PRODUCTION AND OPERATIONS MANAGEMENT

2023/2024

ISEG Lisbon School of Economics & Management

U LISBOA | UNIVERSIDADE DE LISBOA

Quality Management
Statistical Process Control

Chapter 6 and Supplement 6

Two Ways Quality Improves Profitability

Improved Quality

Sales Gains via

- Improved response
- Flexible pricing
- Improved reputation

Reduced Costs via

- Increased productivity
- Lower rework and scrap costs
- Lower warranty costs

Increased Profits

Defining Quality

An operations manager's objective is to build a total quality management system ***that identifies and satisfies customer needs***

"The totality of features and characteristics of a product or service that bears on its ability to satisfy stated or implied needs"

American Society for Quality

Different Views

- ***User based***: better performance, more features
- ***Manufacturing based***: conformance to standards, making it right the first time
- ***Product based***: specific and measurable attributes of the product

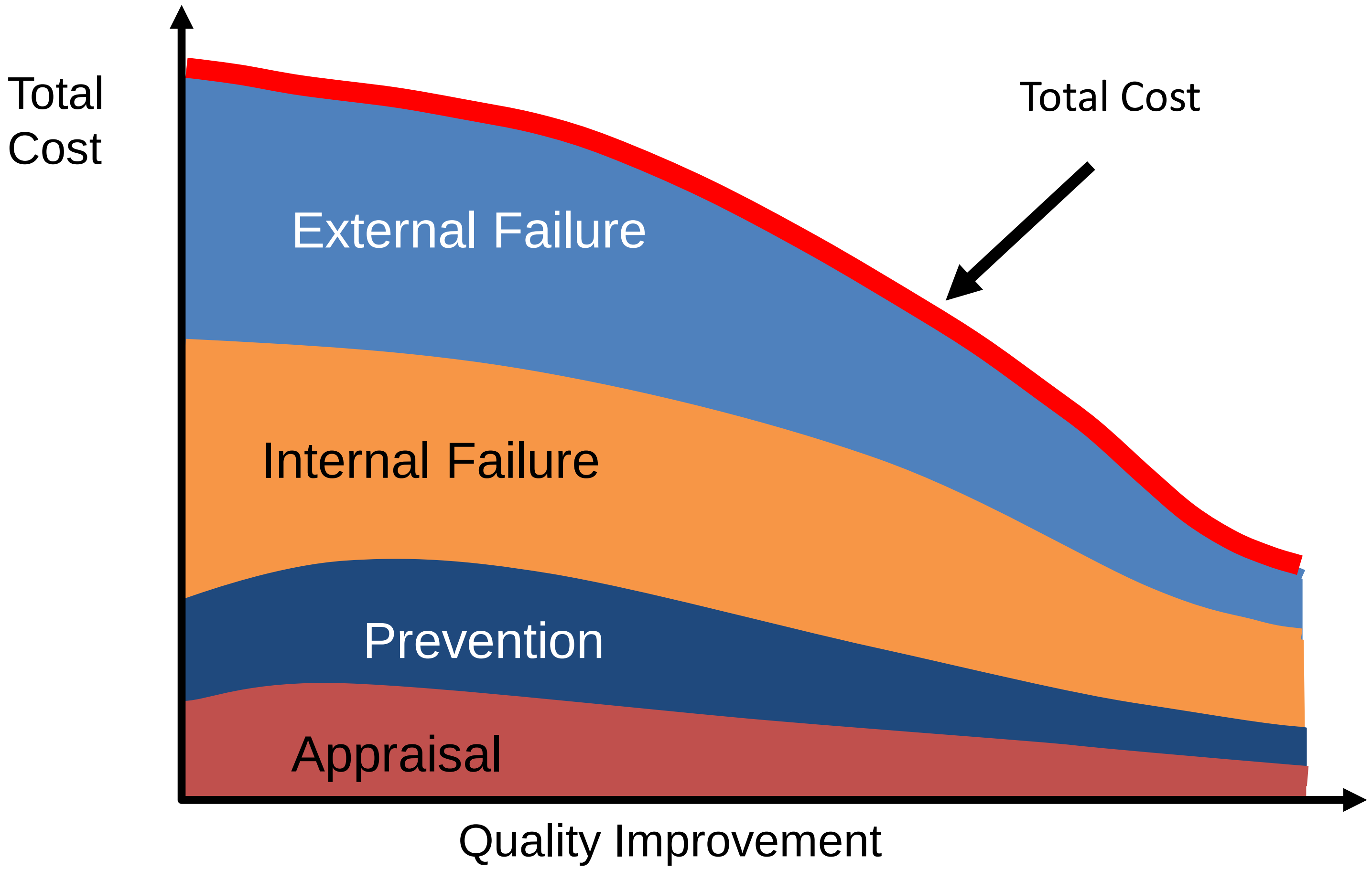
Implications of Quality

1. Company reputation
   - Perception of new products
   - Employment practices
   - Supplier relations
2. Product liability
   - Reduce risk
3. Global implications
   - Improved ability to compete

Costs of Quality

- *Prevention costs* - reducing the potential for defects (e.g., error-proofing systems; statistical control)
- *Appraisal costs* - evaluating products, parts, and services (e.g., quality audits; raw material inspection)
- *Internal failure costs* - producing defective parts or service before delivery (e.g., rework; scrapping)
- *External failure costs* - defects discovered after delivery (e.g., warranties; claims)

Costs of Quality



Seven Concepts of Total Quality Management

- Encompasses entire organization from supplier to customer
- Stresses a commitment by management to have a continuing companywide drive toward excellence in all aspects of products and services that are important to the customer

1) Continuous improvement
2) Six Sigma
3) Employee empowerment
4) Benchmarking
5) Just-in-time (JIT)
6) Taguchi concepts
7) Knowledge of TQM tools

Total Quality Management

Continuous Improvement

- Never-ending process of continuous improvement
- Covers people, equipment, suppliers, materials, procedures
- Every operation can be improved
- ***Kaizen*** describes the ongoing process of unending improvement
- ***TQM*** and ***zero defects*** also used to describe continuous improvement

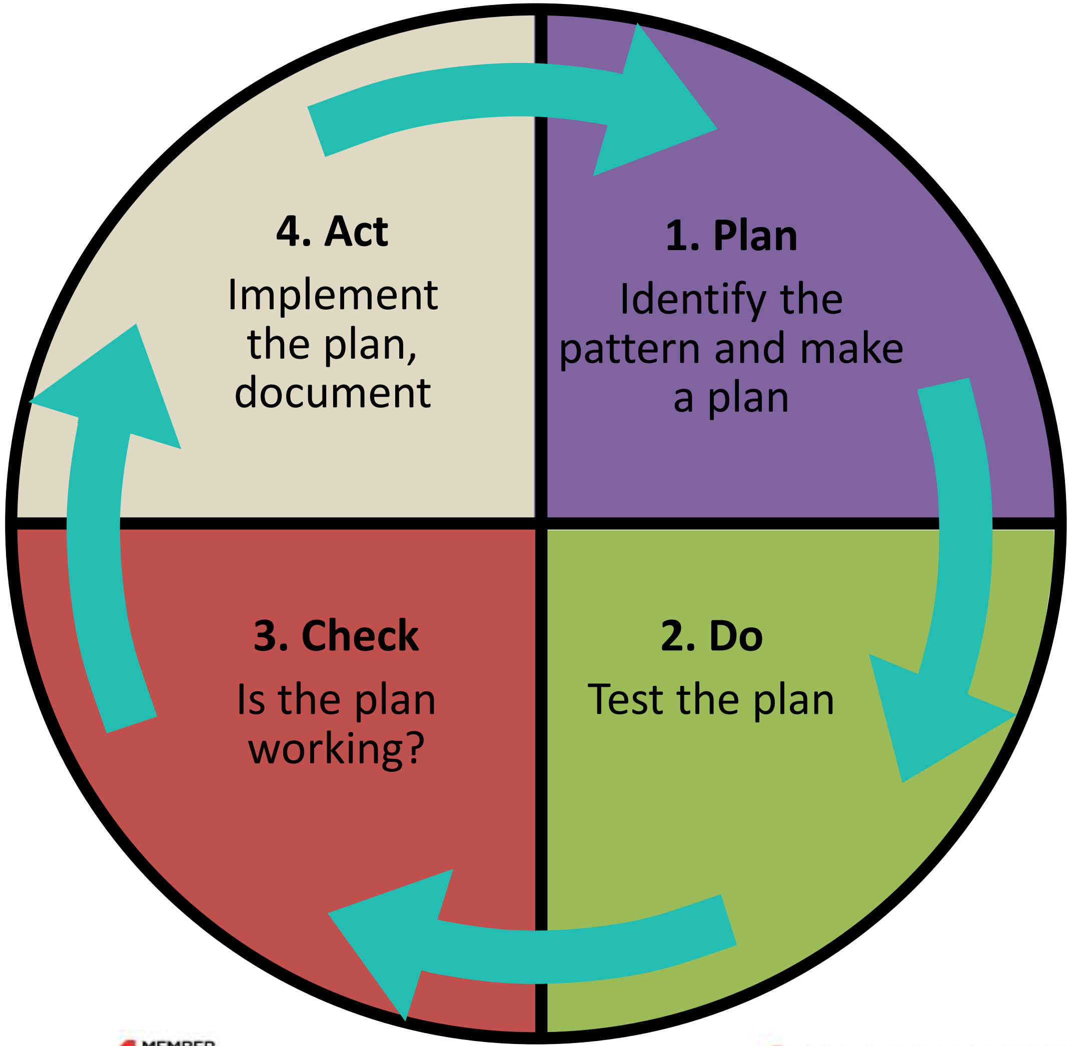
PDCA Model

Act

- Undertake actions to continuously improve process performance and achieve the defined objectives

Plan

- Identify the processes that enable the achievement of objectives and results oriented to customer satisfaction



Check

- Monitor, measure, analyze processes
- report the results

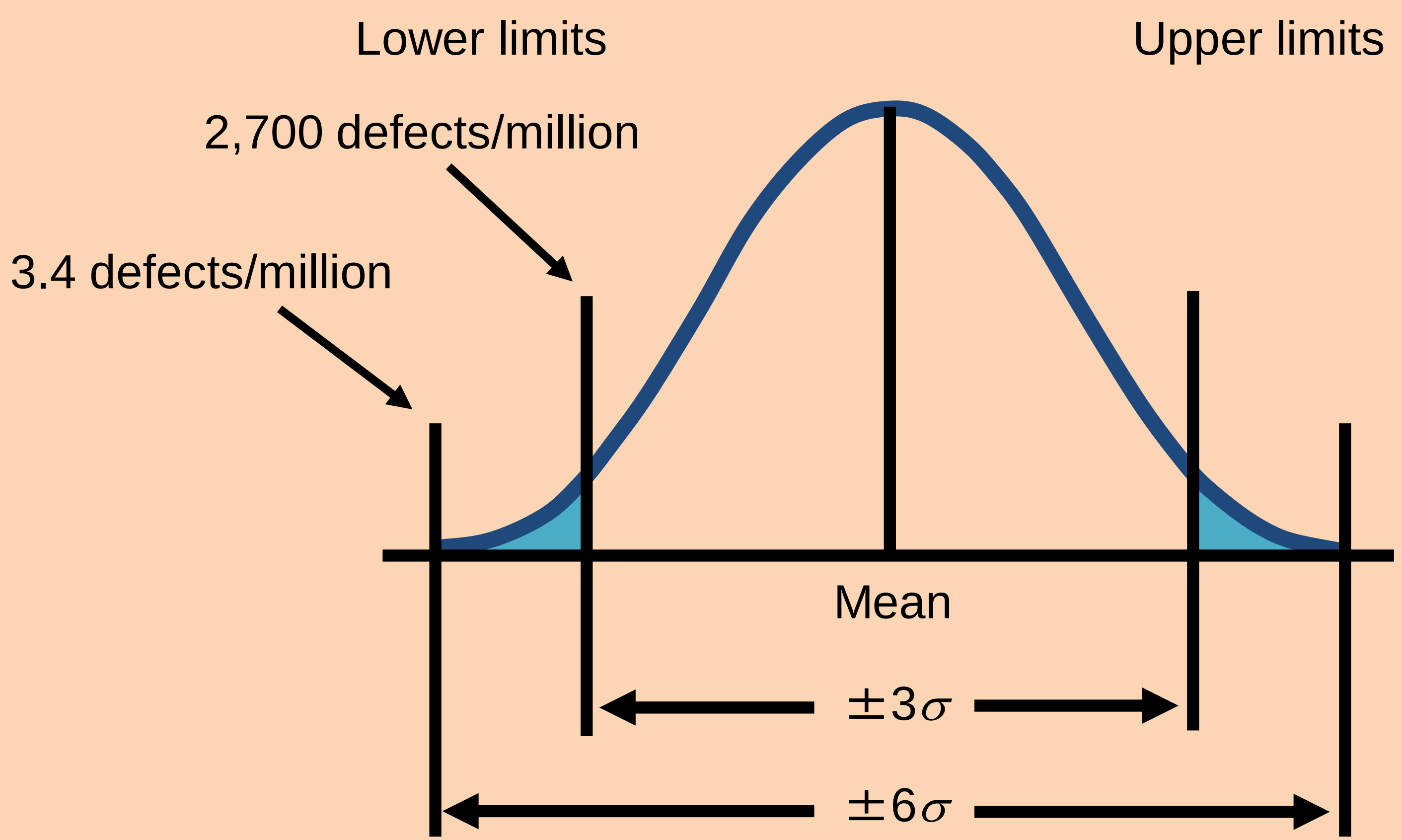
Do

- Implementing the processes

Six Sigma

- Two meanings in TQM
  - ***Statistical*** definition of a process that is 99.9997% capable, 3.4 defects per million opportunities (DPMO)
  - A ***program*** designed to reduce defects, lower costs, save time, and improve customer satisfaction
- Highly structured approach to process improvement
  - It is a ***strategy*** because it focuses on total customer satisfaction
  - It is a ***discipline*** because it follows the formal Six Sigma Improvement Model known as DMAIC.
  - It is a ***set of seven tools:*** check sheets, scatter diagrams, cause-and-effect diagrams, Pareto charts, flowcharts, histograms, and statistical process control.

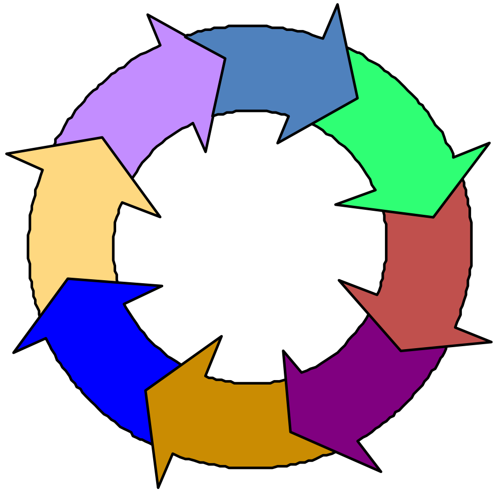
Six Sigma


Lower limits
Upper limits
2,700 defects/million
3.4 defects/million
Mean
±3σ
±6σ

Six Sigma

1. ***Defines*** the project's purpose, scope, and outputs, then identifies the required process information keeping in mind the customer's definition of quality
2. ***Measures*** the process and collects data
3. ***Analyzes*** the data, ensuring repeatability and reproducibility
4. ***Improves*** by modifying or redesigning existing processes and procedures
5. ***Controls*** the new process to make sure performance levels are maintained

Define Measure Analyze Improve Control (DMAIC) Approach



Six Sigma

- Emphasize defects per million opportunities as a standard metric
- Provide extensive training
- Focus on top management leadership (Champion)
- Create qualified process improvement experts (Black Belts, Green Belts, etc.)
- Set stretch objectives

Six Sigma

- Emphasize defects per million opportunities as a standard metric
- Provide extensive training
- Focus on to ... ion)
- Create quali ... vement experts (Black Belts, Green Belts, ...)
- Set stretch objectives

This cannot be accomplished without a major commitment from top level management

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Employee Empowerment

- Getting employees involved in product and process improvements
  - 85% of quality problems are due to materials and process
  - Techniques

1) Build communication networks that include employees
2) Develop open, supportive supervisors
3) Move responsibility to employees
4) Build a high-morale organization
5) Create formal team structures (e.g., *quality circles*)

Employee Empowerment

Quality Circles

- Group of employees who meet regularly to solve problems
- Trained in planning, problem solving, and statistical methods
- Often led by a *facilitator*
- Very effective when done properly

Benchmarking

Selecting best practices to use as a standard for performance

1. Determine what to benchmark
2. Form a benchmark team
3. Identify benchmarking partners
4. Collect and analyze benchmarking information
5. Take action to match or exceed the benchmark

Best Practices for Resolving Customer Complaints

Table 6.3

BEST PRACTICE	JUSTIFICATION
Make it easy for clients to complain	It is free market research
Respond quickly to complaints	It adds customers and loyalty
Resolve complaints on first contact	It reduces cost
Use computers to manage complaints	Discover trends, share them, and align your services
Recruit the best for customer service jobs	It should be part of formal training and career advancement

Just-in-Time (JIT)

- 'Pull' system of production scheduling including supply management
  - Production only when signaled
- Allows reduced inventory levels
  - Inventory costs money and hides process and material problems
- Encourages improved process and product quality
  - JIT cuts the cost of quality
  - JIT improves quality
  - Better quality means less inventory and better, easier-to-employ JIT system

Quality concepts according to Taguchi

- Engineering and experimental design methods to improve product and process design
  - Identify key component and process variables affecting product variation
  - Concepts
    - ***Quality robustness***
      - ***Target-oriented quality***
      - ***Quality loss function***

Quality concepts according to Taguchi

Quality robustness

- Ability to produce products uniformly in adverse manufacturing and environmental conditions
  - Remove the *effects* of adverse conditions (often cheaper than removing the causes)
  - Small variations in materials and process do not destroy product quality

Target-oriented quality

- A philosophy of continuous improvement to bring a product exactly on target

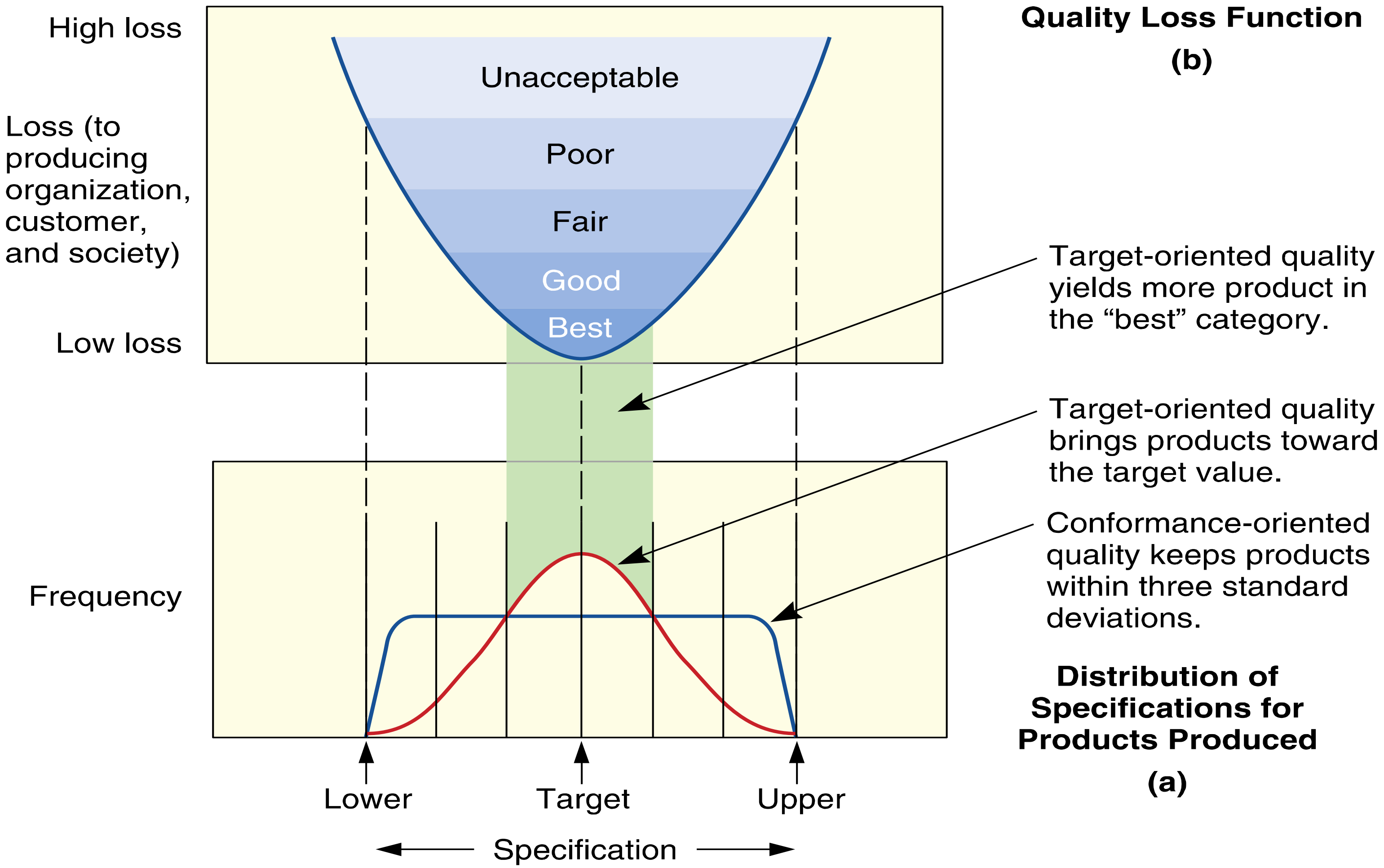
Quality concepts according to Taguchi

Quality loss function

- Shows that costs increase as the product moves away from what the customer wants
- Costs include customer dissatisfaction, warranty and service, internal scrap and repair, and costs to society
- Traditional conformance specifications are too simplistic

Quality concepts according to Taguchi

Quality Loss Function



Seven Tools of TQM

- Tools for Generating Ideas
  - Check Sheet
  - Scatter Diagram
  - Cause-and-Effect Diagram
- Tools to Organize the Data
  - Pareto Chart
  - Flowchart (Process Diagram)
- Tools for Identifying Problems
  - Histogram
  - Statistical Process Control Chart

Seven Tools of TQM

(a) ***Check Sheet:*** An organized method of recording data

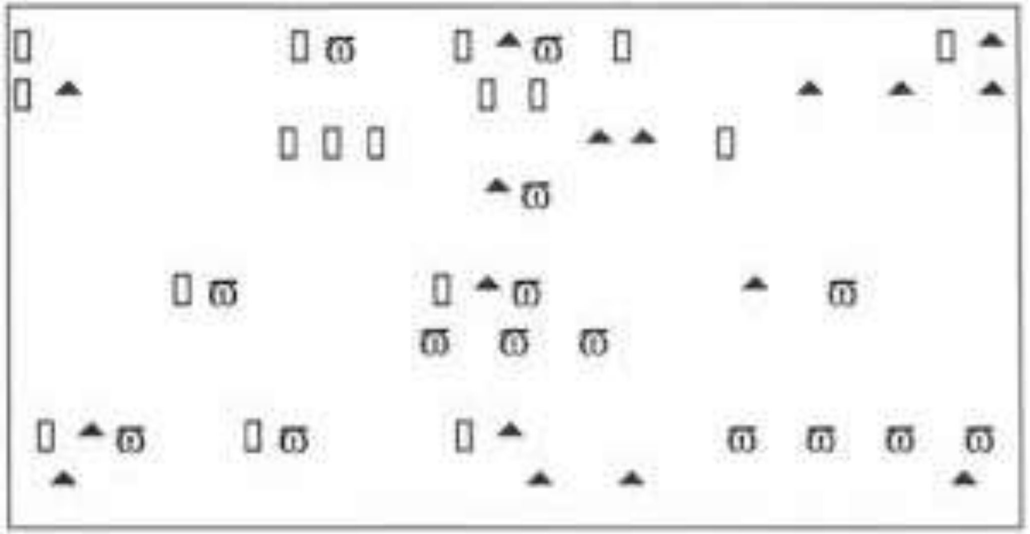
	Hour							
Defect	1	2	3	4	5	6	7	8
A	///	/		/	/	/	///	/
B	//	/	/	/			//	///
C	/	//					//	////

Check Sheet for a swimming pool example

Product: **Data:** **Order:**
Model: **Batch nr.** **Inspector:**

Type	Defects	Sub Total
Riscs	𝍸 𝍸 𝍸 𝍷𝍷	17
Slits	𝍸 𝍸 𝍷	11
Spots	𝍸 𝍸 𝍸 𝍸 𝍸 𝍷𝍷	27
Dirt	𝍷𝍷	2
Others	𝍸	5
	Total of Defects	**62**
Total of Rejeccions	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍷𝍷	**42**
Total number of Inspected products		**1 035**

Check Sheet for a swimming pool example



Example of a defect location sheet

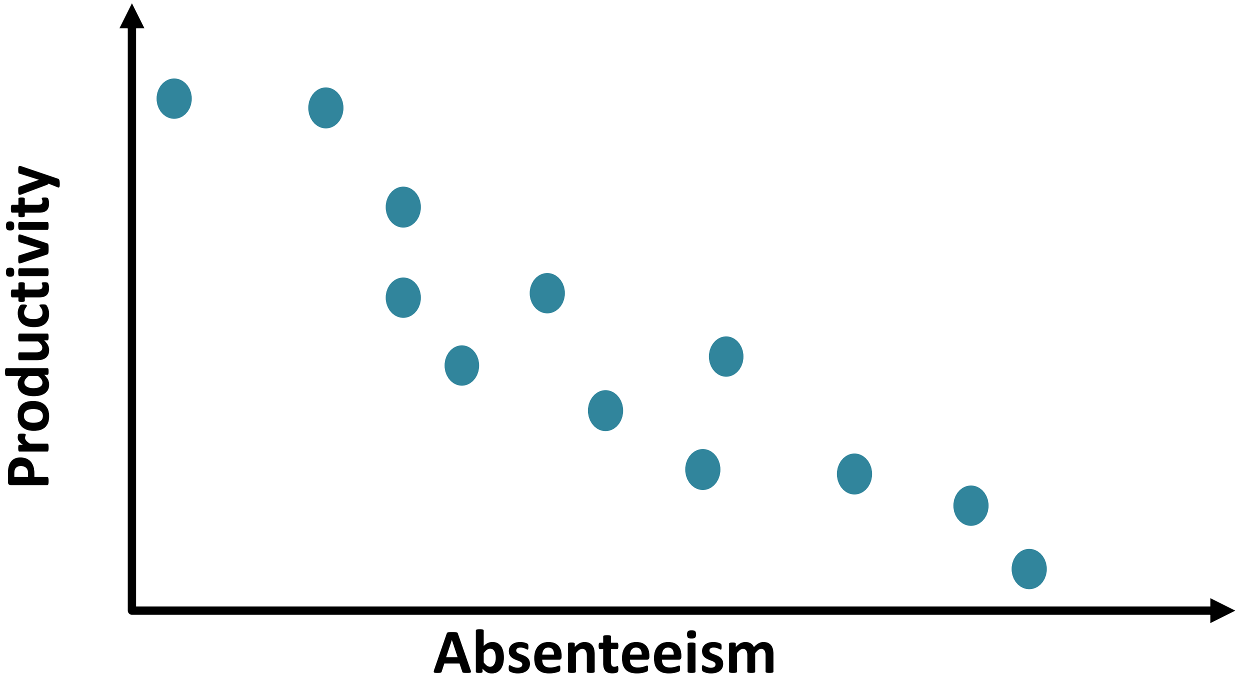
D = Daily   A = As Needed

Hot Tub		Mon.	Tues.	Wed.	Th.	Fri.	Sat.	Sun.
Chemical Test (Add if Needed) ph/chlorine	(D)	7.4						
Temperature	(D)	81°						
Add Water (If Needed)	(D)							
Clean Deck Around Hot Tub	(D)	✓						
Pool								
Chemical Test (Add if Needed)	(D)	7.6						
Add Water (If Needed)	(D)	300 gals.						
Check Temperature	(D)	78°						
Vacuum Pool (If Needed)	(A)							
Filter Backwash (20 lb.)	(A)	✓						
Lint Filter	(D)	✓						
Sweep and Hose Off Deck	(D)	✓						
General Cleaning								
Vacuum Carpets	(D)	✓						
Vacuum and Sweep Building B	(D)	✓						
Clean Tables	(D)	✓						
Sweep and Mop Wooden Deck	(D)	✓						
Clean Outside Deck, Bring in Chairs	(D)	✓						
Take Out Trash	(D)	✓						
Empty Building B Trash Cans	(D)	✓						
Wash Windows	(D)	✓						
Bathrooms								
Scrub Sinks, Toilets, and Showers	(D)	✓						
Sweep and Mop Floors	(D)	✓						
Empty Trash and Check Lockers	(D)	✓						
Cover Hot Tub (At End of the Night)	(D)	✓						
Check Pool Filters—Be Sure It's On	(D)	✓						

Seven Tools of TQM

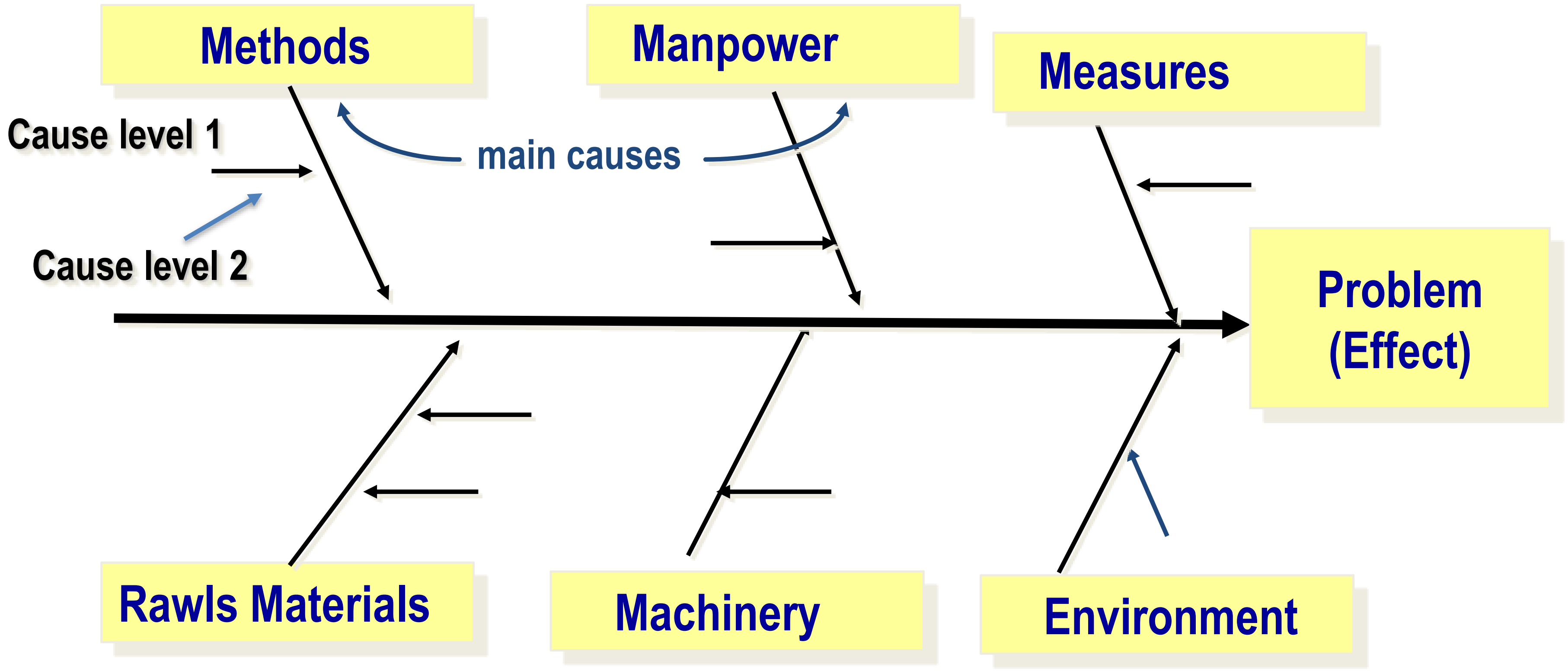
***(b) Scatter Diagram*:** A graph of the value of one variable vs. another variable

Pearson's correlation coefficient can be used to evaluate the linear association between variables (below an example of such variables: Productivity vs Absenteeism)

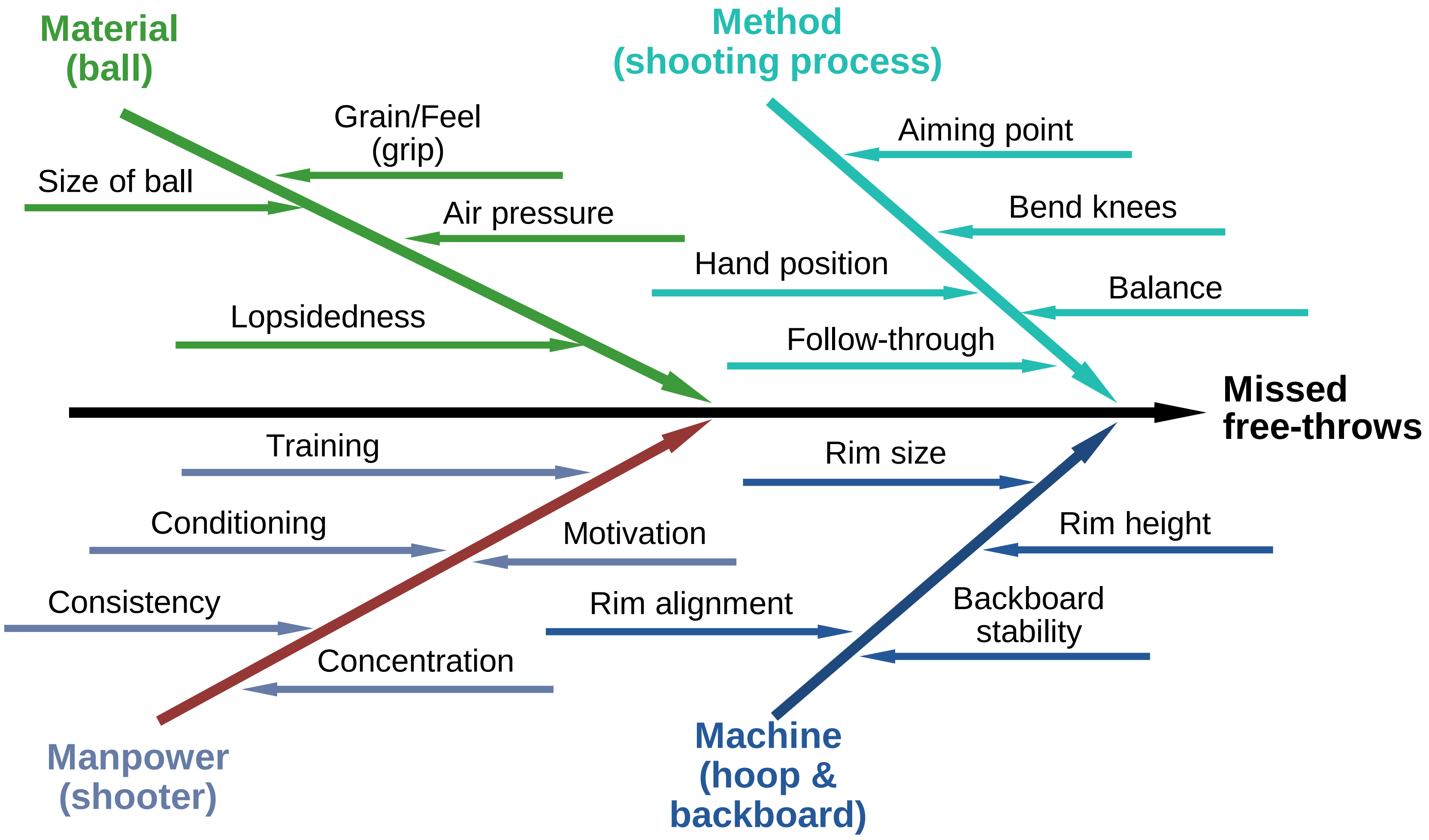


Seven Tools of TQM

(c) ***Cause-and-Effect Diagram*:** A tool that identifies process elements (causes) that may effect an outcome



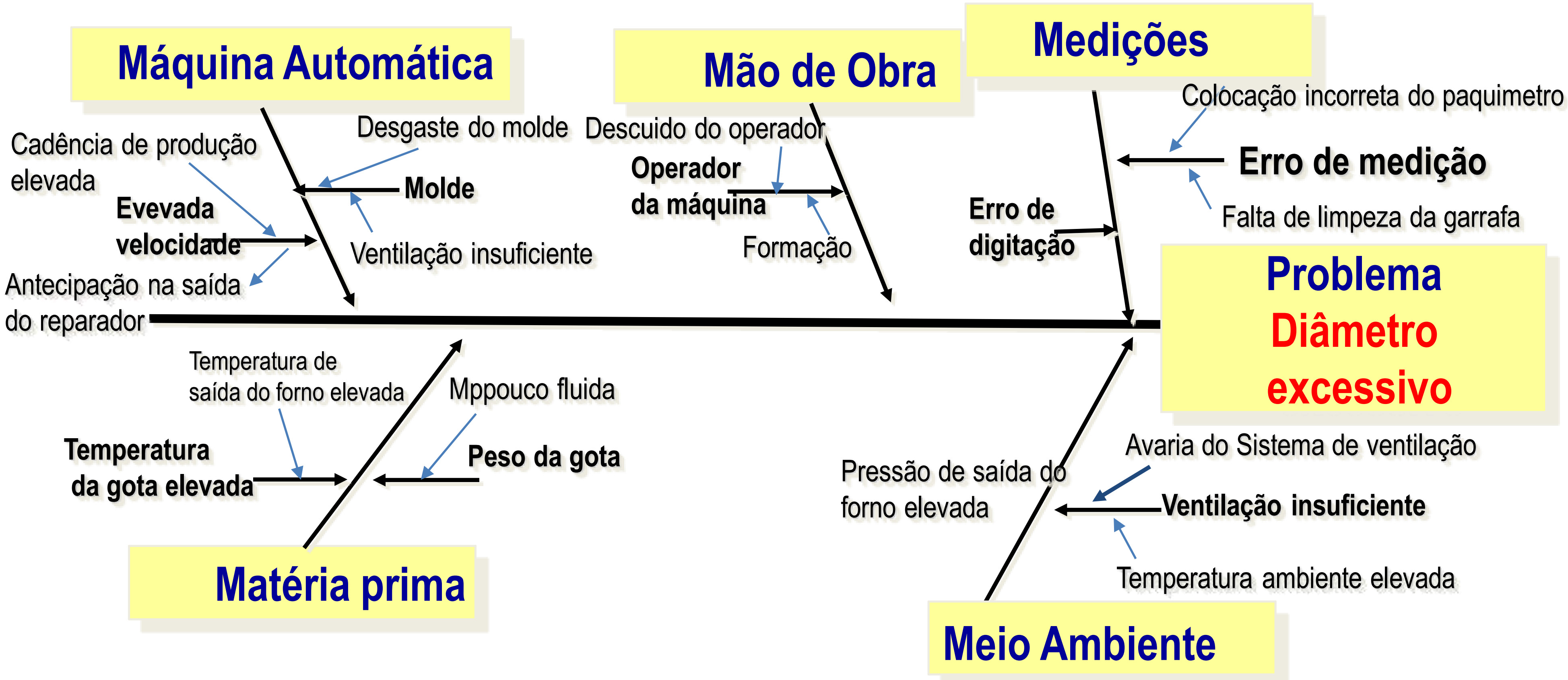
Cause-and-Effect Diagram example



Seven Tools of TQM

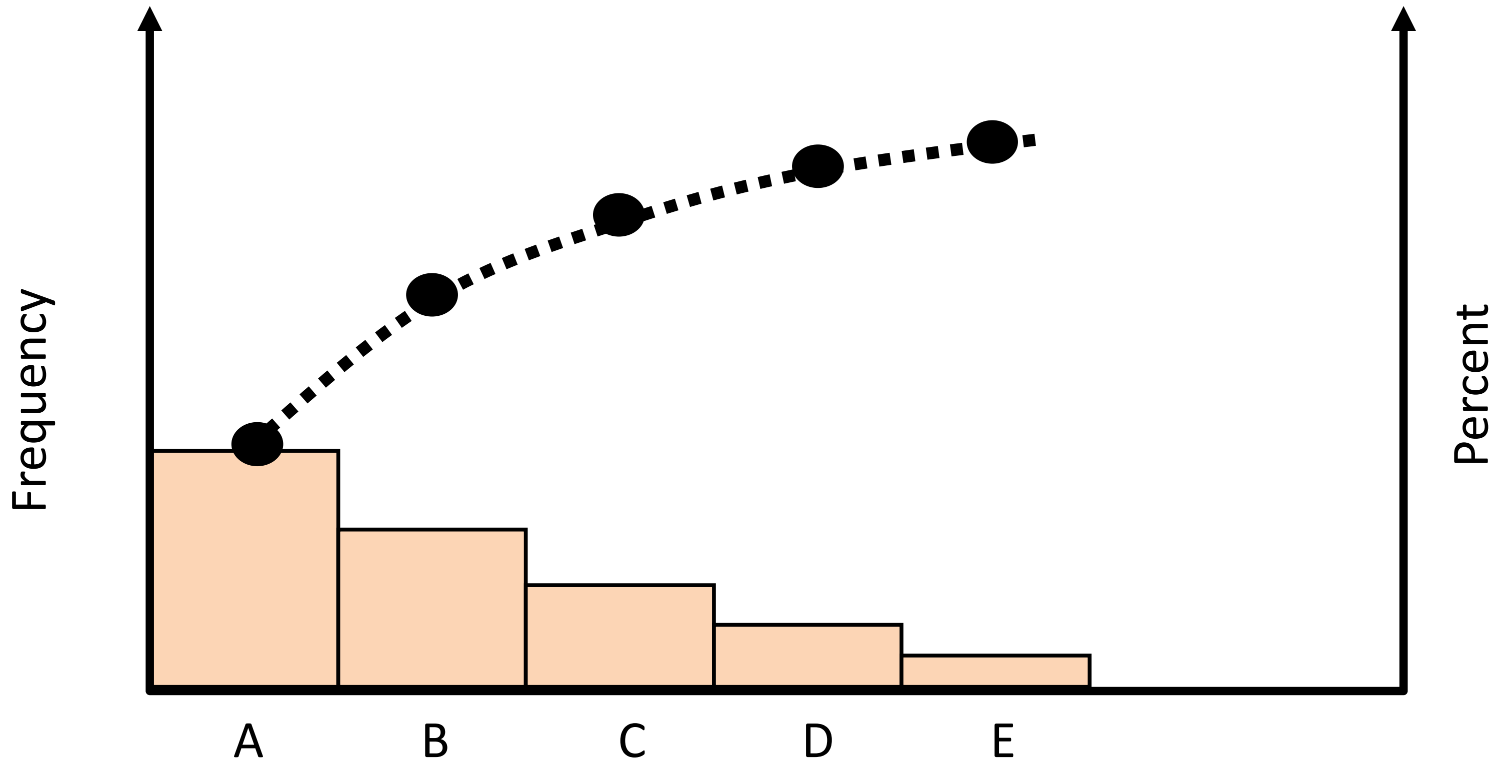
(c) *Cause-and-Effect Diagram*: Example

Problema detetado no fabrico de garrafas de vidro

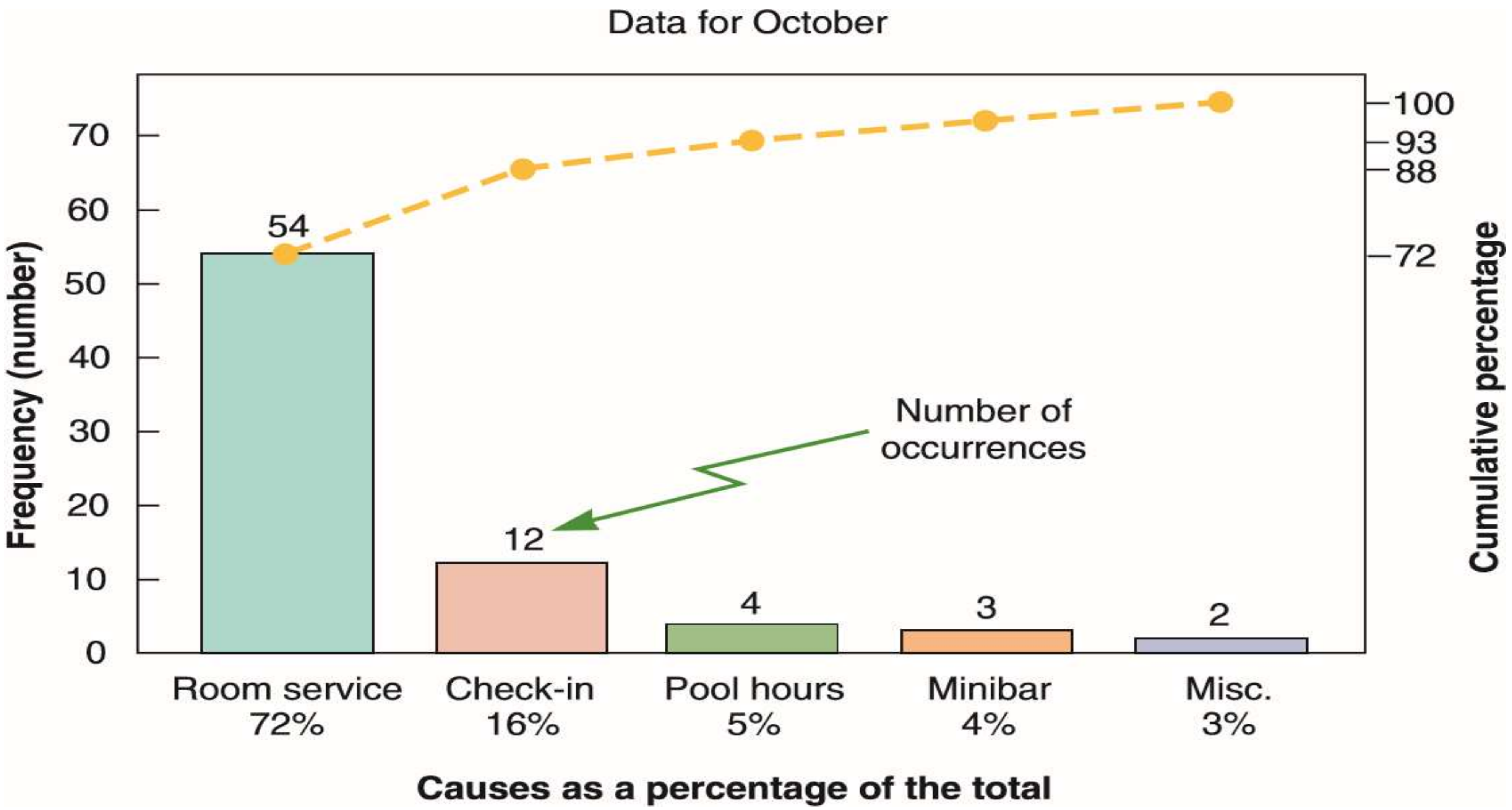


Seven Tools of TQM

(d) ***Pareto Chart*:** A graph to identify and plot problems or defects in descending order of frequency

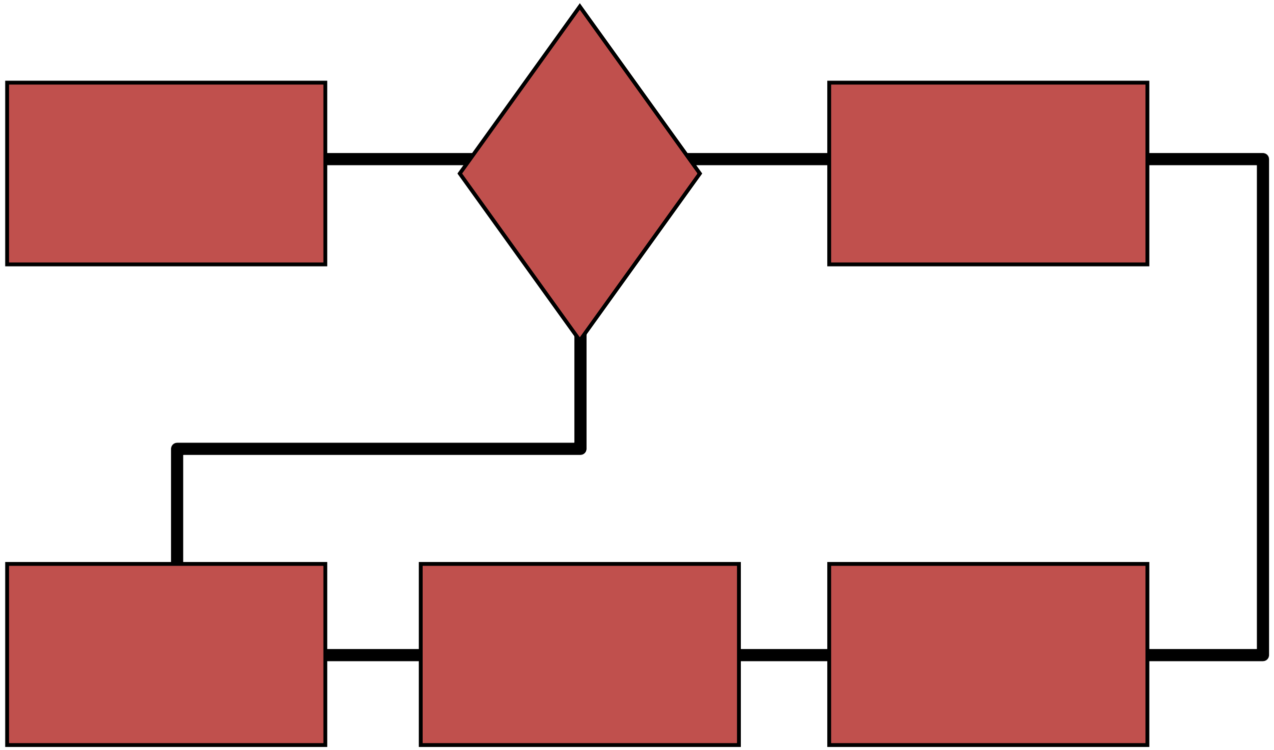


Pareto Chart example



Seven Tools of TQM

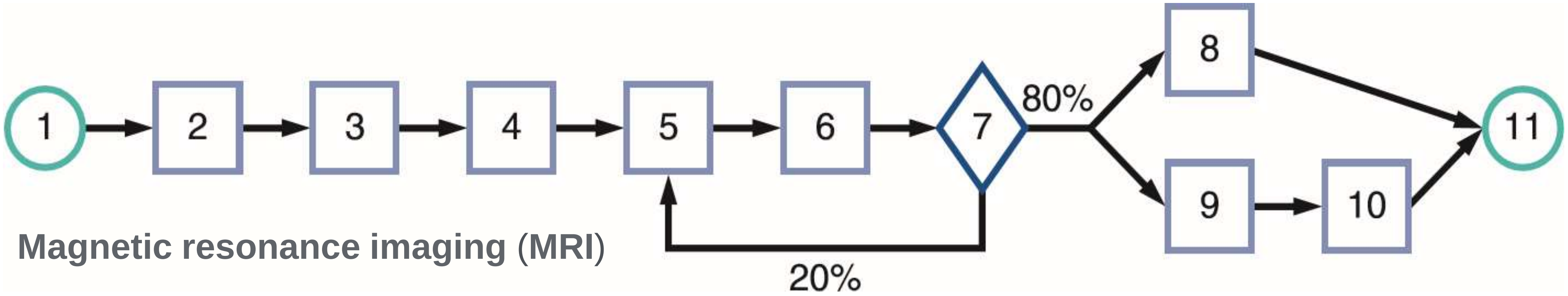
(e) ***Flowchart (Process Diagram)*:** A chart that describes the steps in a process



Flowchart example

MRI Flowchart

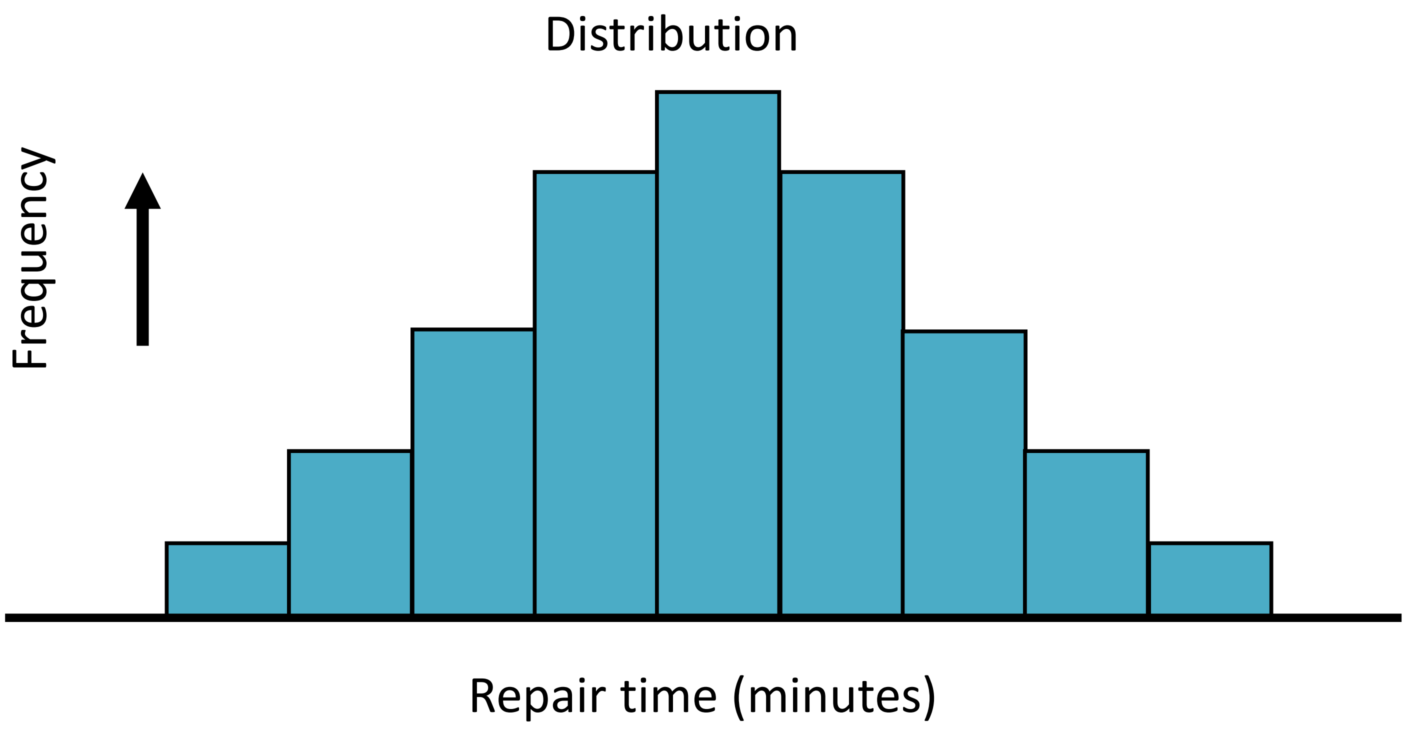
1. Physician schedules MRI
2. Patient taken to MRI
3. Patient signs in
4. Patient is prepped
5. Technician carries out MRI
6. Technician inspects film
7. If unsatisfactory, repeat
8. Patient taken back to room
9. MRI read by radiologist
10. MRI report transferred to physician
11. Patient and physician discuss



Magnetic resonance imaging (MRI)

Seven Tools of TQM

(f) ***Histogram*: A distribution showing the frequency of occurrences of a variable**



Seven Tools of TQM

Statistical Process Control

- Uses statistics and control charts to indicate when corrective actions should be taken
- Drives continuous process improvement
- Four key-steps:
  - Measure the process
  - When a change is detected, find the special cause of variation
  - Eliminate or incorporate the cause
  - Restart process control

Seven Tools of TQM

(g) ***Statistical Process Control Chart:*** A chart with time on the horizontal axis to plot values of a statistic

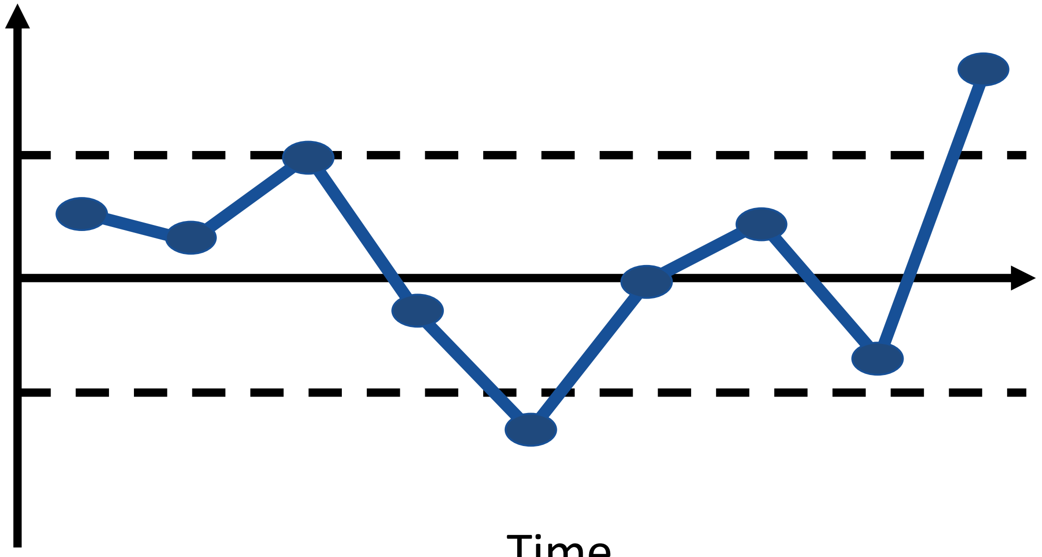
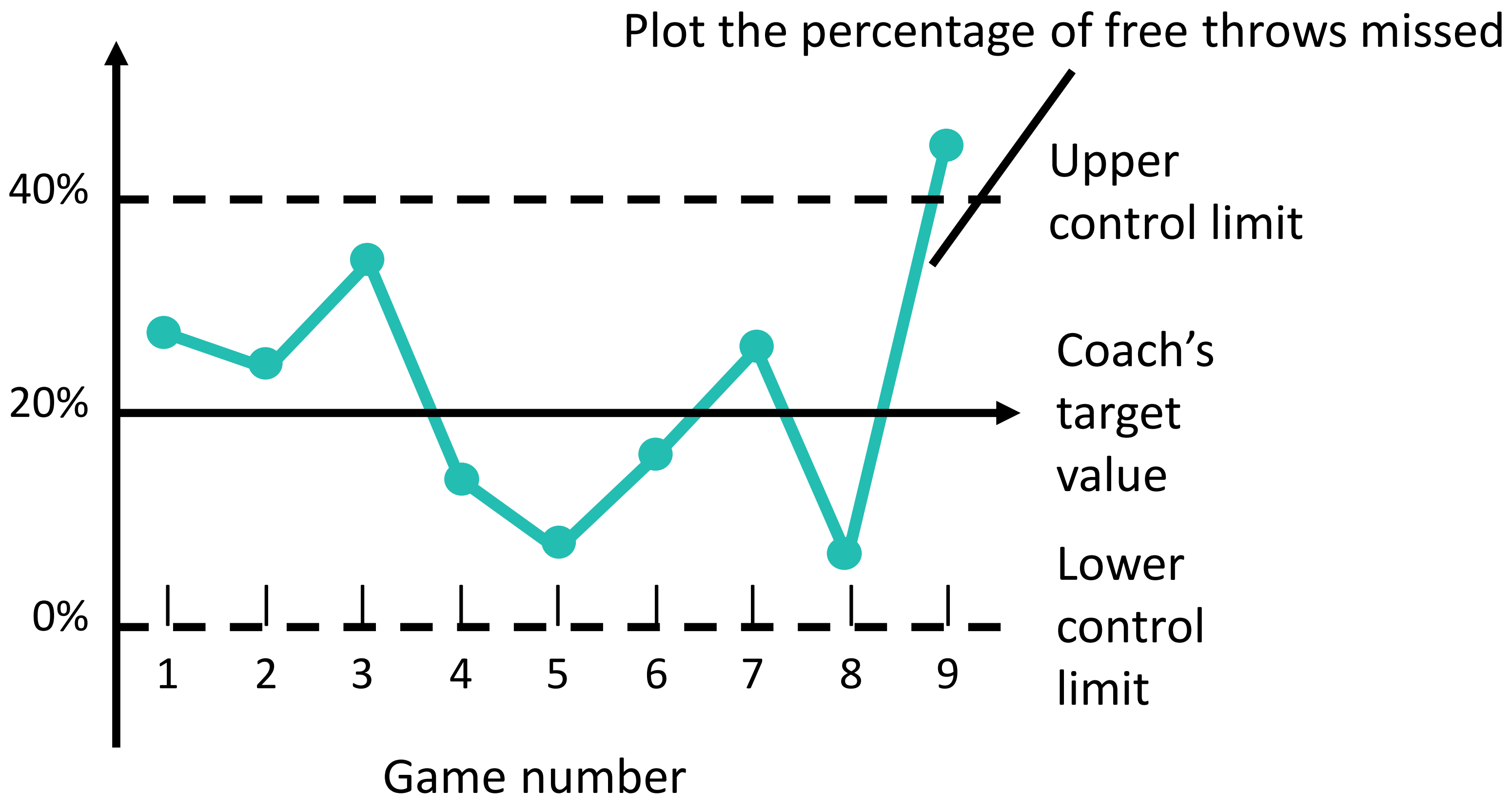


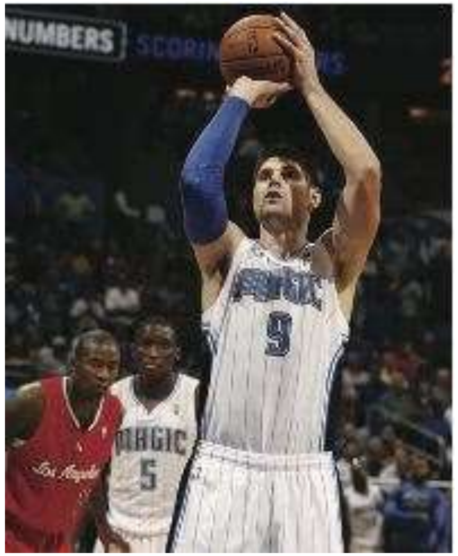
Figure 6.6

Statistical Process Control (SPC)

- Uses statistics and control charts to tell when to take corrective action
- Drives process improvement
- Four key steps
  - Measure the process
  - When a change is indicated, find the assignable cause
  - Eliminate or incorporate the cause
  - Restart the revised process

Control Charts





Inspection

- Involves examining items to see if an item is good or defective
- Detect a defective product
  - Does not correct deficiencies in process or product
  - It is expensive
- Issues
  - When to inspect?
  - Where in process to inspect?

When and Where to Inspect

1. At the supplier's plant while the supplier is producing
2. At your facility upon receipt of goods from your supplier
3. Before costly or irreversible processes
4. During the step-by-step production process
5. When production or service is complete
6. Before delivery to your customer
7. At the point of customer contact

When and Where to Inspect

Table 6.4	**How Samsung Tests Its Smartphones**
Durability	Stress testing with nail punctures, extreme temperatures and overcharging
Visual inspection	Comparing the battery with standardized models
X-ray	Looking for internal abnormalities
Charge and discharge	Power up and down the completed phone
Organic pollution (TVOC)	Looking for battery leakage
Disassembling	Opening the battery cell to inspect tab welding and insulation tape conditions
Accelerated usage	Simulated 2 weeks of real-life use in 5 days
Volatility (OVC)	Checking for change in voltage throughout the manufacturing process

Inspection

- Many problems
  - Worker fatigue
  - Measurement error
  - Process variability
- Cannot inspect quality into a product
- Robust design, empowered employees, and sound processes are better solutions

Source Inspection

- Also known as **Source Control**
- The next step in the process is your customer
- Ensure perfect product to your customer
- **Poka-yoke** is the concept of foolproof devices or techniques designed to pass only acceptable products
- **Checklists** ensure consistency and completeness

Service Industry Inspection

TABLE 6.5 Examples of Inspection in Services		
ORGANIZATION	**WHAT IS INSPECTED**	**STANDARD**
Alaska Airlines	Last bag on carousel	Less than 20 minutes after arrival at the gate
	Airplane door opened	Less than 2 minutes after arrival at the gate
Jones Law Office	Receptionist performance	Phone answered by the second ring
	Billing	Accurate, timely, and correct format
	Attorney	Promptness in returning calls
Hard Rock Hotel	Reception desk	Use customer's name
	Doorman	Greet guest in less than 30 seconds
	Room	All lights working, spotless bathroom
	Minibar	Restocked and charges accurately posted to bill

Service Industry Inspection

TABLE 6.5	Examples of Inspection in Services	
ORGANIZATION	**WHAT IS INSPECTED**	**STANDARD**
Arnold Palmer Hospital	Billing	Accurate, timely, and correct format
	Pharmacy	Prescription accuracy, inventory accuracy
	Lab	Audit for lab-test accuracy
	Nurses	Charts immediately updated
	Admissions	Data entered correctly and completely
Olive Garden Restaurant	Busboy	Serves water and bread within 1 minute
	Busboy	Clears all entrée items and crumbs prior to dessert
	Waiter	Knows and suggest specials, desserts

Attributes versus Variables

- ***Attributes***
  - Items are either good or bad, acceptable or unacceptable
  - Does not address *degree* of failure
- ***Variables***
  - Measures dimensions such as weight, speed, height, or strength
  - Falls within an acceptable range
- Use different statistical techniques

TQM In Services

- Service quality is more difficult to measure than the quality of goods

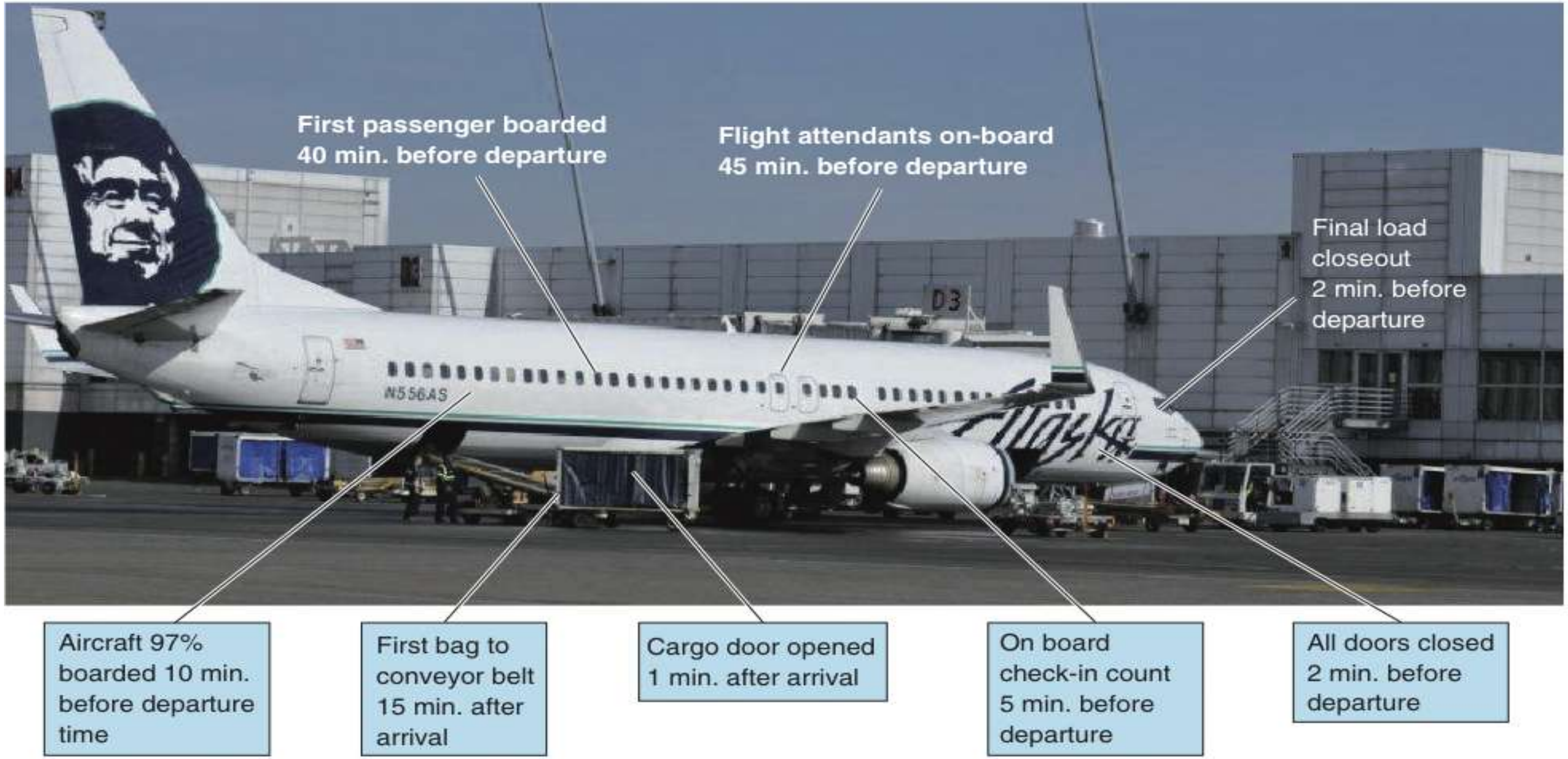
- Service quality perceptions depend on
  1) *Intangible differences between products*
  2) *Intangible expectations customers have of those products*

TQM In Services

The operations manager must recognize:

- The tangible component of services is important
- The service process is important
- The service is judged against the customer's expectations
- Exceptions will occur (the services are heterogeneous)

Example of Service Specifications



Determinants of Service Quality

Table 6.6
Reliability involves consistency of performance and dependability
Responsiveness concerns the willingness or readiness of employees to provide service
Competence means possession of the required skills and knowledge to perform the service
Access involves approachability and ease of contact
Courtesy involves politeness, respect, consideration, and friendliness
Communication means keeping customers informed and listening to them
Credibility involves trustworthiness, believability, and honesty
Security is the freedom from danger, risk, or doubt
Understanding/knowing the customer involves making the effort to understand the customer's needs
Tangibles include the physical evidence of the service

Evaluating Performance

- The **SERVQUAL** technique
- Direct comparisons between customer service expectations and actual service provided
- Focuses on gaps in the 10 service quality determinants
- Most common version collapses the determinants to
  - **Reliability**
  - **Assurances**
  - **Tangibles**
  - **Empathy**
  - **Responsiveness**

SERVQUAL: Expectations

- **To what extent do you agree that ___ service companies should exhibit each of the following characteristics?**

Tangibles

- E1. Companies should have modern equipment
- E2. Physical installations should be visually attractive
- E3. Employees should be well dressed and have a good appearance
- E4. The appearance of physical facilities should be maintained in accordance with the type of service offered

Reliability

- E5. When companies commit to doing something within a set deadline, they should do it
- E6. When customers face problems, these companies should be supportive and helpful
- E7. These companies should be trustworthy
- E8. Companies should provide services within the promised time frame
- E9. Companies should keep their records up to date
- E10. Companies should not be expected to communicate to customers exactly when services will be completed (R)

Responsiveness

- E11. It is unrealistic for customers to expect immediate service from employees of these companies
- E12. Employees don't always have to be willing to help customers (R)
- E13. It's okay if employees are too busy to respond promptly to customer requests

SERVQUAL: Expectations (cont.)

- **To what extent do you agree that ___ service companies should exhibit each of the following characteristics?**

Security

- E14 Customers should be able to trust the employees of these companies
- E15. Customers should be able to feel safe when dealing with employees of these companies
- E16. Your employees should be kind
- E17. Employees should receive adequate support from their companies to perform their tasks well

Empathy

- E18. These companies should not be expected to give individual attention to customers (R)
- E19. Employees of these companies cannot be expected to give personalized attention to customers(R)
- E20. It's unrealistic to expect employees to know what their customers' needs are (R)
- E21. It is unrealistic to expect these companies to be deeply interested in the well-being of customers(R)
- E22.These companies should not be expected to operate at convenient times for all their customers (R)

SERVQUAL: Expectations (cont.)

- **To what extent do you agree that ___ service companies should exhibit each of the following characteristics?**

Security

- E14 Customers should be able to trust the employees of these companies
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- E21. It is unrealistic to expect these companies to be deeply interested in the well-being of customers(R)
- E22.These companies should not be expected to operate at convenient times for all their customers (R)

SERVQUAL: Perceptions

- **To what extent do you agree that ___ service companies should exhibit each of the following characteristics?**

Tangibles

- E1. Company XYZ has modern equipment
- E2. XYZ's physical facilities are visually appealing
- E3. XYZ employees dress well and look good
- E4. The appearance of XYZ's physical facilities is in accordance with the type of service offered

Reliability

- E5. When XYZ commits to doing something within a certain time frame, it does it
- E6. When you have problems, XYZ is supportive and helpful
- E7. XYZ is trustworthy
- E8. XYZ provides services within the promised time frame
- E9. XYZ keeps its records up to date
- E10. XYZ does not communicate to customers exactly when services will be completed (R)

SERVQUAL: Perceptions (cont.)

- **To what extent do you agree that ___ service companies should exhibit each of the following characteristics?**

RESPONSIVENESS

- E11. You are not immediately attended to by XYZ employees
- E12. XYZ employees are not always willing to help customers (R)
- E13. XYZ employees are too busy to respond promptly to customer requests

SECURITY

- E14 You can trust XYZ employees
- E15. You feel safe transacting with XYZ employees
- E16. XYZ employees are kind
- E17. Employees receive adequate support from XYZ to perform their tasks well

EMPATHY

- E18. XYZ does not give you individual attention (R)
- E19. XYZ employees do not give personalized attention to customers(R)
- E20. XYZ employees don't know what your needs are (R)
- E21. XYZ is not deeply interested in your well-being (R)
- E22. XYZ does not operate at convenient times for all of its customers (R)

SERVQUAL

The SERVQUAL survey has two parts: **customer expectations** and **customer perceptions**.

- Advantages of SERVQUAL instrument:
  - It is accepted as a standard for assessing different dimensions of services quality.
  - It has been shown to be valid for a number of service situations.
  - It has been demonstrated to be reliable, meaning that different readers interpret the questions similarly.
  - Each instrument is parsimonious in that it has only 22 items. This means that it can be filled out quickly by customers and employees.
  - Finally, it has a standardized analysis procedure to aid both interpretation and results.

SERVQUAL

SERVQUAL survey:

- **customer expectations**
  - 22 items
- **customer perceptions.**
  - 22 items

Dimension	Items
Tangibles	1-4
Reliability	5-9
Responsiveness	10-13
Assurance	14-17
Empathy	18-22

SERVQUAL items

	Strongly Disagree						Strongly Agree	
1. XYZ Co. has modern-looking equipment.	1	2	3	4	5	6	7	TANGIBLES
2. XYZ Co.'s physical facilities are visually appealing.	1	2	3	4	5	6	7	
3. XYZ Co.'s employees are neat-appearing.	1	2	3	4	5	6	7	
4. Materials associated with the service (such as pamphlets or statements) are visually appealing at XYZ Co.	1	2	3	4	5	6	7	
5. When XYZ Co. promises to do something by a certain time, it does so.	1	2	3	4	5	6	7	RELIABILITY
6. When you have a problem, XYZ Co. shows a sincere interest in solving it.	1	2	3	4	5	6	7	
7. XYZ Co. performs the service right the first time.	1	2	3	4	5	6	7	
8. XYZ Co. provides its services at the time it promises to do so.	1	2	3	4	5	6	7	
9. XYZ Co. insists on error-free records.	1	2	3	4	5	6	7	
10. Employees in XYZ Co. tell you exactly when services will be performed.	1	2	3	4	5	6	7	
11. Employees in XYZ Co. give you prompt service.	1	2	3	4	5	6	7	RESPONSIVENESS
12. Employees in XYZ Co. are always willing to help you.	1	2	3	4	5	6	7	
13. Employees in XYZ Co. are never too busy to respond to your requests.	1	2	3	4	5	6	7	

SERVQUAL items

14. The behavior of employees in XYZ Co. instills confidence in you.	1	2	3	4	5	6	7	ASSURANCE
15. You feel safe in your transactions with XYZ Co.	1	2	3	4	5	6	7	
16. Employees in XYZ Co. are consistently courteous with you.	1	2	3	4	5	6	7	
17. Employees in XYZ Co. have the knowledge to answer your questions.	1	2	3	4	5	6		
18. XYZ Co. gives you individual attention.	1	2	3	4	5	6	7	EMPATHY
19. XYZ Co. has operating hours convenient to all its customers.	1	2	3	4	5	6	7	
20. XYZ Co. has employees who give you personal attention.	1	2	3	4	5	6	7	
21. XYZ Co. has your best interests at heart.	1	2	3	4	5	6	7	
22. Employees of XYZ Co. understand your specific needs.	1	2	3	4	5	6	7	

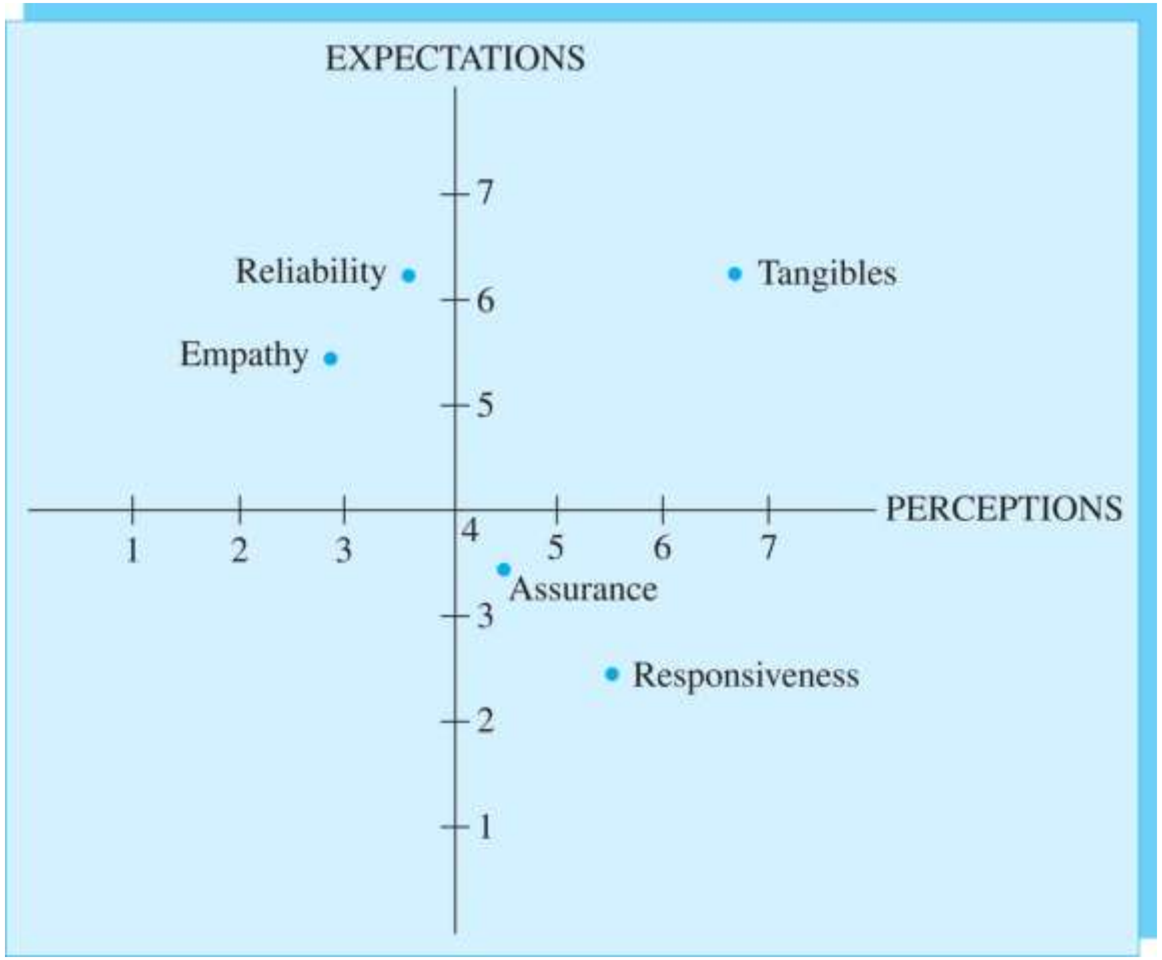
Assessing Differences in Expectations by Using the Differencing Technique

- Steps:
  - Administer the expectations and perceptions SERVQUAL instruments to your customers.
    - Typically need a sample size of between **50-100**
  - Compute a difference score for SERVQUAL by separating the dimensions as follows (see table).
  - For each respondent, sum the SERVQUAL scores for each set of items relating to a given dimension.
  - Sum across the n respondents and divide by the total n.

	Perceptions		Expectations		Gap
Tangibles	6,65	-	6,425	=	0,225
Reliability	3,4	-	6,02	=	-2,62
Responsiveness	5,525	-	2,4	=	3,125
Assurance	4,5	-	3,275	=	1,225
Empathy	2,9	-	5,86	=	-2,96

Two-Dimensional Differencing

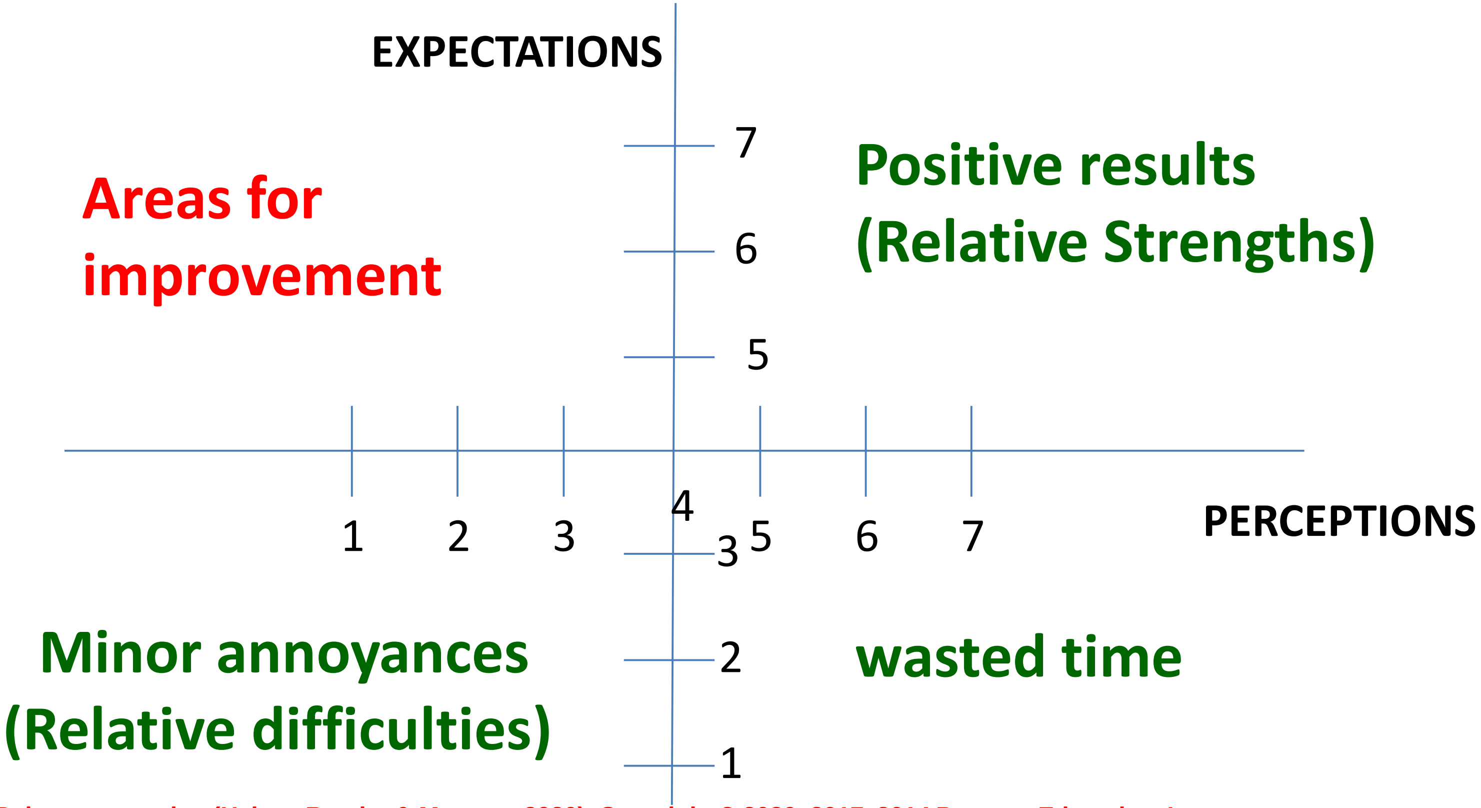
- The two-dimensional differencing technique is very useful for evaluating S E R V Q U A L responses if there is enough variation in the responses given to different dimensions.
- The two-dimensional differencing technique **allows the firm to determine which services it should emphasize to improve customer perceptions and those that make little difference.**
- The vertical axis reflects the expectations score.
- The horizontal axis relates to the perceptions score.
- The value 4 (the neutral response) is used as the origin.



Adapted from Foster, S. T. (2017). Managing Quality – Integrating the Supply Chain (6th ed.). Boston, MA: Pearson Education.

Two-Dimensional Differencing

Two-dimensional differencing plane



Statistical Process Control (SPC)

- Variability is inherent in every process
  - Natural or common causes
  - Special or assignable causes
- Provides a statistical signal when assignable causes are present
- Allows faster action to be taken to eliminate special causes of variation

Statistical Process Control (SPC)
Natural Variations

- Also called common causes
- Affect virtually all production processes
- Expected amount of variation
- Output measures follow a probability distribution
- For any distribution there is a measure of central tendency and dispersion
- If the distribution of outputs falls within acceptable limits, **the process is said to be "in control"**

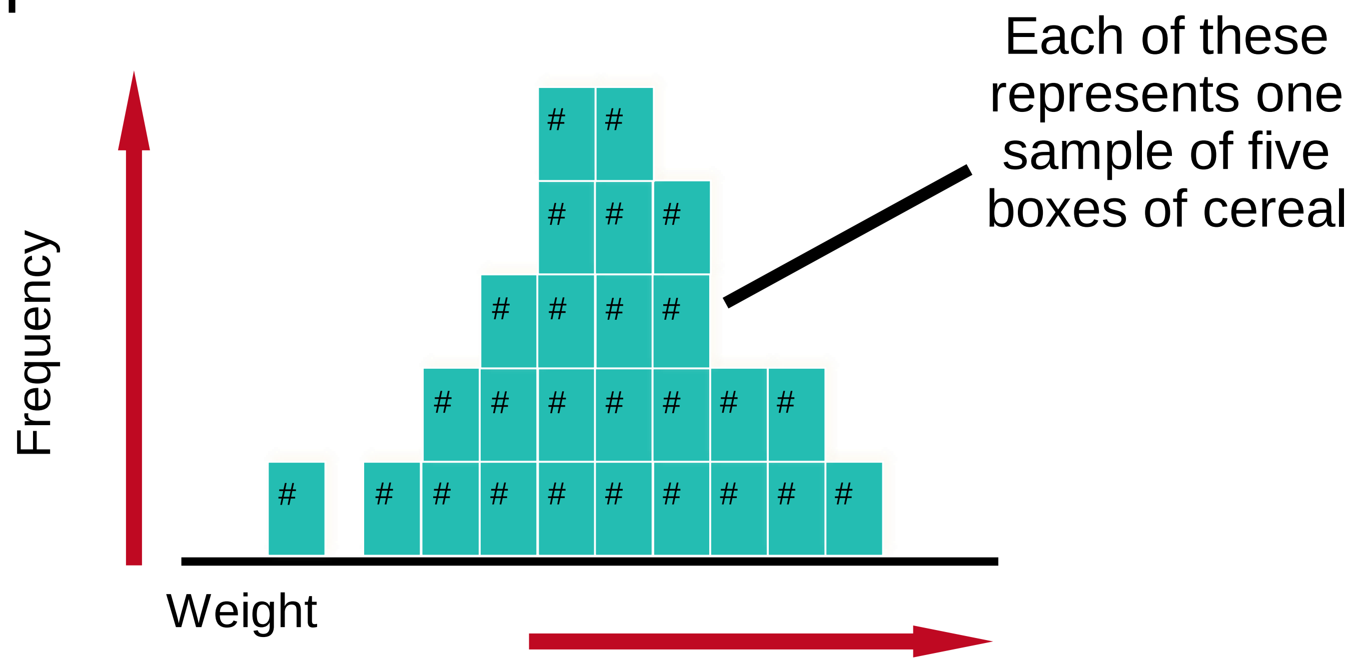
Statistical Process Control (SPC)
Assignable Variations

- Also called special causes of variation
  - Generally this is some change in the process
- Variations that can be traced to a specific reason
- The objective is to discover when assignable causes are present
  - Eliminate the bad causes
  - Incorporate the good causes

Statistical Process Control (SPC)
Samples

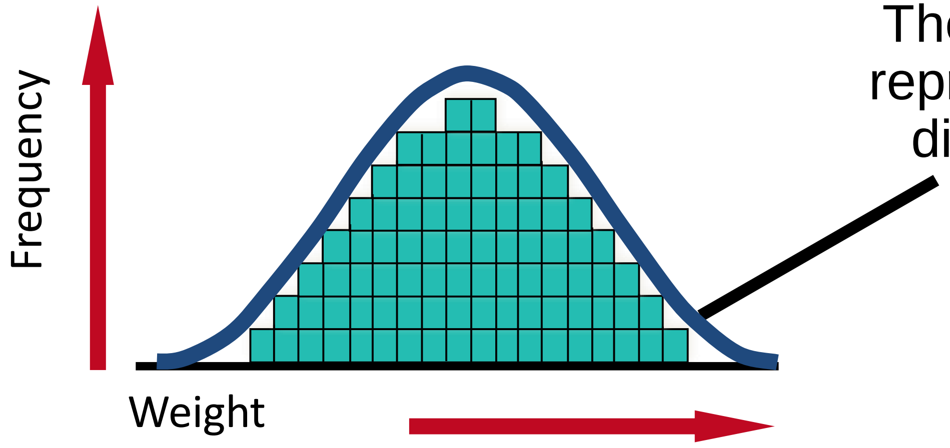
To measure the process, we take samples and analyze the sample statistics following these steps

(a) Samples of the product, say five boxes of cereal taken off the filling machine line, vary from each other in weight

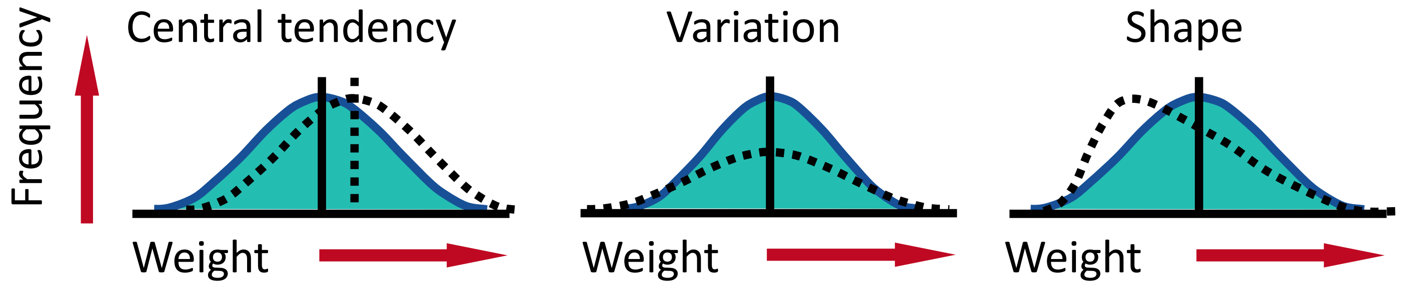


Statistical Process Control (SPC) Samples

(b) After enough samples are taken from a stable process, they form a pattern called a *distribution*

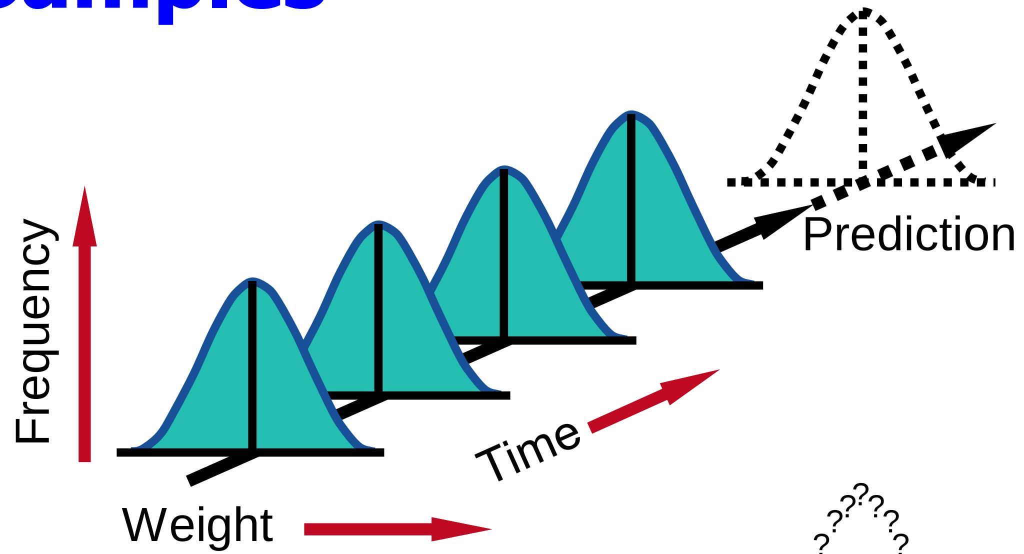


(c) There are many types of distributions, including the normal (bell-shaped) distribution, but distributions do differ in terms of central tendency (mean), standard deviation or variance, and shape

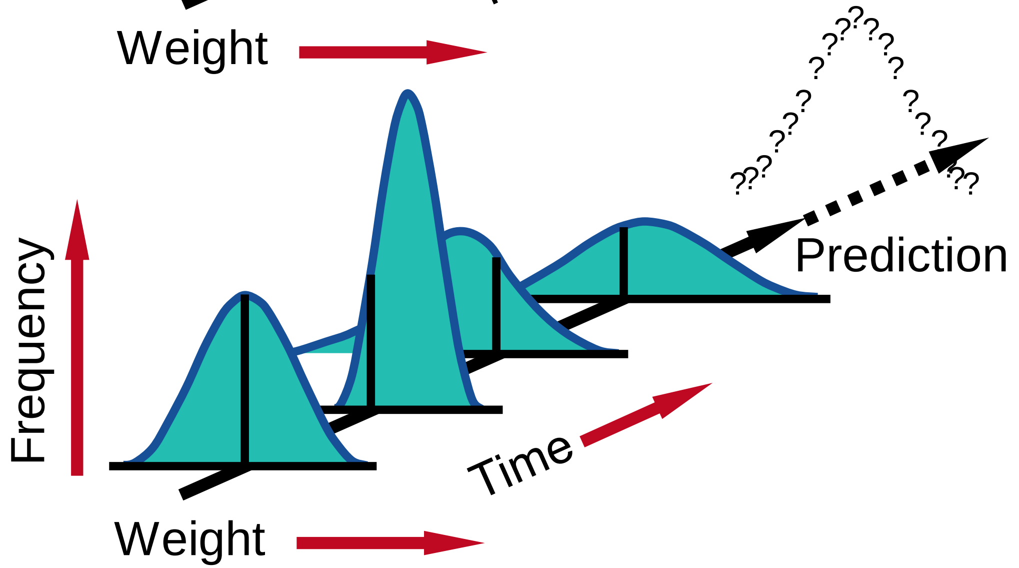


Statistical Process Control (SPC) Samples

(d) If only natural causes of variation are present, the output of a process forms a distribution that is stable over time and is predictable

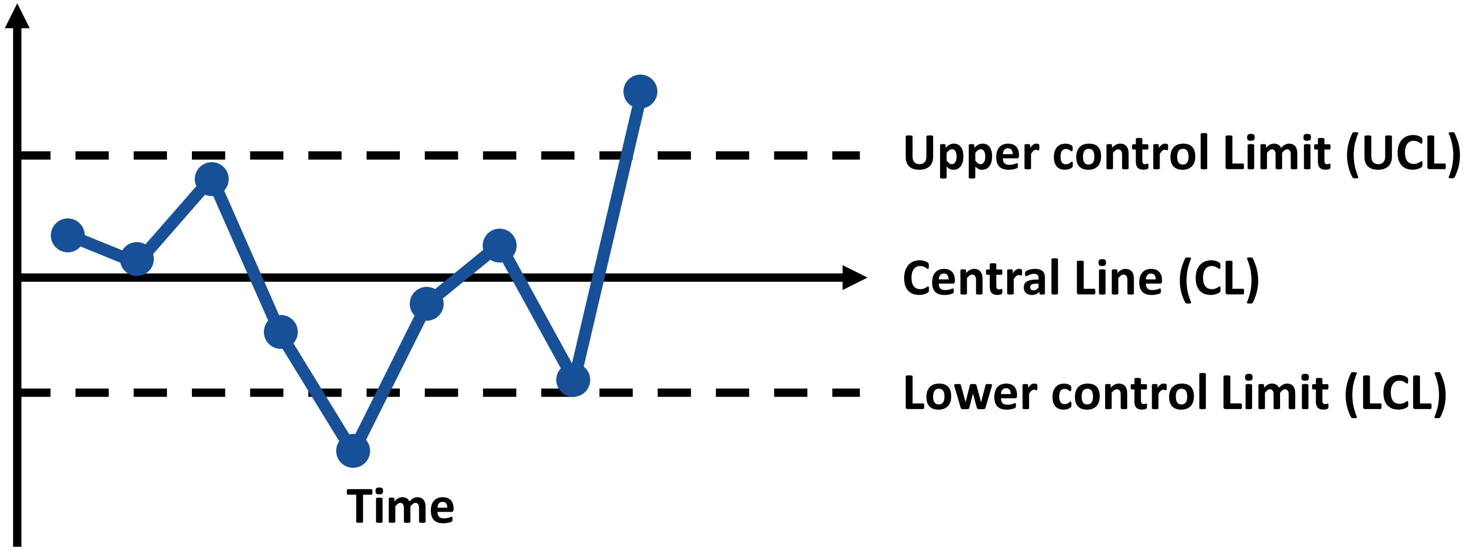


(e) If assignable causes are present, the process output is not stable over time and is not predicable

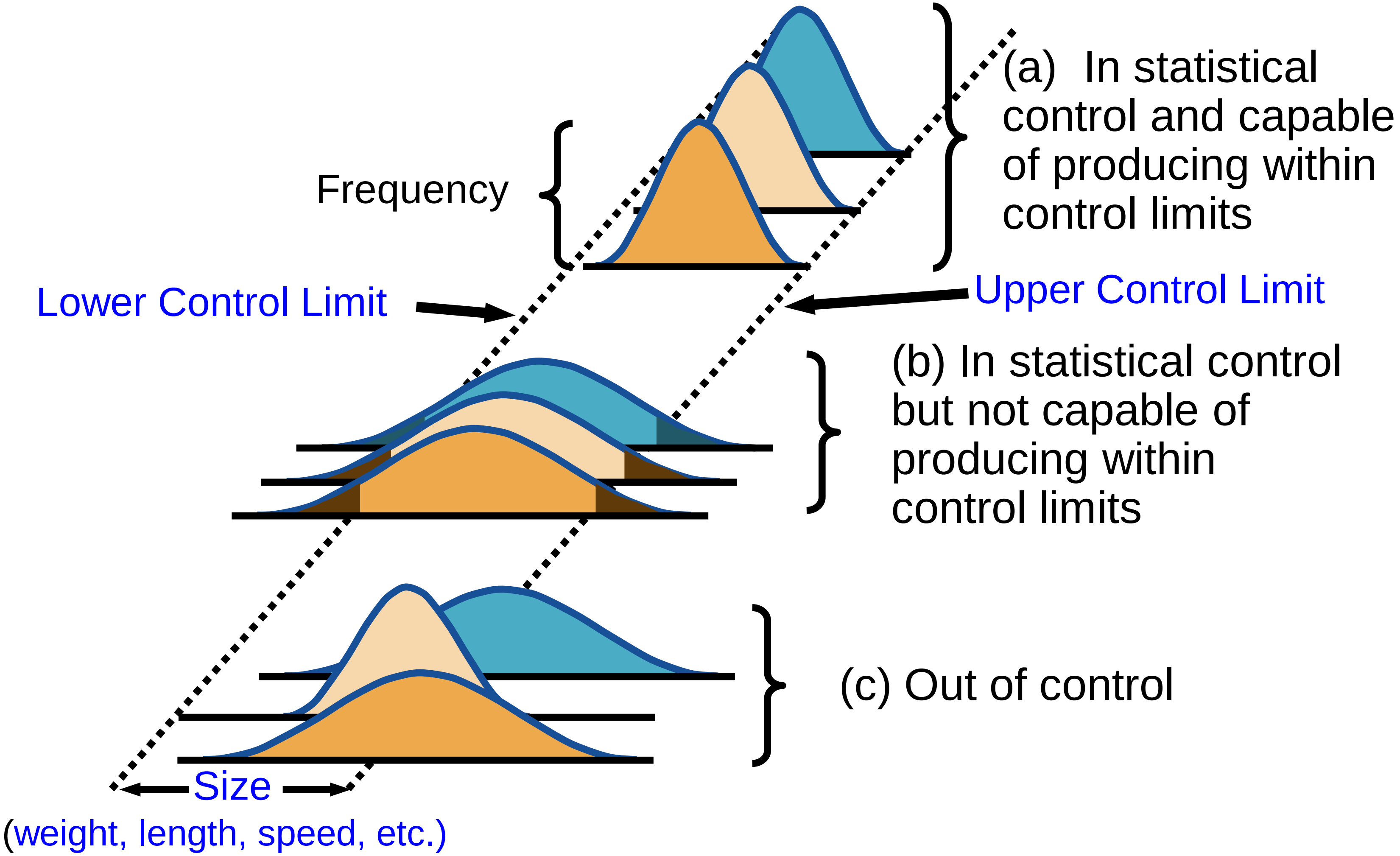


Statistical Process Control (SPC) Samples

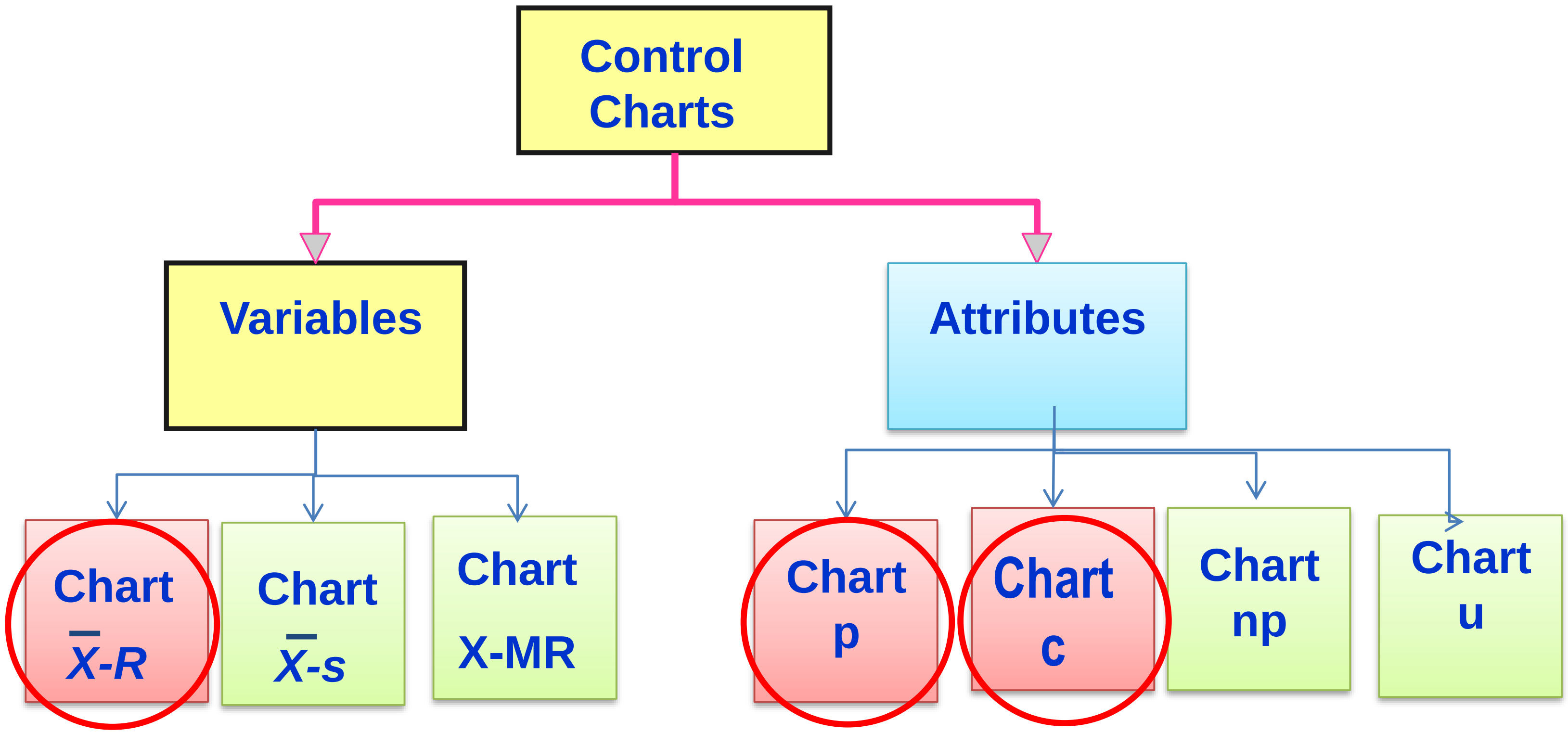
Constructed from historical data, the purpose of control charts is to help **distinguish between natural variations and variations due to assignable causes**



Statistical Process Control (SPC) Samples



Statistical Process Control (SPC)



Statistical Process Control (SPC)
Variable Control Charts

- Characteristics that can take any real value
- May be in whole or in fractional numbers
- Continuous random variables

$\bar{X}$-chart tracks changes in the central tendency

***R*-chart** indicates a gain or loss of dispersion

These two charts must be used together

Statistical Process Control (SPC)
Variable Control Charts (cont.)

Regardless of the distribution of the population, the distribution of sample means drawn from the population will tend to follow a normal curve

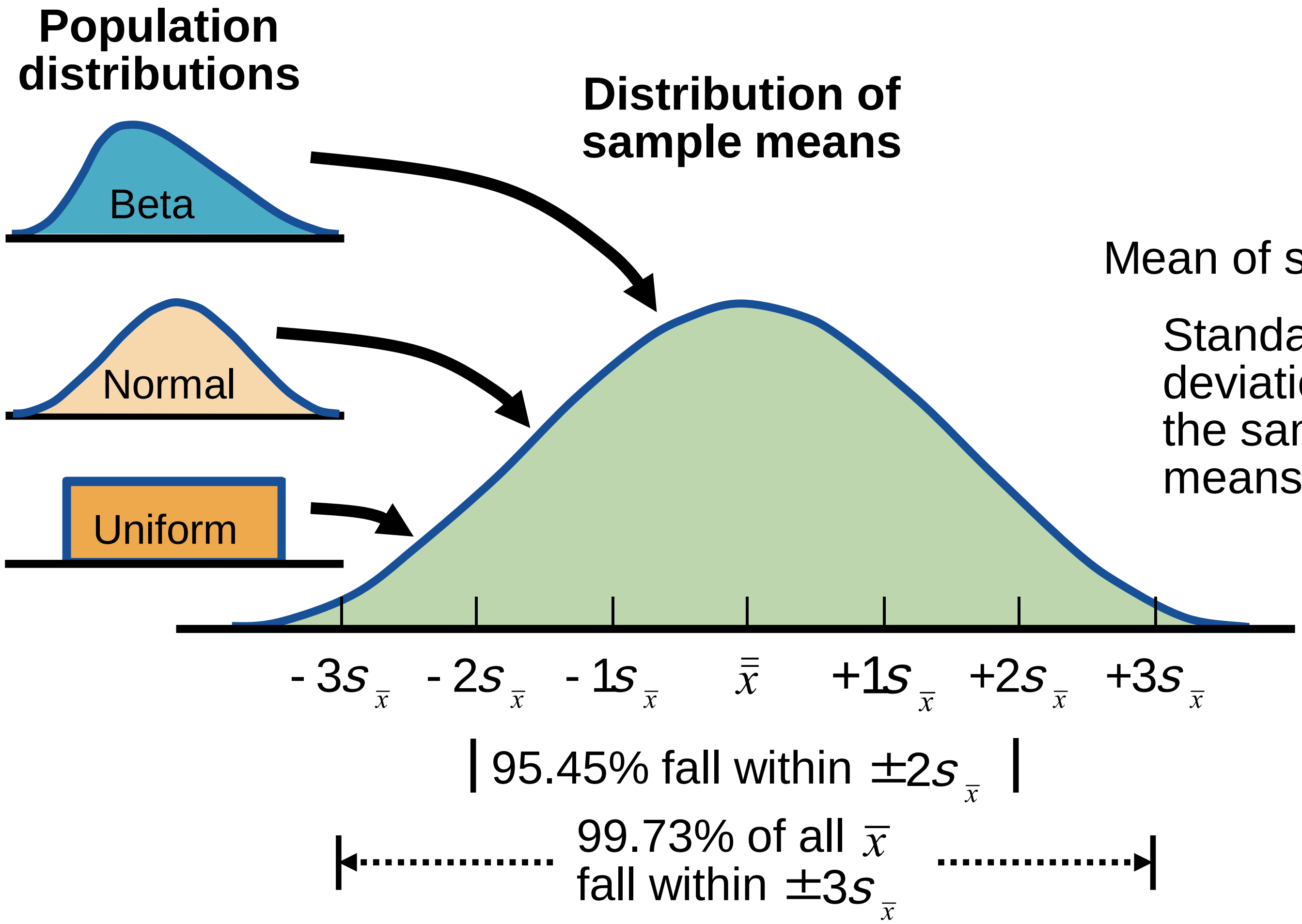
1) The mean of the sampling distribution will be the same as the population mean μ

$$\bar{\bar{x}} = n$$

2) The standard deviation of the sampling distribution ($s_{\bar{x}}$) will equal the population standard deviation (*s*) divided by the square root of the sample size, *n*

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

Statistical Process Control (SPC)
Central Limit Theorem



Mean of sample means = $\bar{\bar{x}}$

Standard deviation of the sample means $= s_{\bar{x}} = \dfrac{s}{\sqrt{n}}$

Statistical Process Control (SPC)

Control limits for *x*-charts when we don't know σ

$$UCL = \bar{\bar{X}} + \frac{3\hat{\sigma}}{\sqrt{n}} = \bar{\bar{X}} + \frac{3\bar{R}}{d_2\sqrt{n}} = \bar{\bar{X}} + A_2\bar{R}$$

$$LCL = \bar{\bar{X}} - \frac{3\hat{\sigma}}{\sqrt{n}} = \bar{\bar{X}} - \frac{3\bar{R}}{d_2\sqrt{n}} = \bar{\bar{X}} - A_2\bar{R}$$

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} \qquad \sigma = \frac{\bar{R}}{d_2}$$

where $\bar{R} = \frac{\sum_{i=1}^{k} R_i}{k}$ = average range of the samples

A_2 = control chart factor found in Table S6.1

$\bar{\bar{x}}$ = mean of the sample means

R_i = range for sample *i*

k = total number of samples

Statistical Process Control (SPC)

TABLE S6.1	Factors for Computing Control Chart Limits (3 sigma)		
SAMPLE SIZE, *n*	**MEAN FACTOR, A_2**	**UPPER RANGE, D_4**	**LOWER RANGE, D_3**
2	1.880	3.268	0
3	1.023	2.574	0
4	.729	2.282	0
5	.577	2.115	0
6	.483	2.004	0
7	.419	1.924	0.076
8	.373	1.864	0.136
9	.337	1.816	0.184
10	.308	1.777	0.223
12	.266	1.716	0.284

SPC – Setting Control Limits

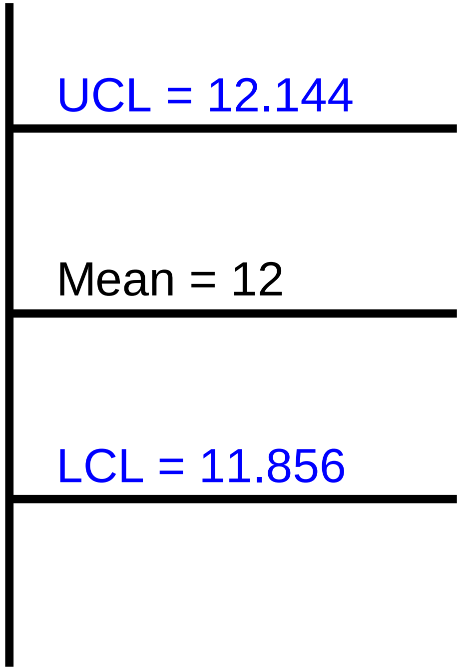
Super Cola example labeled as "net weight 12 ounces"

Process average = 12 ounces
Average range = .25 ounces
Sample size = 5

$$UCL_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R}$$
$$= 12 + (.577)(.25)$$
$$= 12 + .144$$
$$= 12.144 \text{ ounces}$$

From Table S6.1

$$LCL_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R}$$
$$= 12 - .144$$
$$= 11.856 \text{ ounces}$$



SPC – Range *(R)* Chart

- Type of variables control chart
- Shows sample ranges over time
  - **Difference between smallest and largest values in sample**
- Monitors process variability
- Independent from process mean

SPC – Setting Control Limits for *R*-Charts

$$UCL = \bar{R} + 3\hat{\sigma}_R = \bar{R} + 3d_3\hat{\sigma} = \bar{R} + 3d_3\frac{\bar{R}}{d_2} = \bar{R}\left(1 + 3\frac{d_3}{d_2}\right) = D_4\bar{R}$$

$$LCL = \bar{R} - 3\hat{\sigma}_R = \bar{R} - 3d_3\hat{\sigma} = \bar{R} - 3d_3\frac{\bar{R}}{d_2} = \bar{R}\left(1 - 3\frac{d_3}{d_2}\right) = D_3\bar{R}$$

Upper control limit $(UCL_R) = D_4\bar{R}$

Lower control limit $(LCL_R) = D_3\bar{R}$

d_3 and **d_2** from Table of Constants for Control Charts

where

UCL_R = upper control chart limit for the range

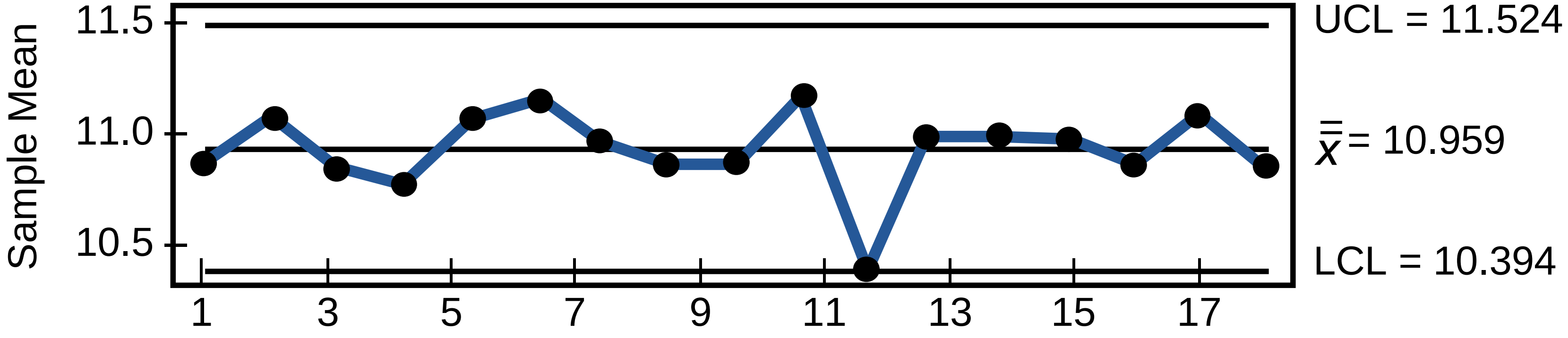
LCL_R = lower control chart limit for the range

D_4 and D_3 = values from Table S6.1

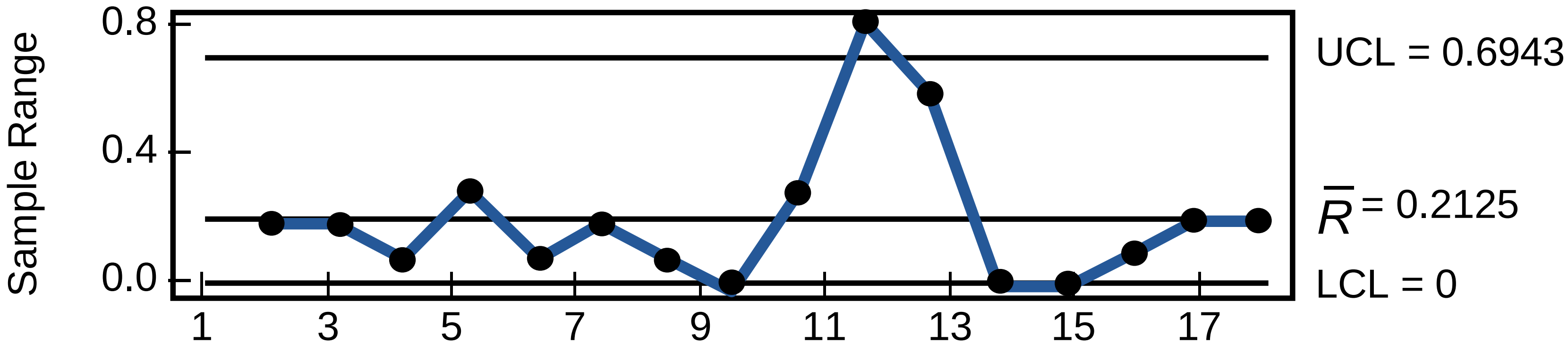
SPC – Restaurant Control Limits

For salmon fillets at Darden Restaurants (weight)

x Bar Chart



Range Chart



SPC – Steps In Building Control Charts

1. Collect 20 to 25 samples, often of $n = 4$ or $n = 5$ observations each, from a stable process, and compute the mean and range of each

2. Compute the overall means ($\bar{\bar{x}}$ and $\bar{R}$), set appropriate control limits, usually at the 99.73% level, and calculate the preliminary upper and lower control limits

SPC – Steps In Building Control Charts

3. Graph the sample means and ranges on their respective control charts and determine whether they fall outside the acceptable limits

4. Investigate points or patterns that indicate the process is out of control – try to assign causes for the variation, address the causes, and then resume the process

5. Collect additional samples and, if necessary, revalidate the control limits using the new data

SPC – Setting Other Control Limits

TABLE S6.2	**Common *Z* Values**
DESIRED CONTROL LIMIT (%)	*Z*-VALUE (STANDARD DEVIATION REQUIRED FOR DESIRED LEVEL OF CONFIDENCE)
90.0	1.65
95.0	1.96
95.45	**2.00**
99.0	2.58
99.73	**3.00**

SPC – Control Chart for Attributes

- For variables that are categorical
  - *Defective/nondefective*, good/bad, yes/no, acceptable/unacceptable
- Measurement is typically counting defectives
- Charts may measure
  1. *Percent* defective (***p*-chart**)
  2. *Number* of defects (***c*-chart**)

SPC – Setting Control Limits for *p*-Charts

Population will be a **Binomial distribution**, but applying the Central Limit Theorem allows us to assume a normal distribution for the sample statistics

$$UCL_p = \bar{p} + z s_p$$

$$LCL_p = \bar{p} - z s_p$$

s_p is estimated by

$$\hat{s}_p = \sqrt{\frac{\bar{p}(1 - \bar{p})}{n}}$$

where

$\bar{p}$ = mean fraction (percent) defective in the samples

z = number of standard deviations

s_p = standard deviation of the sampling distribution

n = number of observations in *each* sample

Statistical Process Control - SPC

***Example**: Data for a p chart with sample size equal to 100*

SAMPLE NUMBER	NUMBER OF DEFECTIVES	FRACTION DEFECTIVE	SAMPLE NUMBER	NUMBER OF DEFECTIVES	FRACTION DEFECTIVE
1	6	.06	11	6	.06
2	5	.05	12	1	.01
3	0	.00	13	8	.08
4	1	.01	14	7	.07
5	4	.04	15	5	.05
6	2	.02	16	4	.04
7	5	.05	17	11	.11
8	3	.03	18	3	.03
9	3	.03	19	0	.00
10	2	.02	20	4	.04
				80	

SPC – *p*-Chart for Data Entry

$$\bar{p} = \frac{\text{Total number of errors}}{\text{Total number of records examined}} = \frac{80}{(100)(20)} = .04$$

$$\hat{s}_p = \sqrt{\frac{(.04)(1 - .04)}{100}} = .02 \text{ (rounded up from .0196)}$$

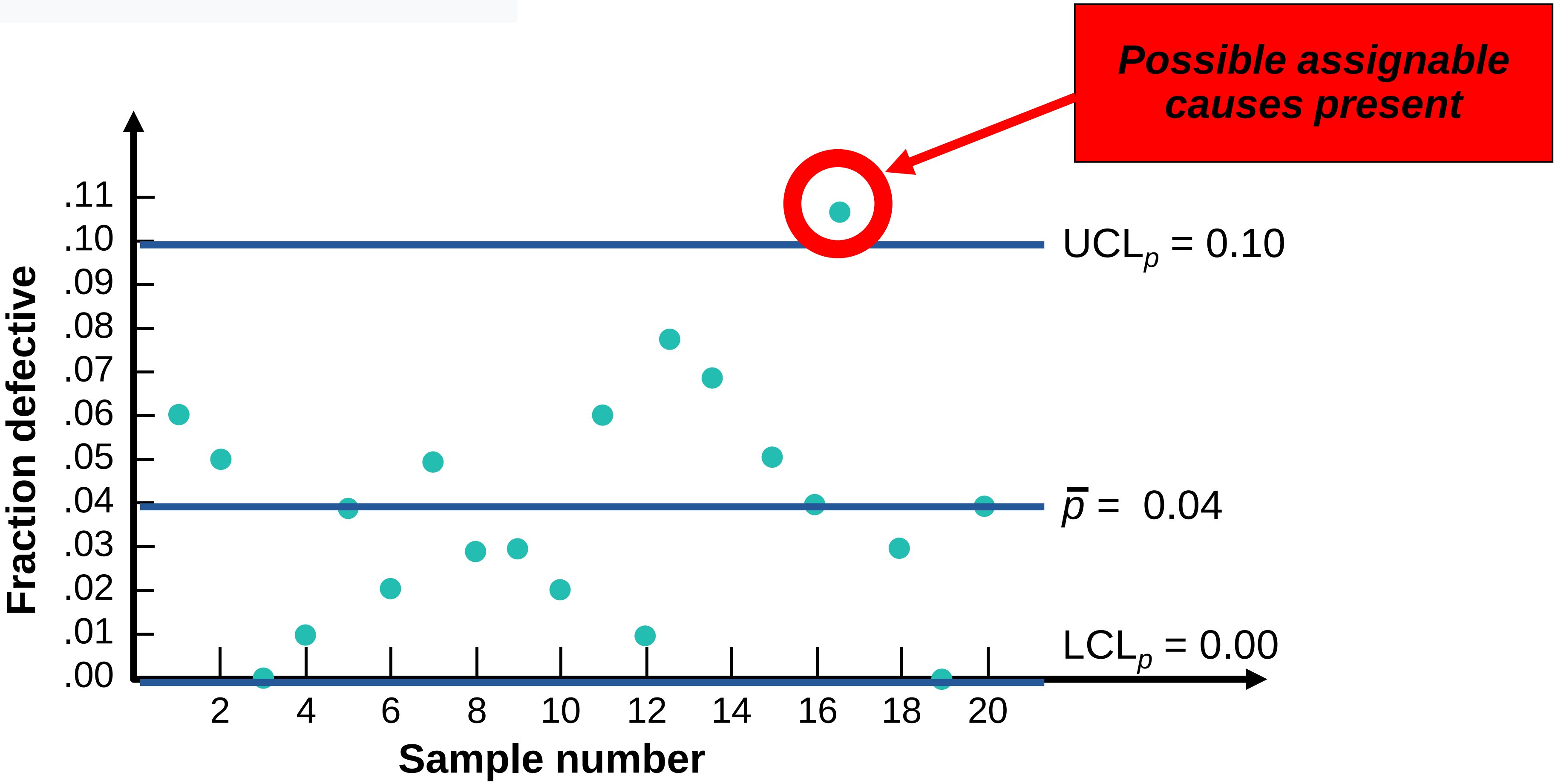
$$UCL_p = \bar{p} + z\hat{s}_p = .04 + 3(.02) = .10$$

$$LCL_p = \bar{p} - z\hat{s}_p = .04 - 3(.02) = 0$$

Because we cannot have a negative percent defective

SPC – *p*-Chart for Data Entry

Example: Data for a chart *p*



SPC – Setting Control Limits for *c*-Charts

Population will be a **Poisson distribution**, but applying the Central Limit Theorem allows us to assume a Normal distribution for the sample statistics

$\bar{c}$ = mean number of defects per unit

$\sqrt{\bar{c}}$ = standard deviation of defects per unit

$$\text{Control limits (99.73\%)} = \bar{c} \pm 3\sqrt{\bar{c}}$$

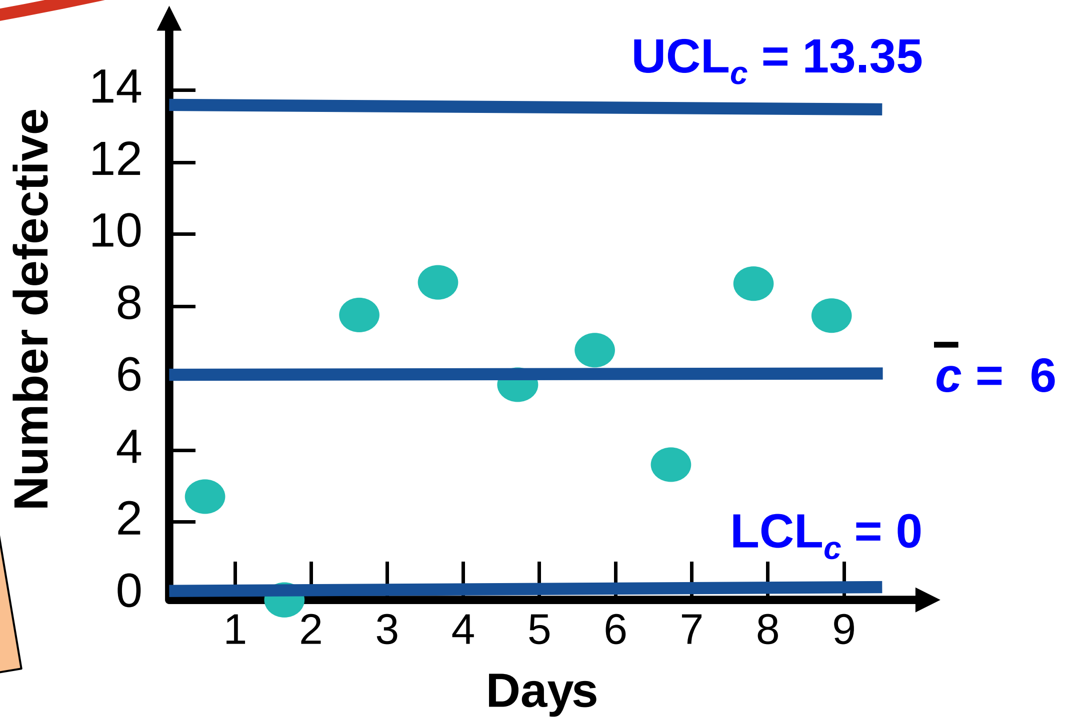
SPC – *c*-Chart for Cab Company

$$\bar{c} = 54 \text{ complaints}/9 \text{ days} = 6 \text{ complaints}/\text{day}$$

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}}$$
$$= 6 + 3\sqrt{6}$$
$$= 13.35$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}}$$
$$= 6 - 3\sqrt{6}$$
$$= 0$$

Cannot be a negative number



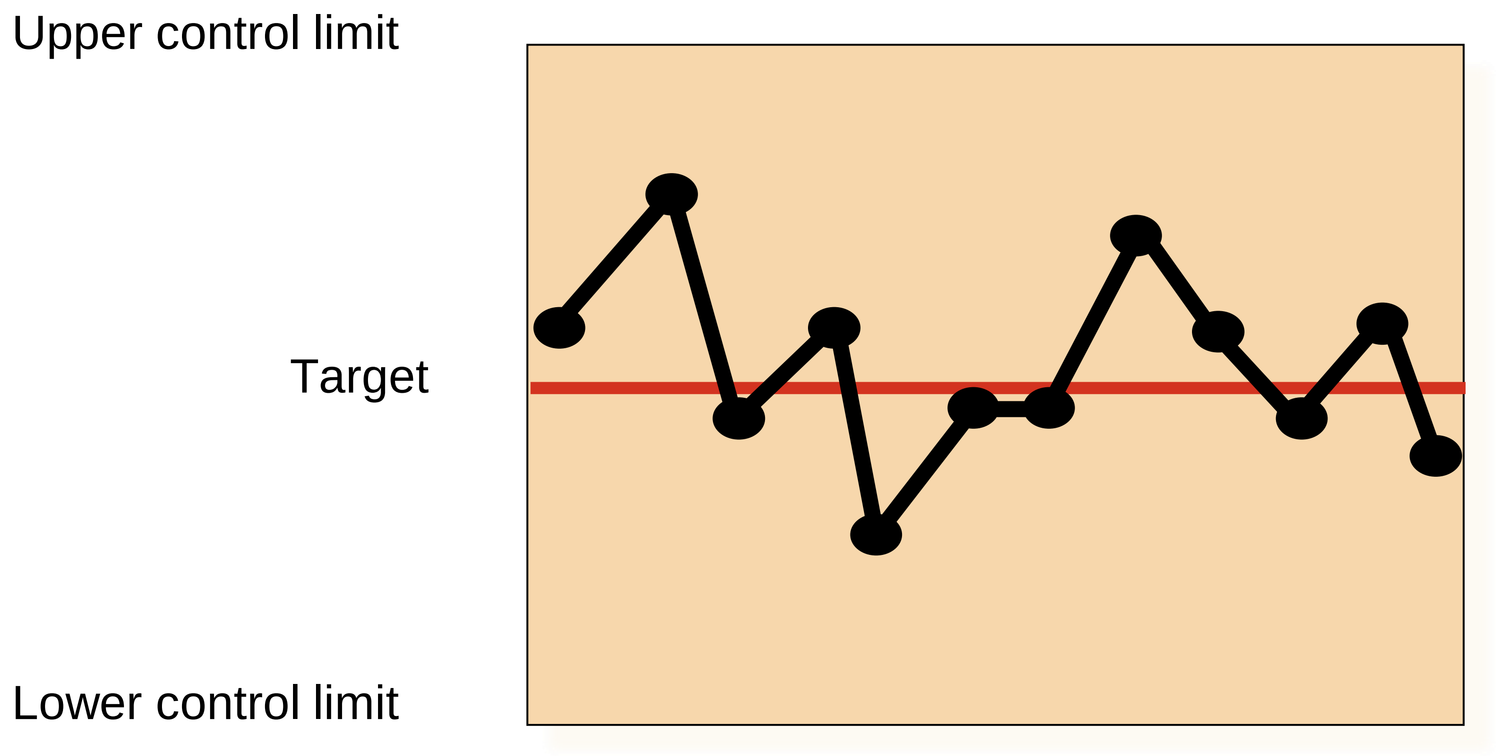
Managerial Issues and Control Charts

Three major management decisions:

- Select points in the processes that need SPC
- Determine the appropriate charting technique
- Set clear and specific SPC policies and procedures

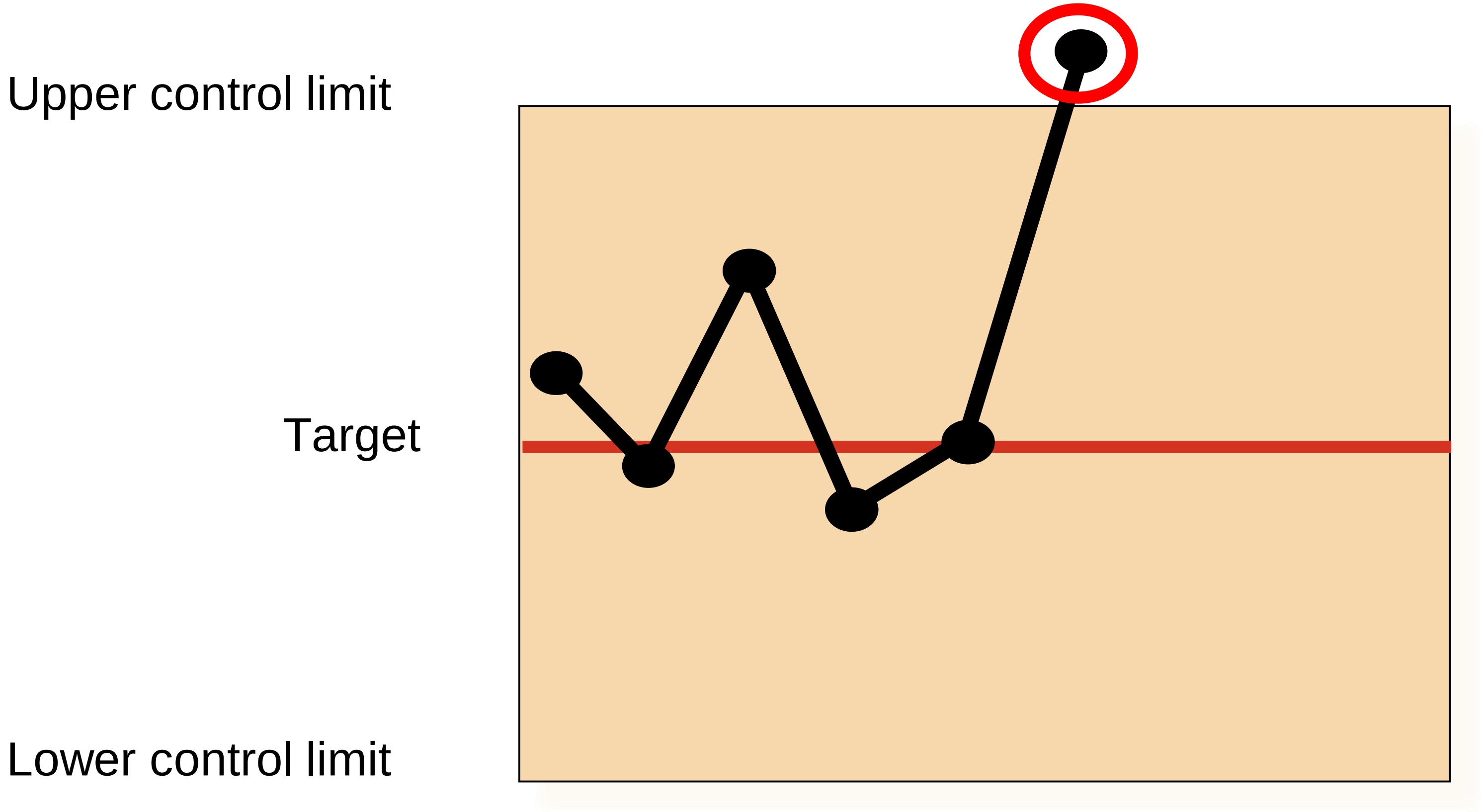
(for example, defining what should be considered a defect in a visual inspection)

SPC – Patterns in Control Charts



Normal behavior. Process is "in control."

SPC – Patterns in Control Charts



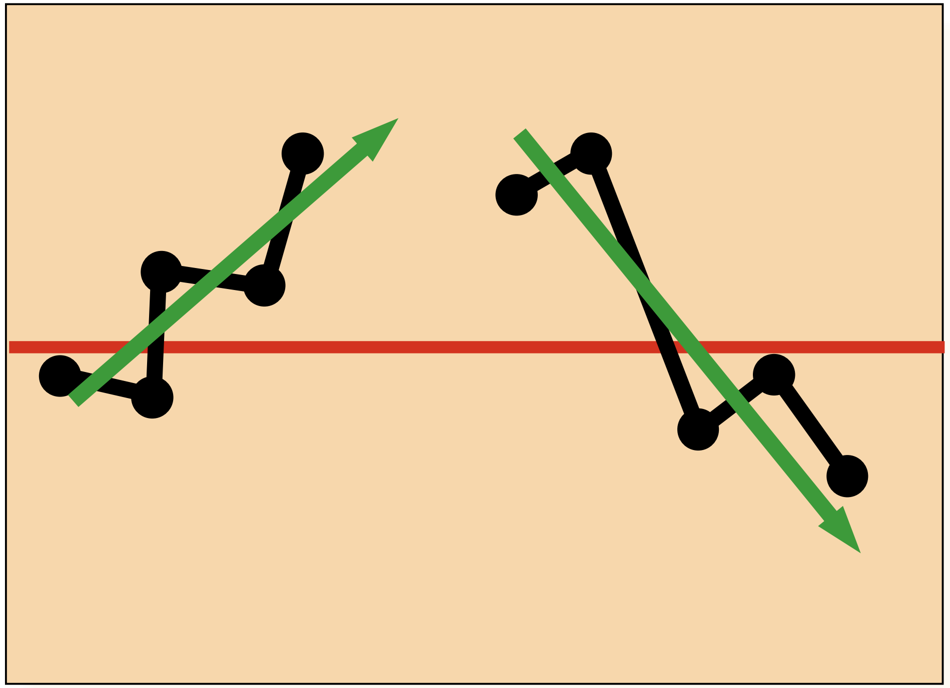
One plot out above (or below). Investigate for cause. Process is “out of control“.

SPC – Patterns in Control Charts

Upper control limit

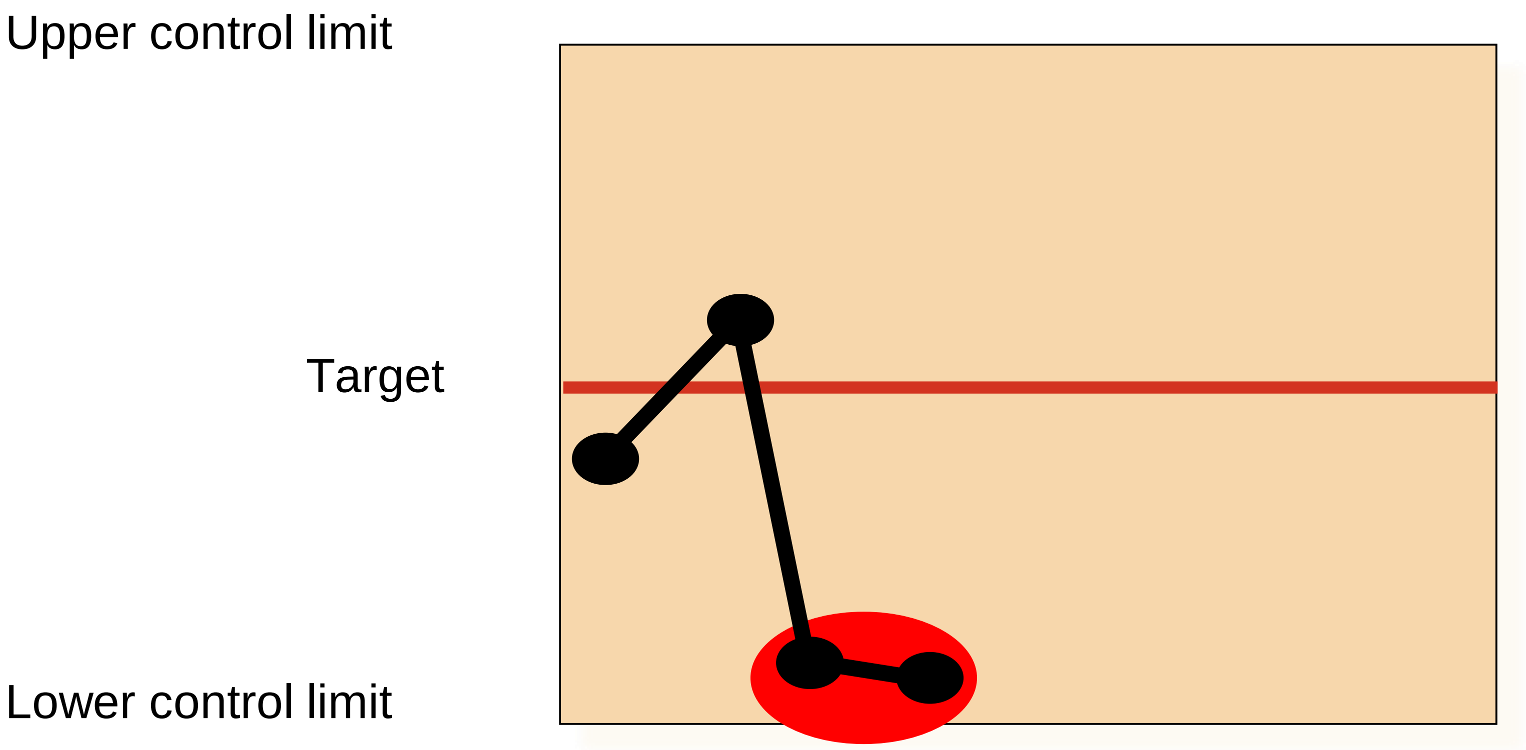
Target

Lower control limit



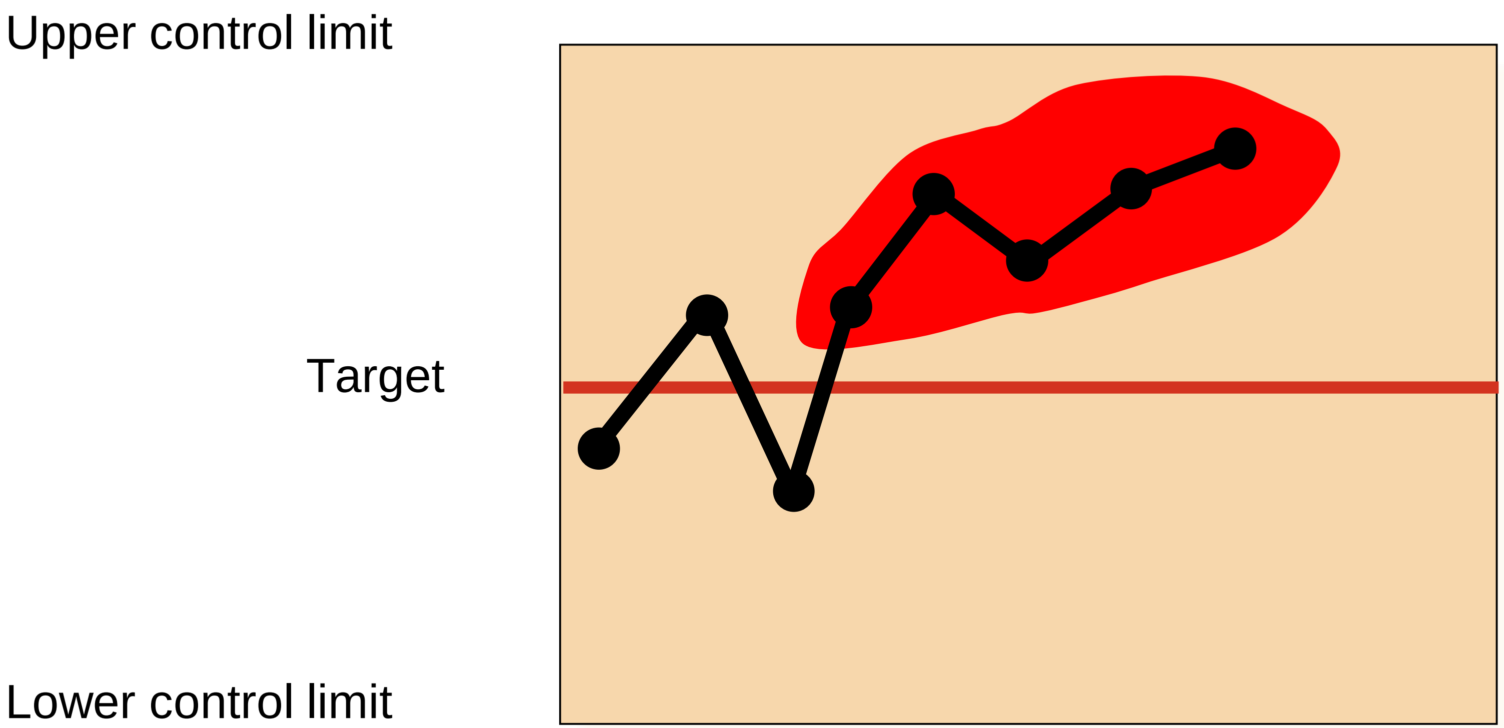
Trends in either direction, 5 plots. Investigate for cause of progressive change.

SPC – Patterns in Control Charts



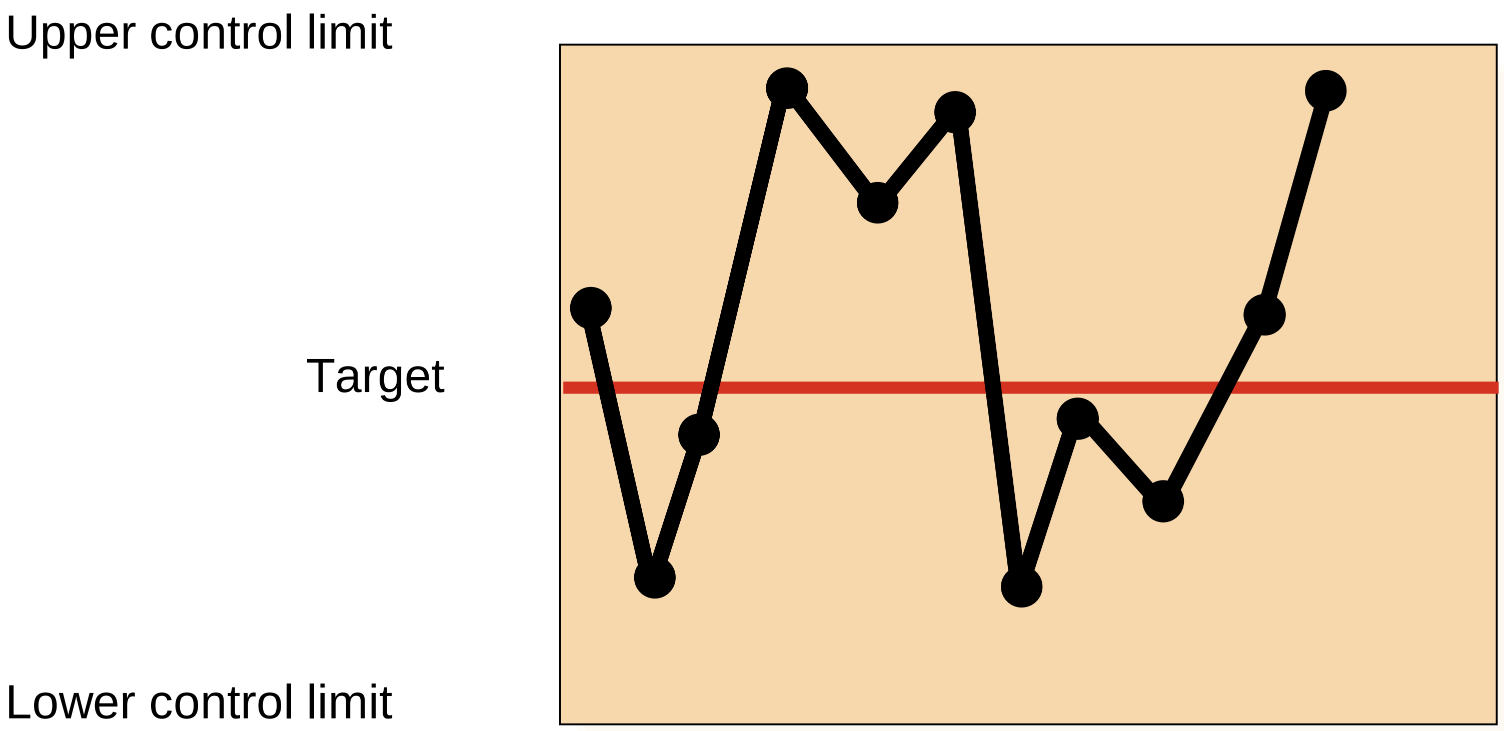
Two plots very near lower (or upper) control. Investigate for cause.

SPC – Patterns in Control Charts



Run of 5 above (or below) central line. Investigate for cause.

SPC – Patterns in Control Charts



Erratic behavior. Investigate.

Statistical Control Process (SPC)

Process Capability

- The natural variation of a process should be small enough to produce products that meet the standards required
- A process in statistical control does not necessarily meet the design specifications
- **Process capability** is a measure of the relationship between the natural variation of the process and the design specifications

Statistical Control Process (SPC)

Process Capability Ratio - C_p

$$C_p = \frac{\text{Upper Specification} - \text{Lower Specification}}{6\sigma}$$

- A capable process must have a C_p of at least 1.0
- Does not look at how well the process is centered in the specification range
- Often a target value of $C_p = 1.33$ is used to allow for off-center processes
- Six Sigma quality requires a $C_p = 2.0$

Statistical Control Process (SPC)
Process Capability Index

The formula for C_{pk} is:

$$C_{pk} = \text{minimum of} \left[\frac{\text{Upper Specification Limit} - \bar{x}}{3\sigma}, \text{ or } \frac{\bar{x} - \text{Lower Specification Limit}}{3\sigma} \right]$$

where $\bar{x} = \text{process mean}$

$\sigma = \text{standard deviation of the process population}$

C_{pk} = Minimum of
[(Upper specification limit – $\bar{X}$)/3σ,
or ($\bar{X}$ - Lower specification limit)/3σ]
where
$\bar{X}$ = process mean
σ = standard deviation of the process population

- A capable process must have a C_{pk} of at least 1.0
- A capable process is not necessarily in the center of the specification, but it falls within the specification limit at both extremes

Statistical Control Process (SPC)
Process Capability Index

Example: New Cutting Machine

New process mean $\bar{x}$ = .250 inches
Process standard deviation σ = .0005 inches
Upper Specification Limit = .251 inches
Lower Specification Limit = .249 inches

$$C_{pk} = \text{minimum of} \left[\frac{(.251) - .250}{(3).0005}\right], \left[\frac{.250 - (.249)}{(3).0005}\right]$$

Both calculations result in:

$$C_{pk} = \frac{.001}{.0015} = 0.67$$

New machine is NOT capable

Statistical Control Process (SPC)

Interpreting C_{pk}

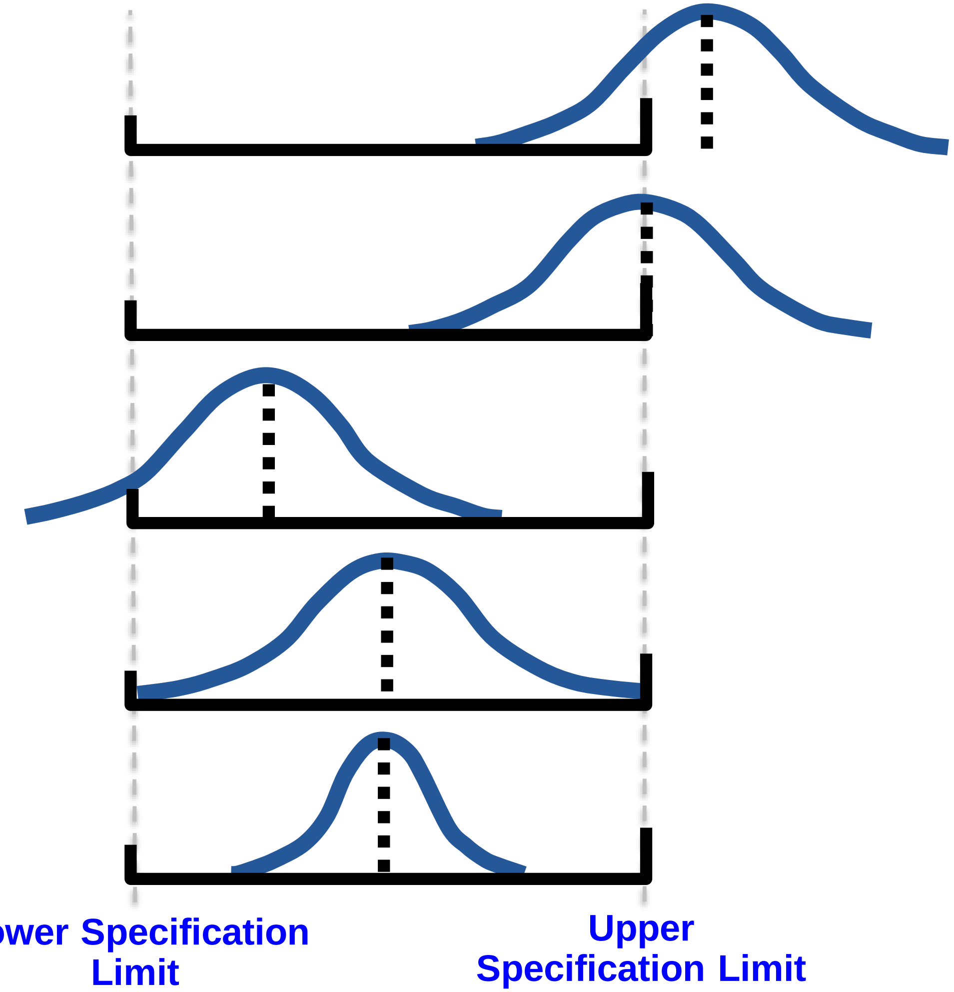
C_{pk} = negative number

C_{pk} = zero

C_{pk} = between 0 and 1

C_{pk} = 1

C_{pk} > 1



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