	74.006	74.010	74.018	74.003	74.000	74.007	0.0070
19	73.984	74.002	74.003	74.005	73.997	73.998	0.0085
20	74.000	74.010	74.013	74.020	74.003	74.009	0.0080
21	73.982	74.001	74.015	74.005	73.996	74.000	0.0122
22	74.004	73.999	73.990	74.006	74.009	74.002	0.0074
23	74.010	73.989	73.990	74.009	74.014	74.002	0.0119
24	74.015	74.008	73.993	74.000	74.010	74.005	0.0087
25	73.982	73.984	73.995	74.017	74.013	73.998	0.0162

$$\bar{\bar{x}} = \frac{\Sigma \bar{x}}{k} = 1{,}850 / 25 = 74.001 \text{ and } \bar{S} = \frac{\Sigma S}{k} = 0.2351 / 25 = 0.0094$$

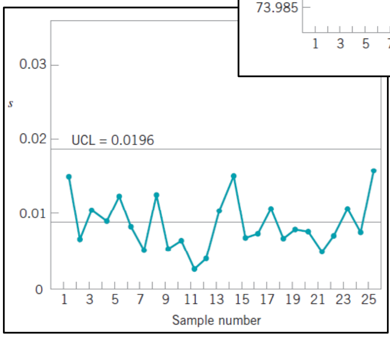
For X Bar Control Limits:

$UCL = \bar{\bar{x}} + A_3\bar{S} = 74.001 + (1.427)(0.0094) = 74.014$
CL $= \bar{\bar{x}} = 74.001$
$LCL = \bar{\bar{x}} - A_3\bar{S} = 74.001 - (1.427)(0.0094) = 73.988$



For S Chart Control Limits:

$UCL = B_4\bar{S} = (2.089)(0.0094) = 0.0196$
CL $= \bar{S} = 0.0094$
$UCL = B_3\bar{S} = (0)(0.0094) = 0$



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REMINDER: Collect measurements for two additional subgroups and add the X and S plot points to their respective charts. Then recalculate the control limits (excluding the out-of-control points) for both charts, and if the most recent plot points are in control, extend the limits into the future. Continue to monitor the process. Closely watch the chart for future abnormal variation, and look for ways to further reduce the level of S.

2.7.11 IX – MR Charts (Individual X – Moving Range Charts)

It is a control chart for variable data used to monitor the behavior of a process using the individual measurements of a product characteristic.

It is best used when opportunities to obtain data are limited, such a low production volume or testing. Sampling sizes that are greater than one simply do not apply, such as when sampling from homogenous batches, or when samples have very small short term variation or for business processes.

In order to use this chart, the following conditions must be met first:

- Low production rate.
- Subgroup size of 1.
- One part number.
- One characteristic per part.
- Assumes normal distribution of measurements.
- Should have at least 20 (preferably 30 or more) subgroups before calculating the control limits.

To Calculate Plot Points, Center and Control Limits:

Chart	Control Limits	Centerlines	Plot Points	Subgroup Size
IX	$UCL = \bar{x} + 2.33\overline{MR}$ $LCL = \bar{x} - 2.33\overline{MR}$	$\bar{x} = \frac{\sum x}{k}$ k = number of subgroups	Individual X measurements	One
S	$UCL = 3.27\overline{MR}$ $LCL = 0$	$\overline{MR} = \frac{\sum MR}{k-1}$	Moving range = positive difference between successive IX measurements.	

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REMINDER: Monitor process for assignable causes. Be alert for signs of special events that could affect the variation in the part. It would be beneficial to collect 10 or 20 more plot points and recalculate the control limits because there is a limited amount of data being used in the calculation of the current control limits.

Example 2.7.11a Solar Wafer Thickness (mm)

Sample	IX	MR
1	2.20	-
2	2.15	0.05
3	2.29	0.14
4	2.20	0.09
5	2.21	0.01
6	2.24	0.03
7	2.12	0.12
8	2.12	0.00
9	2.17	0.05
10	2.19	0.02

$$\bar{x} = \frac{\sum x}{k} = 21.89 / 10 = 2.189$$

$$\overline{MR} = \frac{\sum MR}{k-1} = \frac{0.51}{10} = 0.051$$

For IX Chart Control Limits:

$$UCL = \bar{x} + 2.33\overline{MR} = 2.189 + (2)(0.051) = 2.29$$
$$\text{CL} = \bar{x} = 2.189$$
$$LCL = \bar{x} - 2.33\overline{MR} = 2.189 - (2)(0.051) = 2.09$$

For MR Chart Control Limits:

$$UCL = 3.27\overline{MR} = (3.27)(0.051) = 0.167$$
$$\text{CL} = \overline{MR} = 0.51$$
$$CL = 0$$

2.7.12 The p Chart

It is an attribute control chart for the **fraction defective (p)**. The term **defective** is used here in its common and broad sense. In this case it can be used to mean nonconformance to specification, but it can also be used to mean that customer expectations were not met. The **p, np, c, and u charts can be used whenever there are two possible outcomes**, where items can be placed into two categories and counted (such as pass/fail, high/low, and so on). Subgroup samples are taken from groups of items or lots.

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It is best used when:

- A variable data cannot be obtained for a key characteristic.
- Monitoring the fraction defective and where subgroup sizes may vary.
- Identifying characteristics that should be monitored on variable control charts.
- Tracking the quality level of a process (before any rework is performed.
- Identifying any sudden changes in quality levels, positive or negative.
- Assessing the effects of upstream process improvements.

These are the steps on how construct a p chart:

1) Decide upon an appropriate subgroup size so that at least one (preferably more) defective item will likely be present.
2) Count the number of defective items in the subgroup samples and the plot the proportion defective.
3) Calculate the center line and control limits after a sufficient plot of point are obtained (preferably 20 points).

Ensure that these conditions are met before using the p chart:

- Only the number of defective products is counted, not the number of defects per unit.
- In order to be of help, ensure that there should be some defectives in each observed subgroup.
- The higher the quality level, the larger the subgroup size must be to contain defectives. Consult a statistical text for estimating the needed subgroup size to ensure a sufficiently high probability that the subgroup will contain at least one defective.

To Calculate Plot Points, Center and Control Limits:

Chart	Control Limits	Centerline	Plot Points	Subgroup Size
p	$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}\,(1-\bar{p}\,)}{n}}$ $LCL = \bar{p} - 3\sqrt{\frac{\bar{p}\,(1-\bar{p}\,)}{n}}$	$\bar{p} = \frac{Total\ d}{Total\ n}$ d = total no. of defectives n = total no. items inspected k = number of subgroups	$p_i = \frac{d_i}{n_i}$	Constant or varying

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Example 2.7.12a Defective Cans (subgroup size = 50)

Sample Number	Number of Nonconforming Cans, D_i	Sample Fraction Nonconforming, $\hat{p}_i$	Sample Number	Number of Nonconforming Cans, D_i	Sample Fraction Nonconforming, $\hat{p}_i$
1	12	0.24	17	10	0.20
2	15	0.30	18	5	0.10
3	8	0.16	19	13	0.26
4	10	0.20	20	11	0.22
5	4	0.08	21	20	0.40
6	7	0.14	22	18	0.36
7	16	0.32	23	24	0.48
8	9	0.18	24	15	0.30
9	14	0.28	25	9	0.18
10	10	0.20	26	12	0.24
11	5	0.10	27	7	0.14
12	6	0.12	28	13	0.26
13	17	0.34	29	9	0.18
14	12	0.24	30	6	0.12
15	22	0.44		347	$\bar{p} = 0.2313$
16	8	0.16			

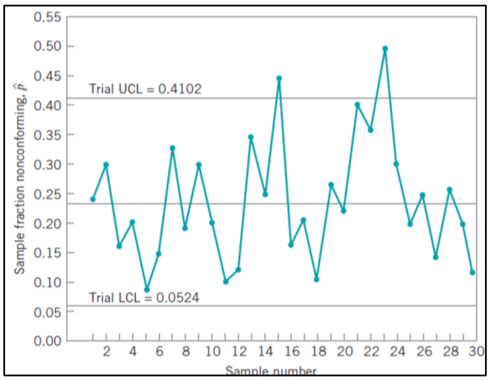
$$\bar{p} = \frac{Total\ d}{Total\ n} = \frac{347}{30x50} = 0.2313$$

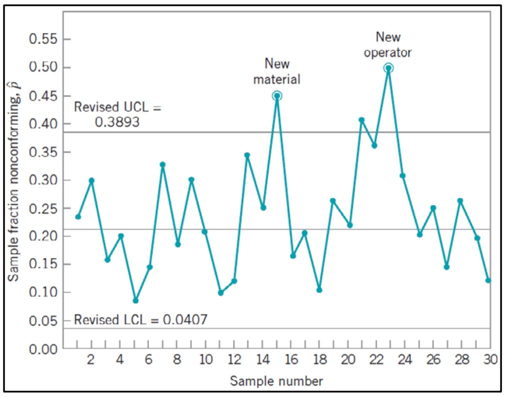
$$UCL = 0.2313 + 3\sqrt{\frac{0.2313\ (1-0.2313\ )}{50}} = 0.4102 \quad LCL = 0.2313 - 3\sqrt{\frac{0.2313\ (1-0.2313\ )}{50}} = 0.0524$$

For revised control limits due to two (2) out of control points, 15 & 23:

$$\bar{p} = \frac{Total\ d}{Total\ n} = \frac{347 - 22 - 24}{(30-2)x50} = 0.2150$$

$$UCL = 0.2150 + 3\sqrt{\frac{0.2150\ (1-0.2150\ )}{50}} = 0.3893 \quad LCL = 0.2150 - 3\sqrt{\frac{0.2150\ (1-0.2150\ )}{50}} = 0.0407$$





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2.7.13 The np Chart

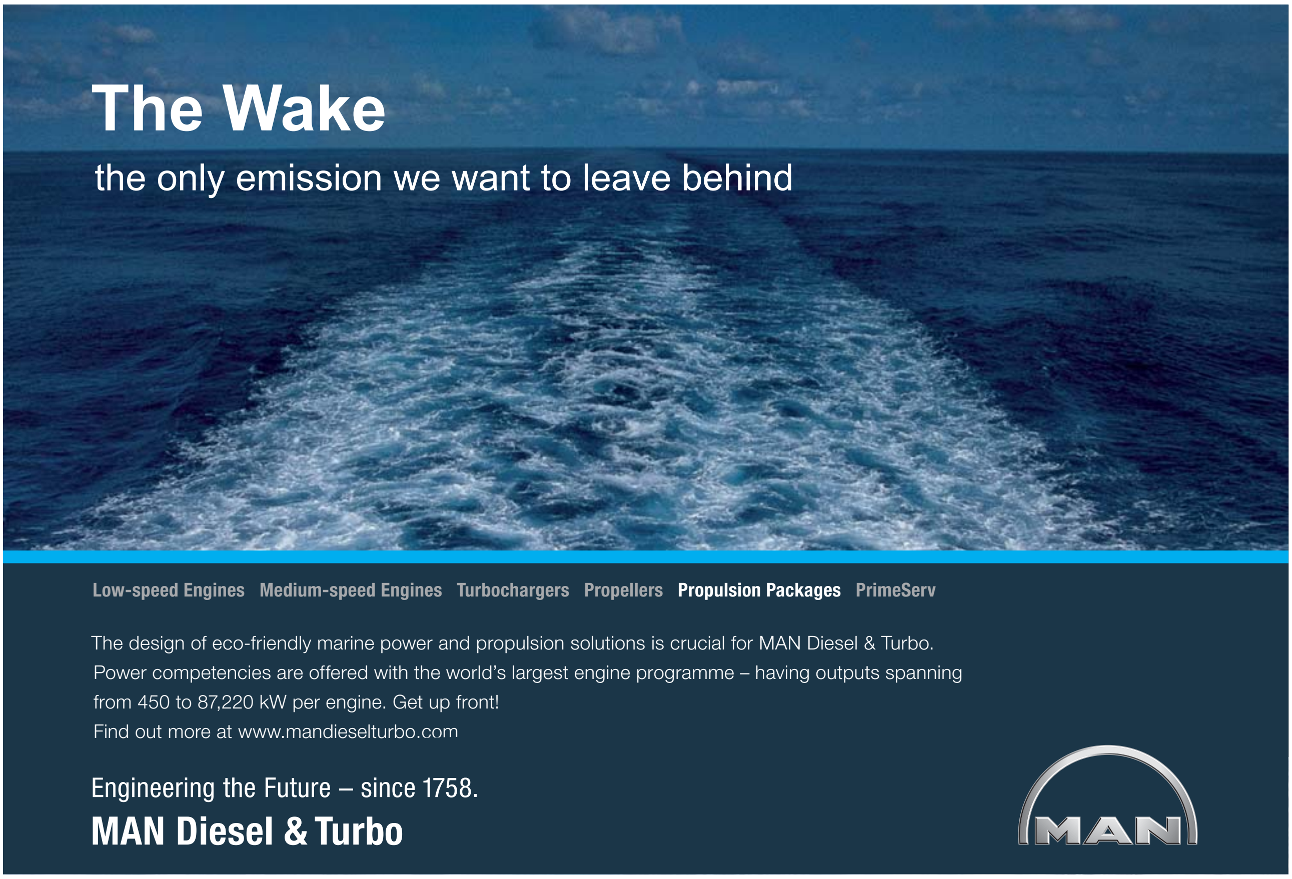
It is an attribute control chart for the number of defectives. It is also possible to base a control chart on the **number nonconforming rather than the fraction nonconforming**. This is often called a number nonconforming **(np) control chart**.

It is best used when:

- A variable data cannot be obtained for a key characteristic.
- Monitoring the number of defectives, and where subgroup sizes are constant.
- Identifying characteristics that should be monitored on variable control charts.
- Tracking the quality level of a process (before any rework is performed).
- Identify any sudden changes to quality levels, positive or negative.
- Assessing the effects of upstream process improvements.

These are the steps on constructing an np chart.

1) Decide upon an appropriate subgroup size so that at least one, preferably more, defective will likely be present.
2) Count and plot the number of defective items in the subgroup samples.
3) Calculate the center and control limits after a sufficient number of plot points are obtained, after 20 points is recommended.



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Ensure that these conditions are met before using the p chart:

- Only the number of defective products is counted, not the number of defects per unit.
- In order to be of help, ensure that there should be some defectives in each observed subgroup.
- The higher the quality level, the larger the subgroup size must be to contain defectives. Consult a statistical text for estimating the needed subgroup size to ensure a sufficiently high probability that the subgroup will contain at least one defective.

To Calculate Plot Points, Center and Control Limits:

Chart	Control Limits	Centerline	Plot Points	Subgroup Size
np	$UCL = n\bar{p} + 3\sqrt{n\bar{p}\,(1-\bar{p}\,)}$ $LCL = n\bar{p} - 3\sqrt{n\bar{p}\,(1-\bar{p}\,)}$	CL = $n\bar{p}$ n = total no. items inspected $\bar{p}$ = proportion defective	$p_i = \frac{d_i}{n_i}$	Constant or varying

Example 2.7.13a Defective Cans (subgroup size = 50)

Let us use the $\bar{p} = 0.2313$ and n is as stated which is 50.

$$UCL = n\bar{p} + 3\sqrt{n\bar{p}\,(1-\bar{p}\,)} = (50)(0.2313) + 3\sqrt{(50)(0.2313)(1-0.2313\,)} = 20.510$$

$$CL = n\bar{p} = (50)(0.2313) = 11.565$$

$$UCL = n\bar{p} - 3\sqrt{n\bar{p}\,(1-\bar{p}\,)} = (50)(0.2313) - 3\sqrt{(50)(0.2313)(1-0.2313\,)} = 2.620$$

2.7.14 The c Chart

It is an attribute control chart for the number of defects per unit. A unit can be a single part, an assembly, an area of material, or any rational grouping of units in which the likelihood of defects is constant from unit to unit.

A nonconforming item is a unit of product that does not satisfy one or more of the specifications for that product. Each specific point at which a specification is not satisfied results in a defect or nonconformity.

Consequently, a nonconforming item will contain at least one nonconformity. However, depending on their nature and severity, it is quite possible for a unit to contain several nonconformities and not be classified as nonconforming.

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It is best used when:

- A variable data cannot be obtained for a key characteristic.
- Monitoring the number of defects found per unit and the unit size is constant from subgroup to subgroup.
- Identifying characteristics that should be monitored on variable control charts.
- Tracking the quality level of a process (before any rework is performed).
- Identifying any sudden changes to quality levels, positive or negative.
- When assessing the effects of upstream process improvements.

These are the steps on constructing a c chart:

1) Decide upon an appropriate definition of a unit. As a rule, the average number of defects per unit (or grouping) should be at least five.
2) Count and plot the number of defects for each unit.
3) Calculate the centerline and the control limits after a sufficient number of plot points are obtained (after 20 plot points is recommended).

Ensure that these conditions are met before using a c chart:

- Constant unit size for all subgroups and one unit per subgroup.
- Several different types of defects per unit are permissible.
- In order for this type of analysis to be of help, there should be some defects in each observed unit.

To Calculate Plot Points, Center and Control Limits:

Chart	Control Limits	Centerline	Plot Points	Subgroup Size
c	$UCL = \bar{c} + 3\sqrt{\bar{c}}$ $LCL = \bar{c} - 3\sqrt{\bar{c}}$	$\bar{c}$ = d / k d = total of defects / total number of inspected units k = number of subgroups (units)	c_i = number of units counted on unit i	One unit

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Example 2.7.14a Nonconformities in Printed Circuit Boards

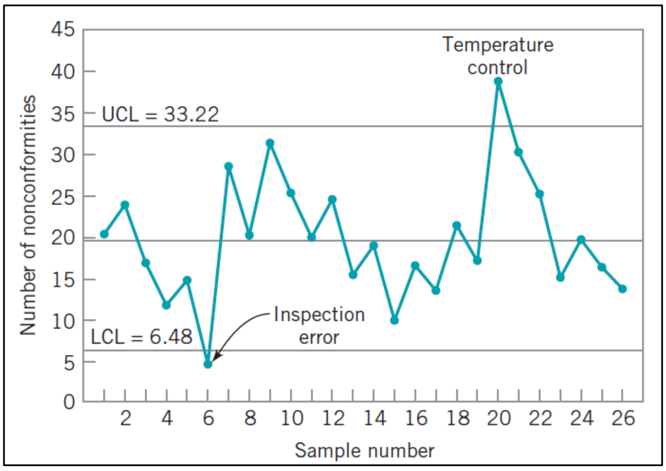
The table below presents the number of nonconformities observed in 26 successive samples of 100 printed circuit boards. Note that the 100 printed circuit boards is considered as one unit or a lot.

Sample Number	Number of Nonconformities	Sample Number	Number of Nonconformities
1	21	14	19
2	24	15	10
3	16	16	17
4	12	17	13
5	15	18	22
6	5	19	18
7	28	20	39
8	20	21	30
9	31	22	24
10	25	23	16
11	20	24	19
12	24	25	17
13	16	26	15

$$\bar{c} = d / k = 516 / 26 = 19.85$$

$$UCL = \bar{c} + 3\sqrt{\bar{c}} = 19.85 + 3\sqrt{19.85} = 33.33$$

$$LCL = \bar{c} - 3\sqrt{\bar{c}} = 19.85 - 3\sqrt{19.85} = 6.48$$



For the revised center and control limits due to two out of control points, 6 & 21:

$$\bar{c} = d / k = 472 / 24 = 19.67$$

$$UCL = \bar{c} + 3\sqrt{\bar{c}} = 19.67 + 3\sqrt{19.67} = 32.97$$

$$LCL = \bar{c} - 3\sqrt{\bar{c}} = 19.67 - 3\sqrt{19.67} = 6.36$$

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3 Problem Solving Process

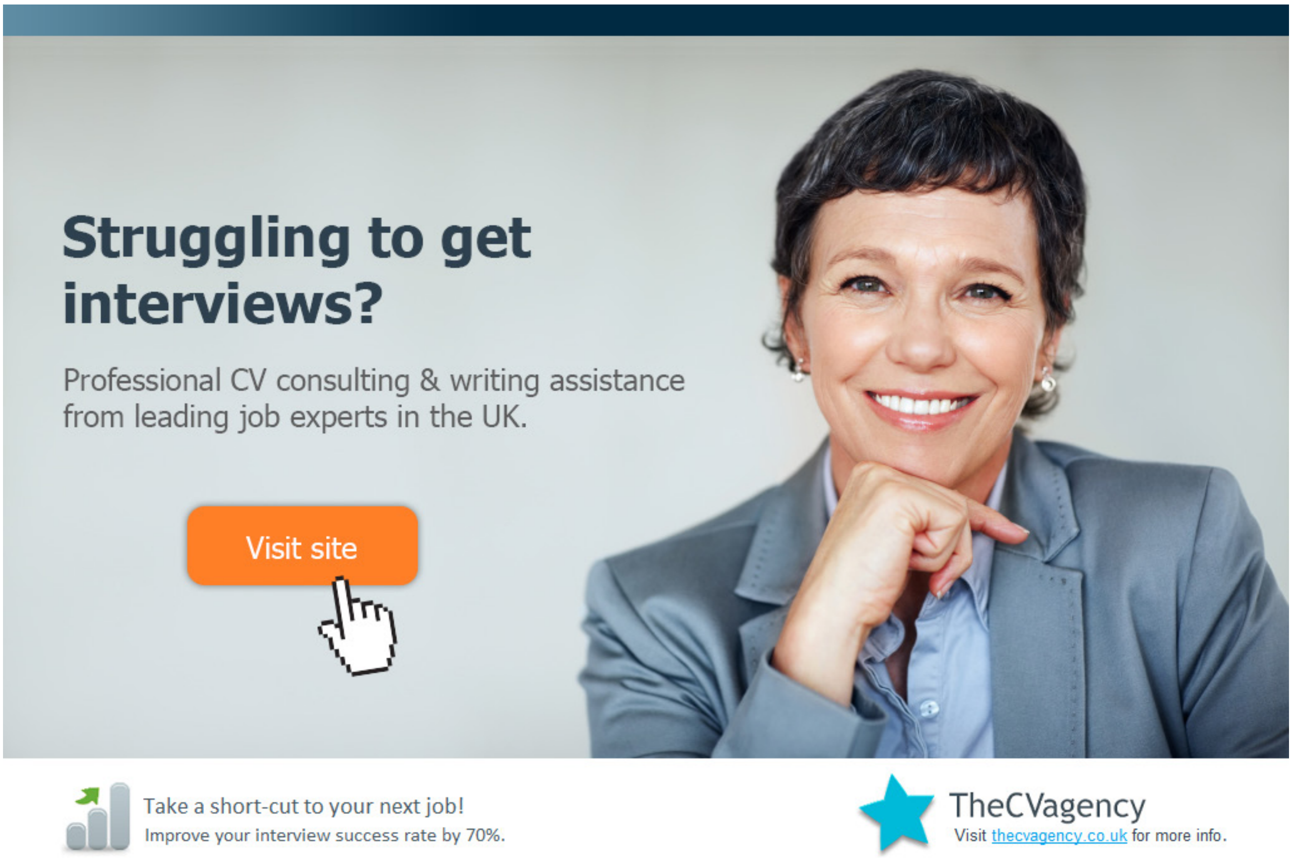
3.1 What is Problem Solving?

Before we discuss what problem solving process is, let us first discuss the three words encompassing the phrase.

A **problem** is defined to be the difference between what is the standard /expected and what the actual / observed results is. This difference can be referred to as a **gap**. Therefore, as the observed result draws closer the expected value, we have less of a problem. A problem may be a practical (poor quality) or statistical (spread or centering).

A **solution** is a defined action, set of activities or a program, that aims to address the gap.

A **process** is an activity of converting inputs to outputs. It is also known to be a systematic approach to execute initiatives. This is an algorithm used in order to efficiently and effectively. It is usually represented by a general set of steps applied to specific setting.



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Therefore, a problem solving process is a systematic approach of finding an optimal solution from a pool of potential solutions to address a particular gap, either it be a problem or an initiative. Furthermore, these are approaches for identifying a problem or an improvement initiative, discovering the root causes of a problem, identifying and evaluating solutions, implementing the solution, measuring the improvement, and ensuring holistic integration of the solution so the problem will not recur.

3.2 Why Use Problem Solving?

- To provide a step by step procedure that can be repeatedly applied to most problems or process improvements.
- To reduce the amount of time to make an improvement or solve a problem.
- To provide a structure to follow that helps ensure positive solutions.
- To standardize the mechanism for improvement and problem solution.
- To aid in communication and facilitate learning.

3.3 What is the Preferred Approach?

There are mainly two (2) general approaches for a problem solving process. These two approaches are the usual method and the analytical preferred method.

Figure 3.3a Usual Method

The **usual method (Figure 3.3a)** of problem solving approach implies that once a fire (problem) occurs, the organization will just fire fight it thru containing the fire using extinguishers, sand and water (quick/temporary fix). Once fire recurs, they will just intend to do the same firefighting as mentioned. The downside of this approach is that no established measure is created to prevent the fire but to only contain it, that is, this approach is said to be reactive. Being reactive, this tends to be more costly as fire is contained not prevented. Every fire occurrence can cost most likely the same as the previous cost of containing it or even more.

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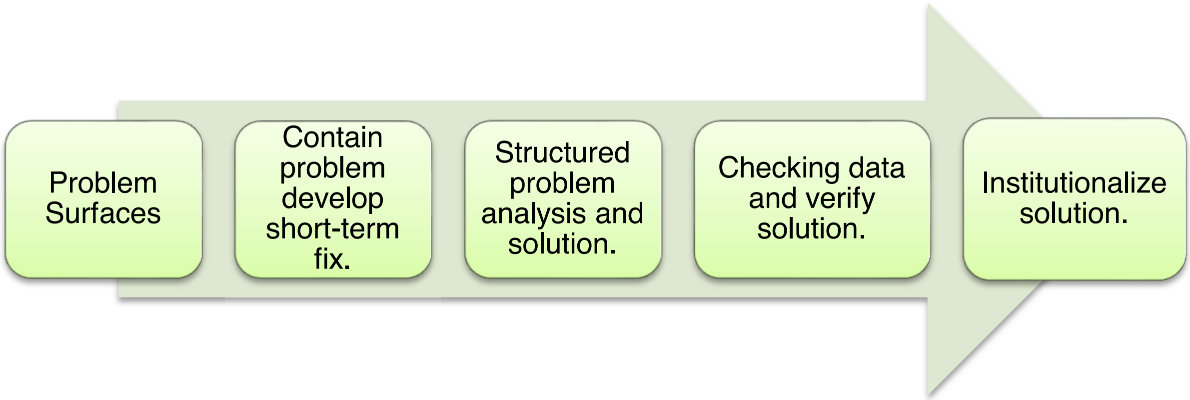

Figure 3.3b Preferred Analytical Method

On the other hand, the **preferred analytical method (Figure 3.3b)** implies that fire (problem) occurs, the organization tries to contain it and develop a quick fix for it say use extinguishers, sand and water. Once the fire is contained, the organization put initiative to create a structure to deploy problem analysis and there by generation solutions and choosing the best solution in order to avoid the recurring fire, counter checking effectives of the chosen solution by measuring results and standardizing the successful solution. With this approach, the probability of fire recurrence is set to be minimized and it generates long term results that are effective and cost efficient.

3.4 What is the Problem Solving Process?

As mentioned earlier, a problem solving process is define to an approach which aims to understand the problem/improvement initiative, apply all needed data analysis and manipulation and deriving an optimal solution/recommendation.

Figure 3.4a depicts what a basic problem solving process looks like. First it requires the identification of the need for a problem solving process, that is, through actual results and comparing to the objectives. The need can arise from a problem to be improved or an improvement initiative to be done. Through further studying of the given situation and data collection, root causes can then be identified and systematically selected. With causes identified, we can now devise particular solutions so that the problem identified or improvement initiated can be addressed. We will develop at least three (3) significant alternatives for our solutions and will implement what is doable based on the consensus of the team. After the implementation, we need to check whether the solution implemented is producing the results expected and/or favoring the favorable outcome or otherwise. In this case that it is not bearing what is required; a need to implement another feasible solution will be done. After the optimal solution is implemented, we need to establish control and review/audit measures for the implemented solution. Improvement is a continuous process that is why we must review regularly the results of our operations thru the use of Key Performance Indexes (KPI).

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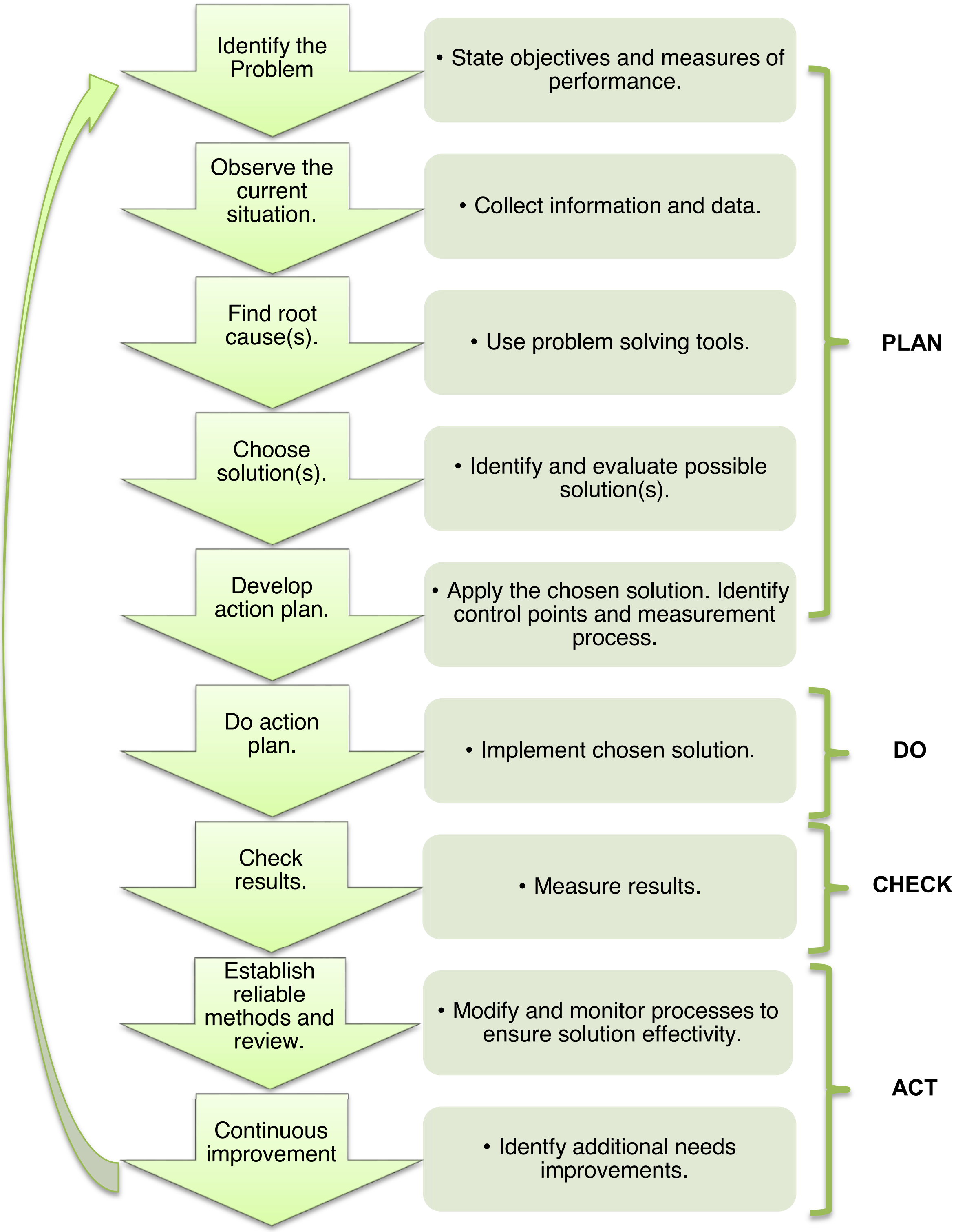

Figure 3.4a Basic Problem Solving Process Flow

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3.5 What is the Relation of PDCA to Problem Solving Process?

The **Plan-Do-Check-Act (PDCA)** cycle is a systematic approach and discipline to problem solving and continuous improvement. It is often conceptually drawn as a wheel showing the feedback nature of the process as shown in **Figure 3.5a**. The specific steps that can be drawn into the cycle are depicted on the **Figure 3.4a.**

The Shewhart PDCA Cycle as described by Deming encompasses:

- **Plan** – a plan for a positive change in improvement.
- **Do** – executing and testing the plan for the improvement.
- **Check** – gathering and analyzing the data collected from the executed improvement plan.
- **Act** – implementing the positive result bearing improvement plan.

We can observe that the PDCA cycle has scientific roots as explained below:

- **Plan** – conceptualization of a theory.
- **Do** – running an experiment.
- **Check** – verification thru data collection and analysis.
- **Act** – the theory is implemented and another is being hypothesized.

Therefore, we can conclude that the use of the problem solving process embark us to the use of the PDCA Cycle as well.

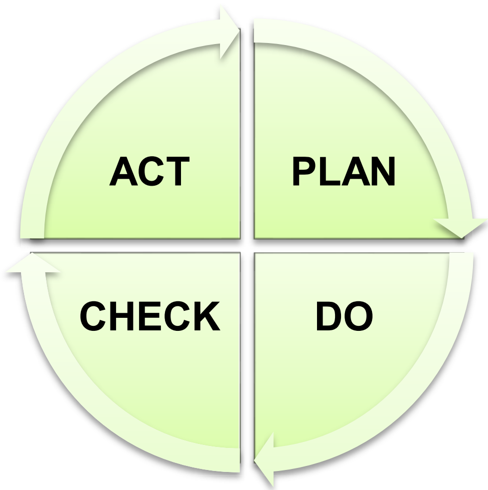

Figure 3.5a PDCA Cycle

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REMINDER: The success of a Problem Solving Process can be maximized thru **Team Efforts**. Therefore, an organization who wants to apply the Process must train individuals about it and then form a team of trained personnel to conduct problem solving activities. Being in a team who are the most knowledgeable allows creative and systematic results. Also, being in a team makes an individual shift from individualistic to being a team player.

3.6 When and What Tools to be Used?

Table 3.6a shows the detailed steps in conducting a problem solving process with the suggested tools to be used. The tools presented are just the basic tools of the Statistics Process Control Tools but yet is assured to bring improvement in an organization if properly utilized.

Steps	Suggested Tools
1) Identify product or process to be improved or problem to be solved.	Check Sheet, Pareto Chart
2) Form and train an improvement team.	Training
3) Defining the problem.	Brainstorming
4) Defining the performance measures and baselines.	Pareto & Control Charts, Check Sheets
5) Data gathering about the problem identified.	Flow Chart, Check Sheets, Historical Information Review
6) Perform root cause analysis.	Cause and Effect Diagram, 5Y, DOE
7) Analyze results, identify root causes and sources of variation.	Cause and Effect Diagram, 5Y, Pareto Chart, Histogram, Scatter Diagram
8) Identify solutions.	Brainstorming, DOE, Control Charts
9) Verifying conclusion by testing the solutions, if successful proceed to Step No. 10, otherwise, go back to Step No. 6.	All
10) Developing corrective and preventive action plan.	Action Planning and Scheduling, Gantt Chart
11) Documenting problem solving process, including data, activities and plans.	Documentation
12) Implementing corrective and preventive action plans.	Control Charts and Histogram
13) Monitoring of performance measurements.	Pareto Chart and Histogram
14) Institutionalizing actions and implementing solution to similar process.	Standardization
15) Collecting customer feedback.	Surveys, Interviews

Table 3.6a Detailed Problem Solving Process and Suggested Tools

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5 About the Author

Felix C. Veroya is a young advocate who believes that education is the key to a person's success. He is from the Philippines and acquired his Degree in BS Industrial Engineering from Batangas State University, 2011. He garnered several awards from his college stint which includes being the 1st Cum Laude of the IE Program in its 17 years of existence, Academic Excellence Awardee for Industrial Engineering, Most Outstanding Alumnus, Top 8 on the Ten Outstanding Students Awardee of the University and one of the Most Outstanding Scholar of the Province.

On March 2012, he successfully passed the Certification for Industrial Engineers (CIE) conferred by the Philippine Institute of Industrial Engineers (PIIE) at 4th Place.

On January 2013, he started attending the Diploma in Logistics Management conducted by the company he is into and have completed 75% of the program as of to date.

On March 2014, under a comprehensive profile review conducted by the Philippine Institute of Industrial Engineers (PIIE), Philippine Technological Council (PTC) and ASEAN Registry, he has been conferred to as an Associate ASEAN Engineer (AAE).

On August 2014, he completed and successfully passed the Lean Sigma Program given by the Six Sigma Management Institute by Dr. Mikel J. Harry, co-creator of Six Sigma, and has conferred to as Lean Sigma Program Qualified.

He is currently working for a beverage company in the Philippines as a Logistics Coordinator, teaching on state university about subjects such Industrial Quality Control, Total Quality Management and Marketing Management, acting as the Vice President for Academics and Research for IExcel Review and Training Center, blogging for IE Hub (iehub.wordpress.com) and freelancing.