Lean Six Sigma Green Belt Training Course

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Lean Six Sigma Green Belt Course

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1 Lean Overview

The goal	• Provide the greatest value for customers using the fewest resources
The methods	• Principles and practices based on the Toyota Production System (TPS)
The barrier	• Culture always defeats methodology
The path forward[*]	• Create a culture of continuous improvement (*kaizen*) • Integrate improvement cycles into the daily work of all employees • Improve all processes, every day

[*] See **Toyota Kata** (2010) by Mike Rother.

Basic principles of Lean

- *Value* is defined from the customer's point of view

  → Reduce or eliminate activities that do not add customer value

- *Value stream* — all activities required to provide a specified family of products or services to the customer

  → Organize workflows by value stream, not by department

Customer defines value

Customer value adding (CVA)

- Activities that are required, from the customer's point of view, to provide the desired products and services
- What the customer is willing to pay for
- Changes the form or function of the product
- Goal: Optimize and standardize these activities

Non-value adding (NVA)

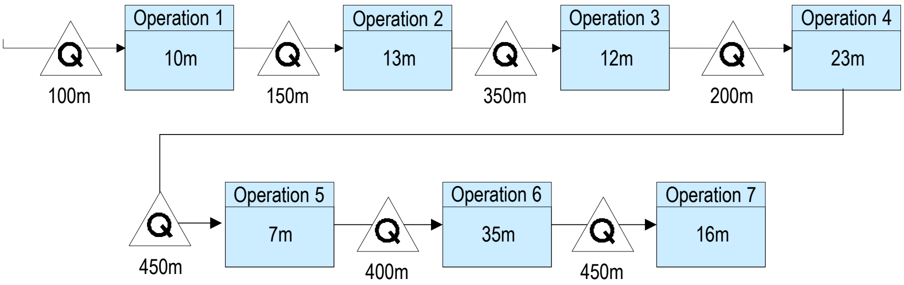
- There exists a feasible future state in which the desired products and services can be provided without these activities
- Goal: Eliminate or reduce

Non-value adding but necessary

- Activities that are not CVA, but cannot feasibly be eliminated under current constraints
- Examples include audits, reporting, regulatory compliance, etc.
- Goal: Question and reduce

Common example of CVA and NVA

Typical current state value stream



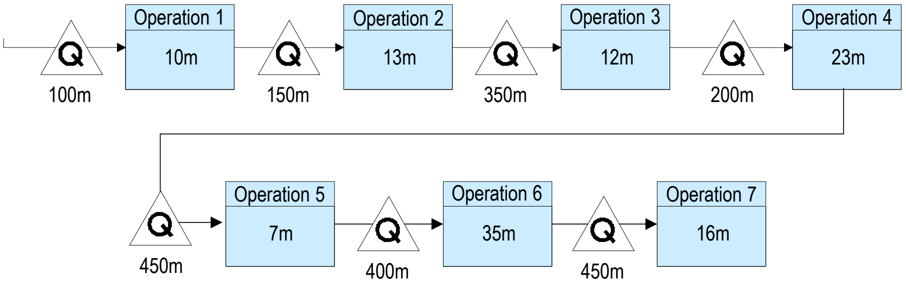
Lead time = 2,216 mins

Process time = 116 mins (5.3%)

Wait time = 2,100 mins (94.7%)

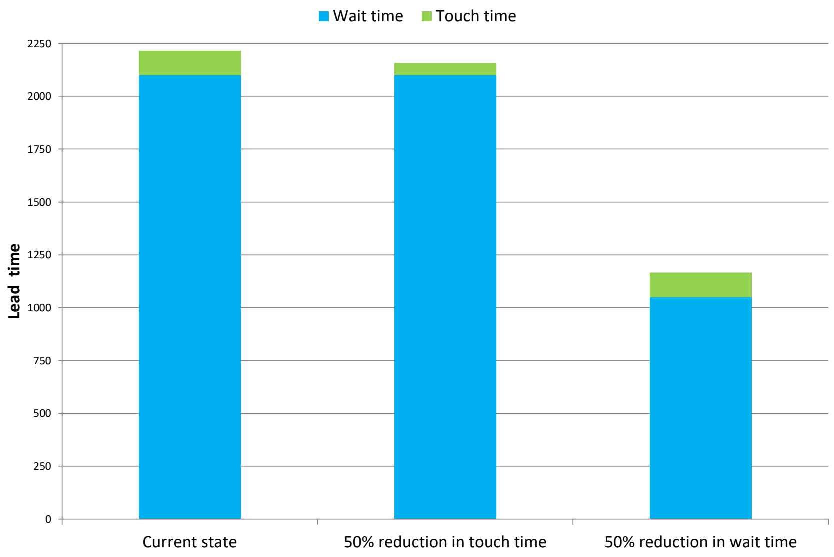
Q Queue (material or transactions waiting to be worked on) → 100% NVA

What is the priority: reducing CVA or reducing NVA?



	Current state	50% reduction in process time	50% reduction in wait time
Process time	116 m	58 m	116 m
Wait time	2,100 m	2,100 m	1,050 m
Lead time	2,216 m	2,158 m	1,166 m
Reduction in lead time →		**2.6%**	**47.4%**

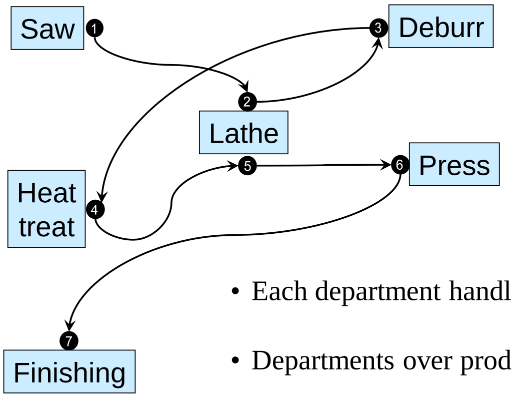
Reduce NVA, not CVA!



Categories of NVA (expanded definitions)

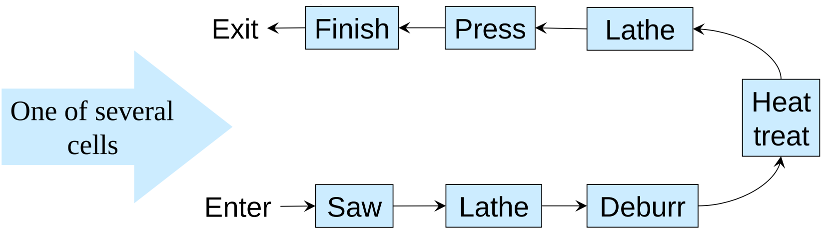
D	*Defects*: Failure to meet expected standards of quality or delivery
O	*Over production*: Making or doing more than is needed at the time
W	*Waiting*: People waiting to work, or things waiting to be worked on
N	*Not utilizing creativity*: Failure to integrate improvement cycles into the daily work of all employees
T	*Transportation*: People or things being moved from one place to another
I	*Inventory*: Supplies, WIP, or finished goods beyond what is needed
M	*Motion*: Excessive motion in the completion of work activities
E	*Extra processing*: Producing or delivering to a higher standard than is required

Example of organizing work by department



- Each department handles all products → inefficient
- Departments over produce → high levels of WIP
- WIP is valued as an asset — in reality it's a cash sink
- WIP moves between departments in large batches → long lead times, long lags before defects are discovered
- Poor layout → excessive transport

Example of organizing work by value stream



Exit ← Finish ← Press ← Lathe ← Heat treat ← Deburr ← Lathe ← Saw ← Enter

One of several cells

- Each cell handles particular, similar products → efficient
- Cells produce only to current customer demand → low levels of WIP, less cash tied up
- WIP moves through each cell in small batches → short lead times
- Proximity of operations → minimal transport, defects identified immediately

The kaizen culture

- *Kaizen* — Japanese word for “continuous improvement”
- Ongoing, daily process yielding many small improvements
- Employees are *expected* to expose and solve problems instead of ignoring and working around them
- Supervisors and managers must banish *kaizen killing language*

“That’s a dumb idea”

“That won’t work”

“We can’t do that”

“We tried that before”

“Stop complaining — just do your job”

The spirit of kaizen

- Open to change
- Positive attitude
- No blaming
- The only bad questions are the ones not asked
- First find the cause of the problem, then seek solutions
- One person, one vote — position doesn’t matter

Kaizen events

- *Kaikaku* — “radical, transformational improvement”
- More commonly known as *kaizen event*
- A “concentrated dose of *kaizen*”
- Core team: pre-event preparation
- Extended team: 3-5 days of 100% dedicated involvement

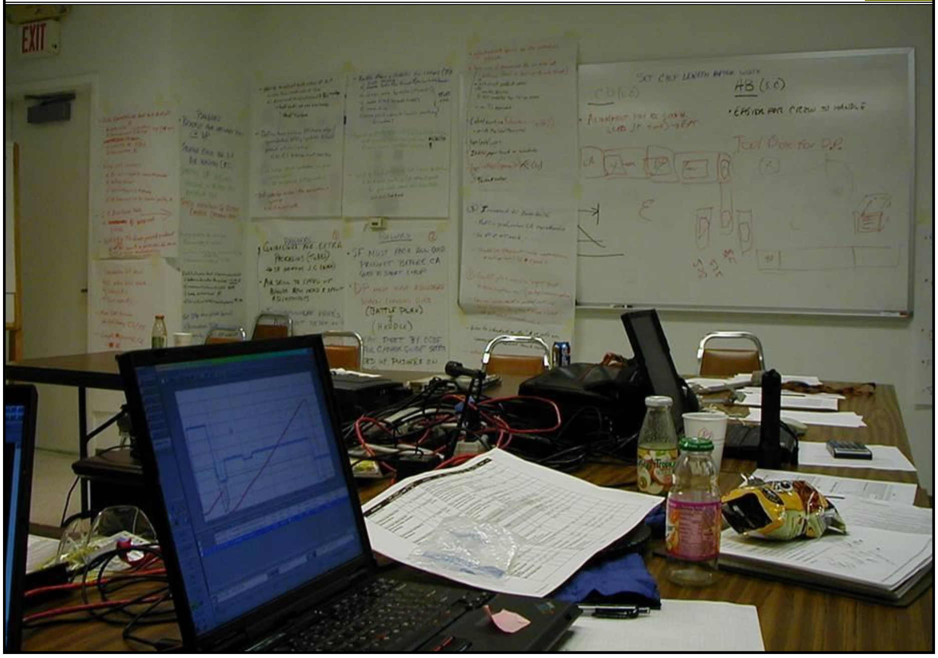
Characteristics of a typical kaizen event

- Emphasis on “tribal knowledge” (*a.k.a.* “wisdom of the organization”)
- Causes of the problem are not difficult to identify
- Solutions are not difficult to develop
- Bias for action
  - ✓ Develop solutions during the event
  - ✓ Reconsider previous solution ideas that were discarded
  - ✓ Implement solutions during the event if possible

Preparation for a typical kaizen event

- ✓ Project charter completed
- ✓ Current state process maps completed
  - Value stream
  - Flowchart
  - Spaghetti
- ✓ Data collected, metrics calculated, goals set
- ✓ Event training material prepared (if needed)
- ✓ Event logistics arranged
  - War room
  - Materials
  - Food
- ✓ Team members, process owners, and resources notified
- ✓ Impacted workers met with and challenges identified

Essential component: the “command center”



Walking the *gemba* (“the actual place”)

Possible pitfalls of kaizen events

- Time constraint drives selection and scoping of projects

  "We tend to choose easy projects that can be completed in 3-5 days."

  ✓ Mitigating strategy – Choose larger projects and develop a solution during kaizen event. Use 30-day homework plan for implementation.

  "We tend to choose projects with very narrow scope — it is not uncommon for us to make improvements in one area only to cause problems in another."

  ✓ Mitigating strategy – Include team members from other potentially impacted areas. Discuss negative side-effects and develop solution that will prevent unintended consequences.

- Gains not sustained after the event

  "The results disappear as soon as the team does. We have a lot of do-overs."

  ✓ Mitigating strategy – Update all necessary documentation, develop a training plan, and create supporting management materials for the new standards.

Possible pitfalls (cont'd)

- Failure to foster *kaizen* culture in the organization

  "We only do kaizen events — there is very little culture building."

  ✓ Mitigating strategy – Culture change takes time. Be patient. Develop problem identification and solving into daily work cycles for all people.

  "We have done many kaizen events, but the fundamental behaviors and processes of top management haven't changed."

  ✓ Mitigating strategy - Include top management in LSS training and improvement events. Change in managerial expectation should come from upper management.

  "Decisions and changes are driven by 'outside experts' rather than the people doing the work."

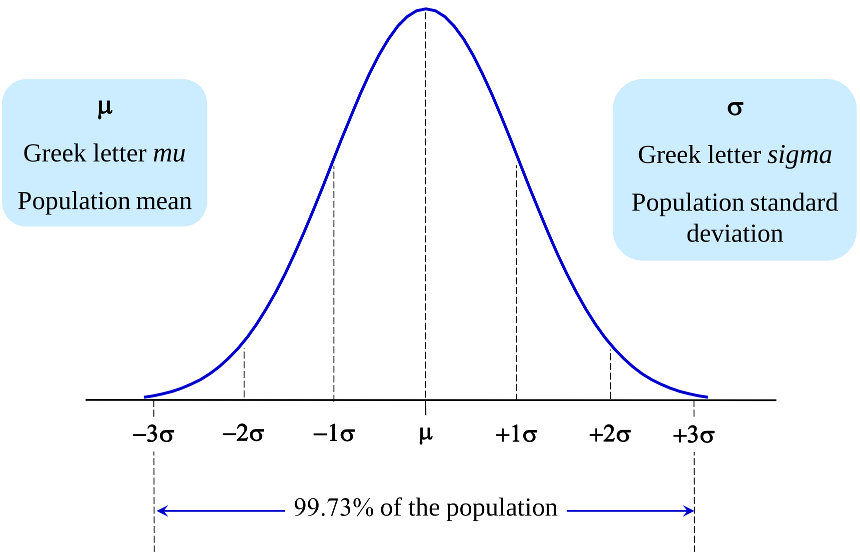
  ✓ Mitigating strategy – The role of outside lean experts is to provide knowledge on the lean process and tools, and to guide the process. Solutions should come from process experts.

2 Six Sigma Overview

- Process spread
- Pursuit of perfect quality
- Pragmatic business initiative

Process spread

Normal distribution (*bell curve*)



μ

Greek letter *mu*

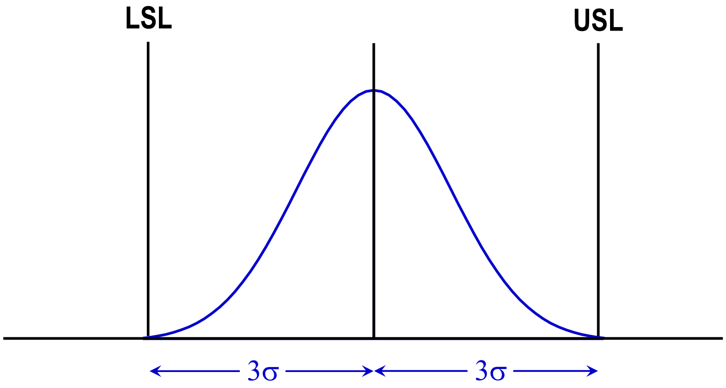
Population mean

σ

Greek letter *sigma*

Population standard deviation

Process capability

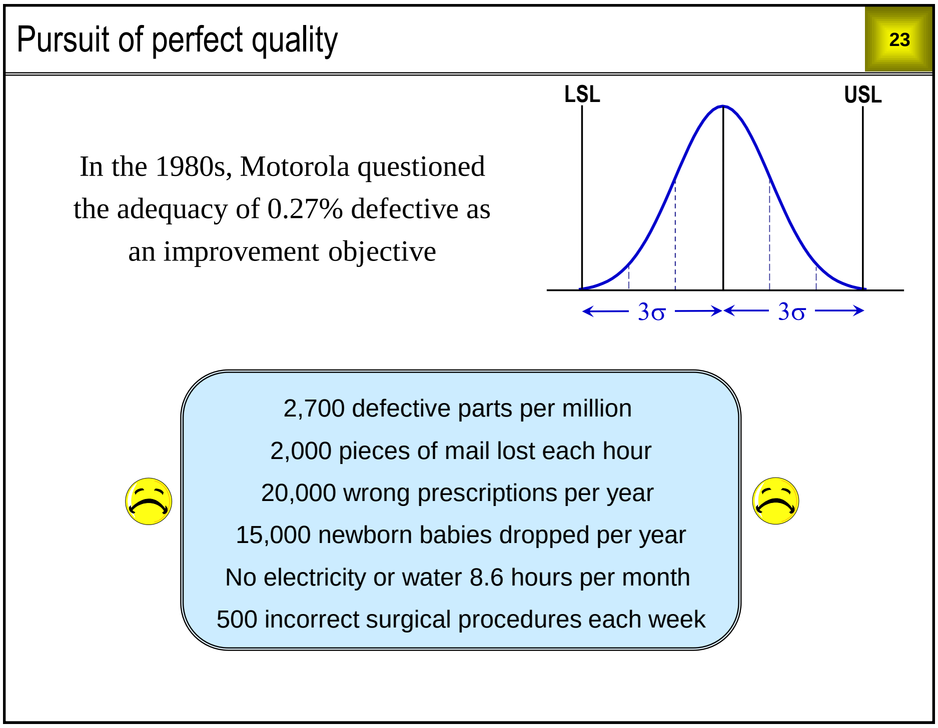


0.27% defective (first pass)

Process capability (cont’d)

USL stands for *Upper Specification Limit*, LSL stands for *Lower Specification Limit*. Specification limits represent the Voice of the Customer with regard to measureable characteristics of products or services.

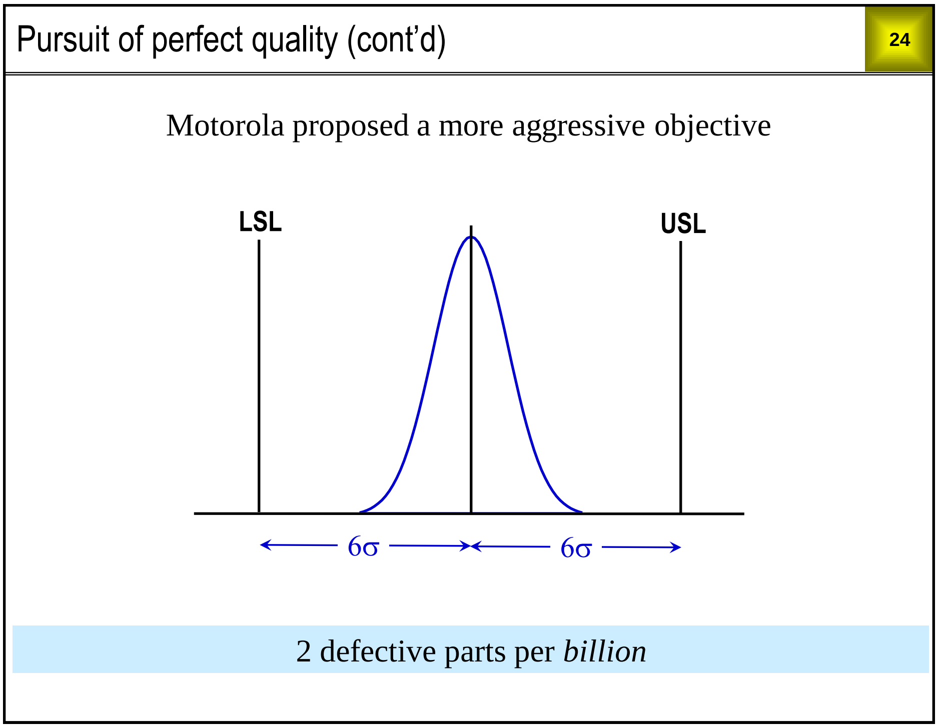
For the Normal distribution shown above, the mean (μ) is equal to the midpoint of the specification range, and the process spread (6σ) is exactly equal to the width of the specification range (USL minus LSL). This means that 99.73% of product or service outcomes produced by this process satisfy the spec limits. Equivalently, 0.27% of outcomes lead to scrap, rework, do-overs, or other costly measures to prevent or respond to customer dissatisfaction.



Pursuit of perfect quality

In the 1980s, Motorola questioned the adequacy of 0.27% defective as an improvement objective

2,700 defective parts per million
2,000 pieces of mail lost each hour
20,000 wrong prescriptions per year
15,000 newborn babies dropped per year
No electricity or water 8.6 hours per month
500 incorrect surgical procedures each week

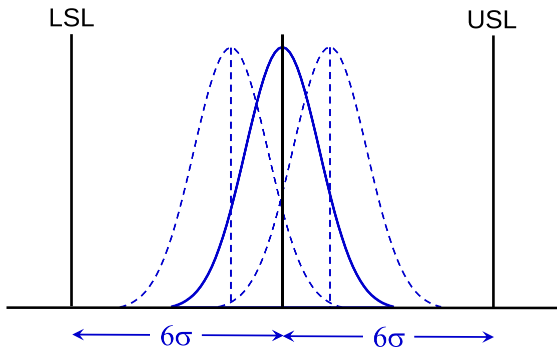


Pursuit of perfect quality (cont'd)

Motorola proposed a more aggressive objective

2 defective parts per *billion*

Allowing the mean to wander



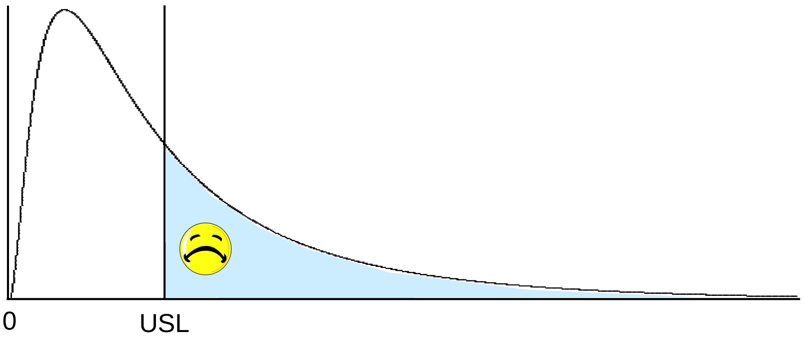
At most 3.4 defective parts per million (DPPM)

Wandering mean (cont'd)

- Motorola backed away from 2 defective parts per billion as the stretch goal
- They allowed that the process mean might wander as much as 1.5σ away from the spec midpoint
- At these extremes, the process would produce 3.4 defective parts per million (DPPM)
- The ± 1.5σ offset was somewhat arbitrary, but 3.4 DPPM became the definition of "Six Sigma quality"

Doesn’t have to be a Normal distribution . . .

Before improvement project

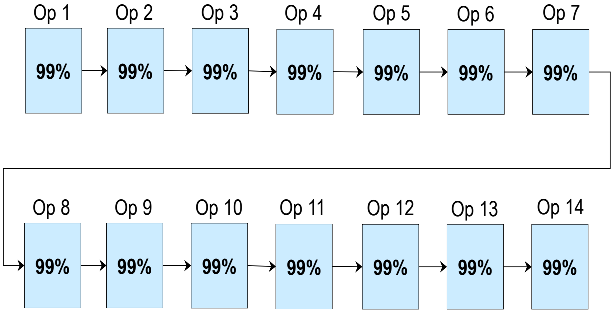


. . . in fact, often it isn’t

After improvement project

Why set the quality bar so high?

Suppose we have 10,000 DPPM (99% yield) for each operation



Area manager: "Our overall yield is 99%"

Is this true?

We can't repeal the laws of probability!

Overall yield* = Probability of no defect in 14 operations

$= 0.99 \times 0.99 \times \cdots \times 0.99$ (14 times)

$= (0.99)^{14}$

$= 0.868746 \rightarrow 86.9\%$

131,254 DPPM

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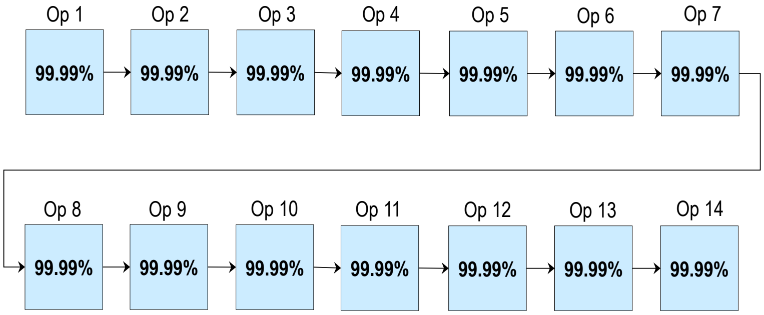
*Also known as **cumulative yield**, **end-to-end yield**, and **rolled throughput yield**

Setting the quality bar (cont'd)

100 DPPM (99.99% yield) in each operation



Op 1	Op 2	Op 3	Op 4	Op 5	Op 6	Op 7
99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%

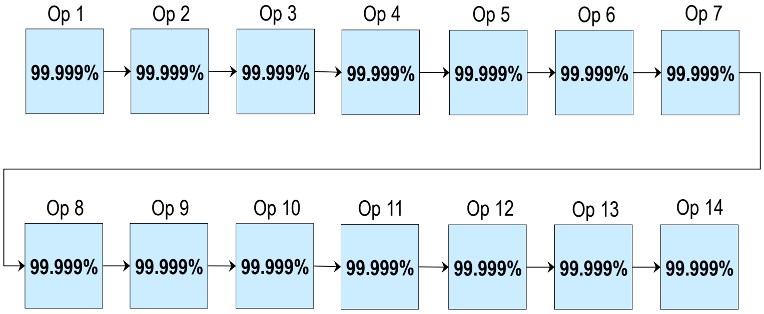
Op 8	Op 9	Op 10	Op 11	Op 12	Op 13	Op 14
99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%

Overall yield $= (0.9999)^{14} = 0.998601 \rightarrow 99.86\%$

1399 DPPM

Setting the quality bar (cont'd)

10 DPPM (99.999% yield) in each operation



Op 1	Op 2	Op 3	Op 4	Op 5	Op 6	Op 7
99.999%	99.999%	99.999%	99.999%	99.999%	99.999%	99.999%

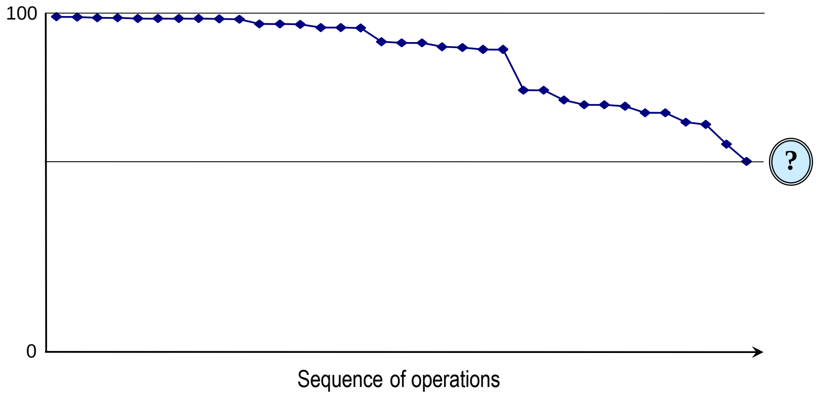
Op 8	Op 9	Op 10	Op 11	Op 12	Op 13	Op 14
99.999%	99.999%	99.999%	99.999%	99.999%	99.999%	99.999%

Overall yield $= (0.99999)^{14} = 0.999860 \rightarrow 99.986\%$

140 DPPM

Exercise 2.1

The average yield for 35 operations in an assembly process is 98.4%. Calculate the overall yield under the simplifying assumption that the yield for each operation is exactly equal to 98.4%. (The real answer would be the product of the actual operation yields.)



Exercise 2.1 (cont'd)

The area manager reported 98.4% as the overall yield of the operation. His reaction to the correct analysis followed the classic grief cycle:

Denial	*"This can't be right. There must be a mistake in your calculation."*
Anger	*"This is ridiculous. You're wasting my time."*
Bargaining	*"Isn't my method just as valid as your method?"*
Depression	*'This is really bad. What am I going to tell everyone?"*
Acceptance	*"I guess you can't solve a problem if you don't know you have it."*

We can count ***defects*** instead of ***defective parts***

- Each potential defect on a part, or potential error in a transaction, is called an *opportunity*
- We can use DPMO (defects per million opportunities) instead of DPPM (defective parts per million)
- DPPM is more *customer* focused

The fact that **anything** is wrong is primary — the **number of things** wrong is secondary

- DPMO is more *process* focused

DPMO is a finer measure than **DPPM** — it responds more rapidly to process changes

- Requirements for using DPMO
  - ✓ A finite number of identifiable opportunities per part or transaction
  - ✓ Statistical independence of defect occurrence at different opportunities

In many cases, failure rates are quantified as percentages

Definition of "opportunity"	Fraction defective	Expressed as a percentage	Focus
Each part	$\frac{\text{Defective parts}}{\text{All parts}}$	% Defective	Customer
Each possible defect on a part	$\frac{\text{Defects}}{\text{(All parts)} \times \text{(possible defects per part)}}$	Defects per 100 opportunities (DPHO)	Process
Each transaction	$\frac{\text{Defective transactions}}{\text{All transactions}}$	% Defective	Customer
Each possible error in a transaction	$\frac{\text{Errors}}{\text{(All transactions)} \times \text{(possible errors per transaction)}}$	Defects per 100 opportunities (DPHO)	Process

Pragmatic business initiative

- In the 1990s, GE shifted the emphasis from the Six Sigma quality goal to *Six Sigma projects* — the way to pursue the goal
- Leaders and Champions define *key performance indicators* (KPIs) — a “balanced scorecard” including but not limited to $$ measures
- KPIs drive a prioritization process
- Prioritization tells us which project(s) should be first in line
- “Black Belts” or “Green Belts” lead the project teams
- “Champions” provide resources and remove barriers for the teams

Champions

- ✓ Management team members
- ✓ Identify and prioritize projects
- ✓ Assign project teams
- ✓ Provide teams with resources as needed
- ✓ Remove organizational barriers to project completion
- ✓ Provide project management support
- ✓ Communicate project results to the organization

Comparison of Green and Black Belts

Prerequisites and roles	Green	Black
• Experience in process improvement	✓	✓
• Strong teamwork, leadership, and people skills	✓	✓
• Basic Excel skills • Ability to acquire intermediate Excel skills	✓	✓
• Receive training in basic statistical concepts and methods	✓	✓
• Lead project teams	✓	✓
• Provide technical support to project teams	✓	✓
• Prior experience with statistical methods		✓
• Able to learn and use statistical software		✓
• Receive training in advanced statistical concepts and methods		✓
• Assist Champions in project identification and prioritization		✓

Examples of projects

Project	Annual $$ benefit
Reduce alpha case on large titanium castings	20,800,000
Reduce cost and lead time to develop extrusion tooling	2,000,000
Reduce wasted medication in hospital central pharmacy	1,100,000
Reduce roll stock inventory in box plant	768,000
Reduce cost of belt grinding in casting finishing	500,000
Improve the court collections process in city government	400,000
Reduce DOA replacement parts in field service	216,000
Reduce DPMO and amount of testing of circuit boards	192,000
Reduce electricity consumption in manufacture of airline storage bins	65,000
Reduce RFQ turnaround time (not counting increased PO hit rate)	34,000

3 Why Combine Lean and Six Sigma?

- They require the same *kaizen* culture
- They employ common strategies
- They focus on complementary problem areas
- They employ complementary methods
- They emphasize fact over opinion and use data to inform decisions
- One improvement infrastructure is better than two

The need for kaizen

- Without *kaizen*, both Lean and Six Sigma fall into “top down, command & control, outside experts” mode
- Culture always beats methodology — benefits will be limited
- Improvement cycles must be integral to the daily work of all employees
- Teamwork across departments must be “business as usual”
- Open discussion of problems must be *safe* — emotionally and professionally
- “It’s not a witch hunt — it’s a *treasure* hunt”

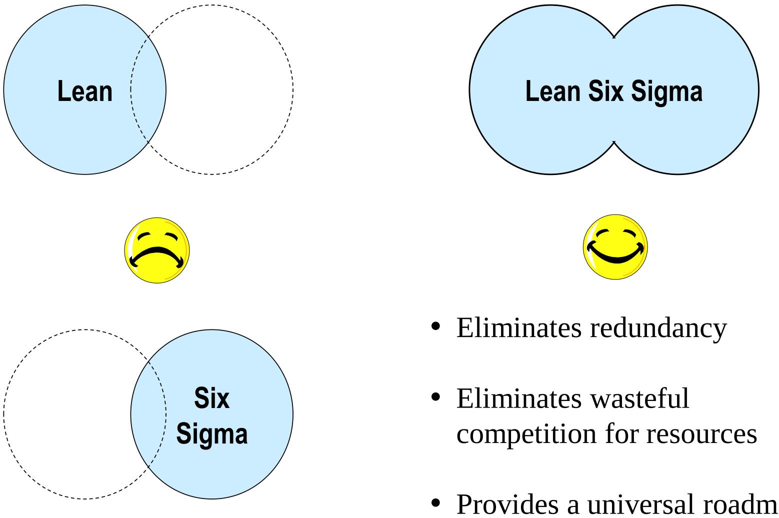
Common strategies

- Driven by Voice of the Customer
- Focus on eliminating waste
- Focus on processes and process improvement
- Improve processes via team projects
- Keep the improvement cycles going

Complementary problem focus and methods

Lean	**Six Sigma**
Lead time WIP Other visible waste	Defects “Invisible” waste
Defects caused by chaos and confusion	Defects caused by materials and equipment
Root causes easier to determine. (Processes directly observable.)	Root causes harder to determine. (Processes often not observable.)
Value stream mapping Geographic mapping	Basic process mapping Cross functional process mapping
Defines and standardizes the “Wisdom of the organization”	Data collection and analysis to discover a new solution
Common TPS solutions can be adapted to many circumstances	Project roadmap provides a method for finding solutions

A single improvement infrastructure



- Eliminates redundancy
- Eliminates wasteful competition for resources
- Provides a universal roadmap for improvement projects

Lean Six Sigma

Originally, TPS included virtually all the tools of what we now call Lean Six Sigma (LSS). When TPS came to the USA, the Lean tools were adopted right away, but the Six Sigma tools were not. This made sense because there was plenty of “low hanging fruit” that could be harvested by Lean without undertaking the difficult task of teaching people statistical concepts and methods.

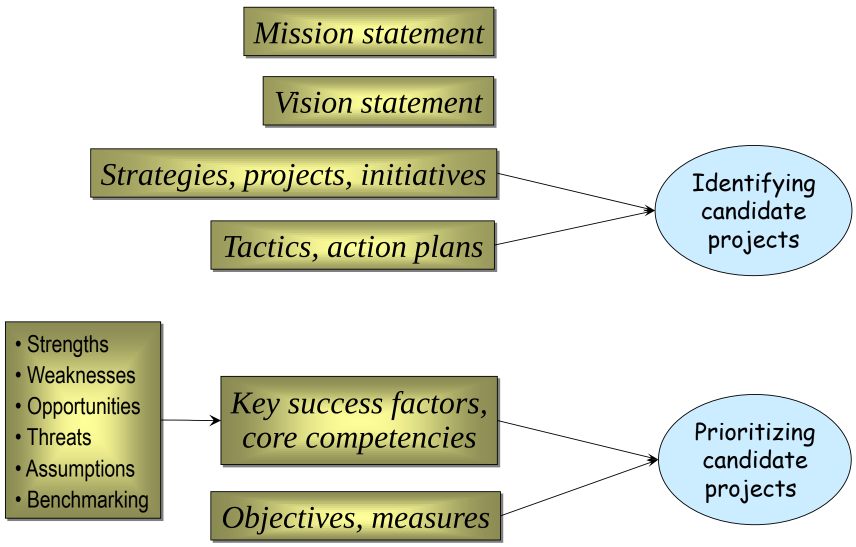
For many organizations, it still makes sense to embrace Lean concepts and methods first. The LSS project roadmap is an excellent vehicle for this. Eventually, organizations will need to tackle more difficult problems that cannot be solved with Lean concepts and methods. When this time comes, the LSS project roadmap provides the Six Sigma concepts and methods needed to solve the more difficult problems.

Thus, in the USA at least, we might think of Lean and Six Sigma as fraternal siblings separated at birth, reunited at last by LSS.

4 Relation of LSS to Other Initiatives

- Strategic planning
- ISO 9001
- Voice of the customer
- Supply chain management
- Balanced scorecard

Strategic planning



Mission statement

Vision statement

Strategies, projects, initiatives

Tactics, action plans

Identifying candidate projects

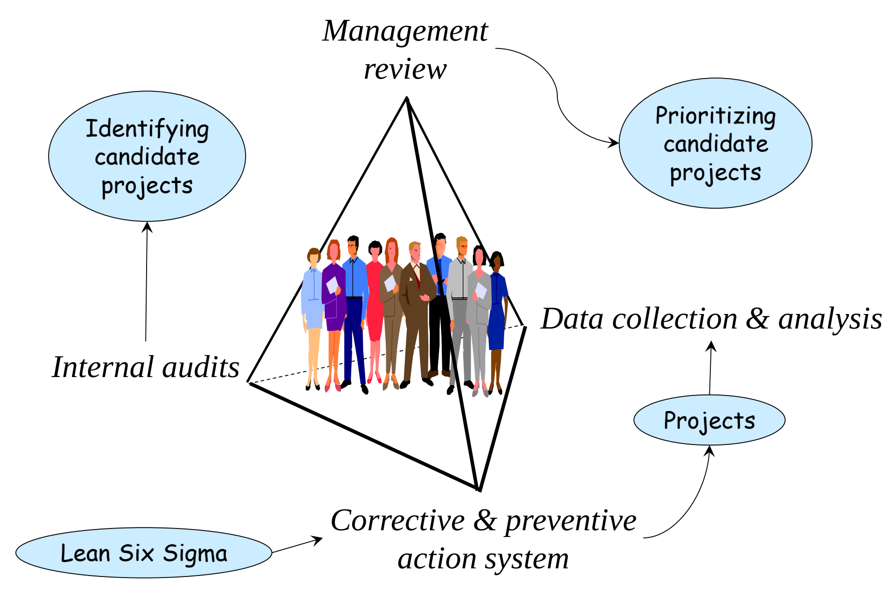
- Strengths
- Weaknesses
- Opportunities
- Threats
- Assumptions
- Benchmarking

Key success factors, core competencies

Objectives, measures

Prioritizing candidate projects

ISO 9001



Management review

Identifying candidate projects

Prioritizing candidate projects

Internal audits

Data collection & analysis

Projects

Lean Six Sigma

Corrective & preventive action system

Voice of the customer

- Resolving complaints does not increase customer satisfaction
- Suppliers must *proactively* discover what customers really want
  - ✓ Collect and analyze data on customer feedback, complaints, returns, . . .
  - ✓ Visit customers in person — observe, listen, learn

Identifying candidate projects

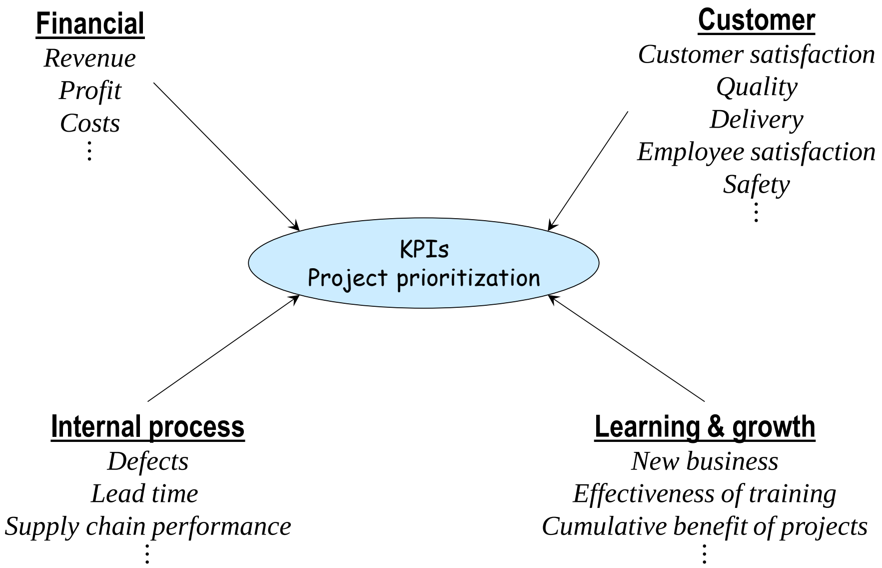
Supply chain management

- Finding the right suppliers
- Building partnerships, not just writing contracts
- Knowing and communicating your needs and expectations
- Listening to the “Voice of the Supplier”
- Monitoring your supplier’s performance
- Giving clear and useful feedback

↓

Joint projects

Balanced scorecard



Financial
Revenue
Profit
Costs
⋮

Customer
Customer satisfaction
Quality
Delivery
Employee satisfaction
Safety
⋮

KPIs
Project prioritization

Internal process
Defects
Lead time
Supply chain performance
⋮

Learning & growth
New business
Effectiveness of training
Cumulative benefit of projects
⋮

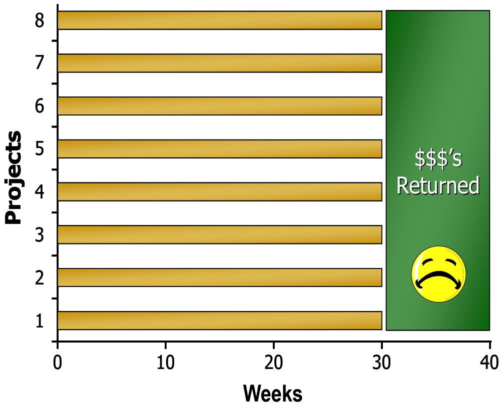
5 Deploying LSS Projects

- Roles and responsibilities
- Limiting projects in process
- The continuous improvement cycle
- LSS and the Fire model

Roles and responsibilities

	Define KPIs	Identify candidate projects	Prioritize candidate projects	Champion projects	Lead projects
Leaders/Mgmt	✓	✓	✓		
Champions	✓	✓	✓	✓	
Black Belts		✓	✓		✓
Green Belts					✓

Must limit projects in process

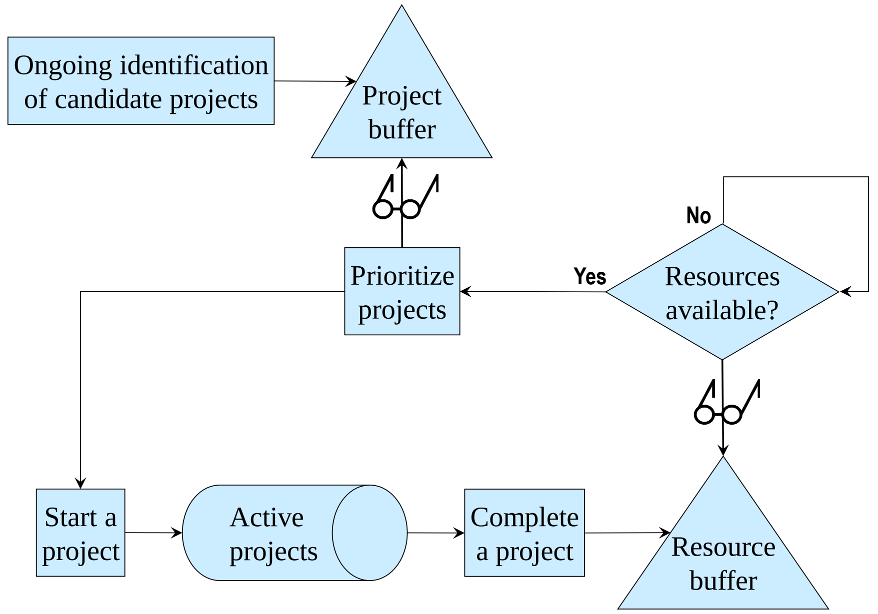


- Suppose we have two “belts”, each leading four projects
- They are spread too thin
- It takes a long time to get the projects done
- It takes a long time to accrue the benefits

Limit projects in process (cont’d)

- Much better to give each of them one project at a time
- Now they have a manageable workload
- Project lead time is dramatically reduced
- Accrual of benefits is accelerated

Continuous improvement cycles



Ongoing identification of candidate projects

Project buffer

Prioritize projects

No

Yes

Resources available?

Start a project

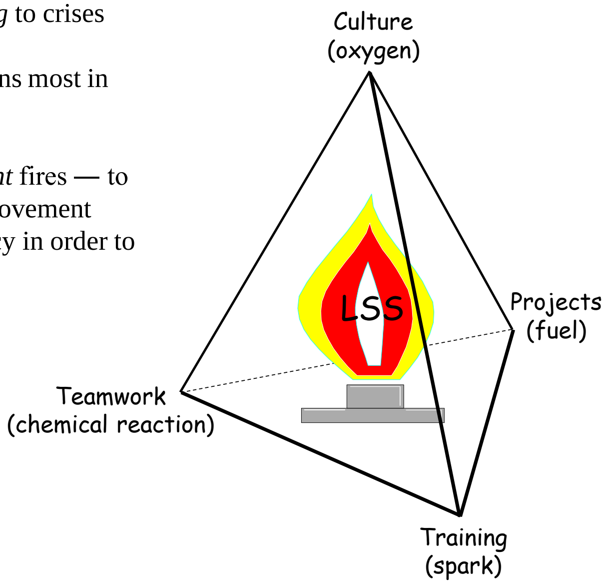
Active projects

Complete a project

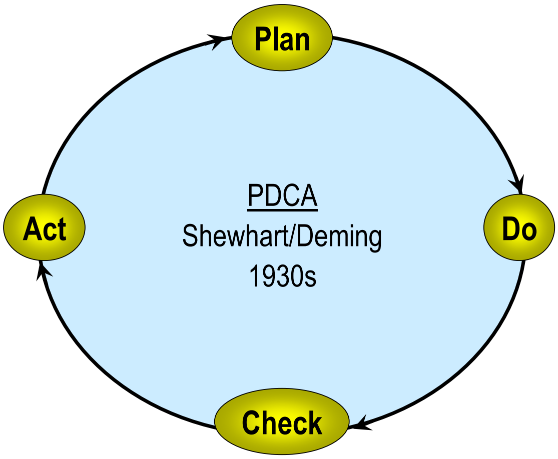
Resource buffer

LSS and the Fire model

- Many organizations are stuck in fire-fighting mode — *reacting* to crises
- These are the organizations most in need of LSS
- The goal of LSS is to *light* fires — to pursue high priority improvement opportunities with urgency in order to *prevent* crises



6 LSS Project Roadmap



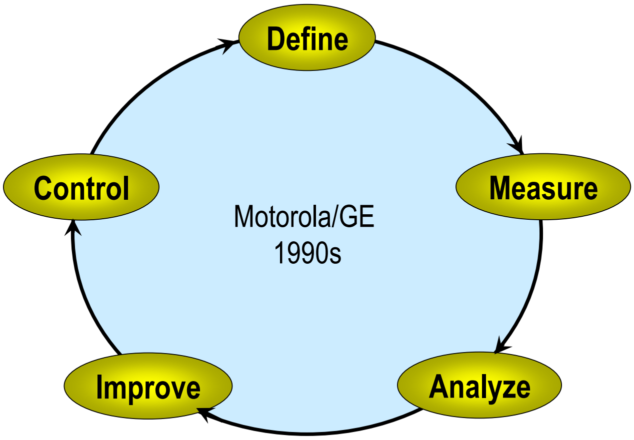
The scientific method applied to business problems

PDCA (cont'd)

Plan	Define the problem to be solved, collect and analyze data on the current state, identify possible causes of the problem.
Do	Identify possible solutions, select the most likely solution, pilot the solution.
Check	Analyze the results to see if the problem is solved.
Act	If the solution is successful, implement it. If the solution is not successful, repeat the cycle.

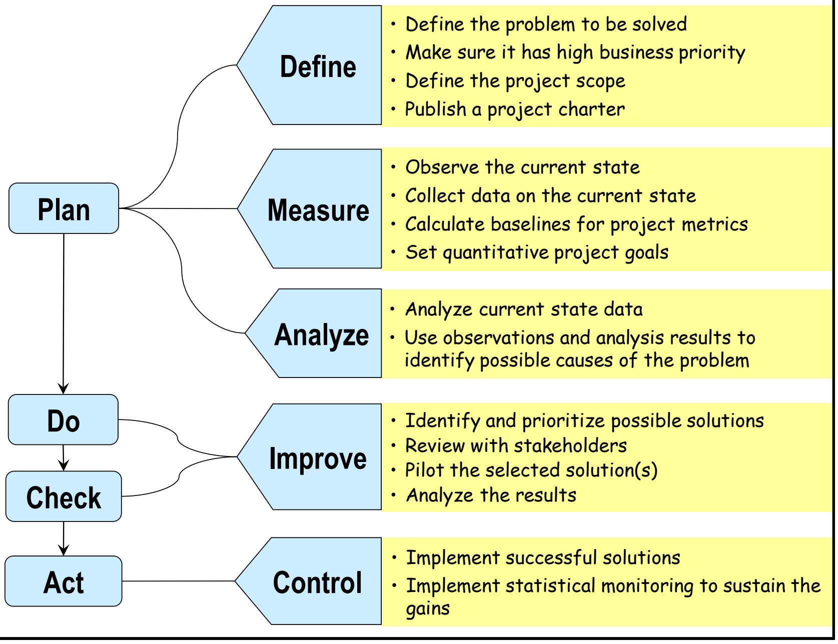
- PDCA is the oldest improvement cycle for manufacturing, business, and service processes
- It has been around for more than 80 years, it has served us well, and it is still in use

DMAIC



A high level description of today's most widely used improvement project roadmap

DMAIC has more "teeth" than PDCA



Define
- Define the problem to be solved
- Make sure it has high business priority
- Define the project scope
- Publish a project charter

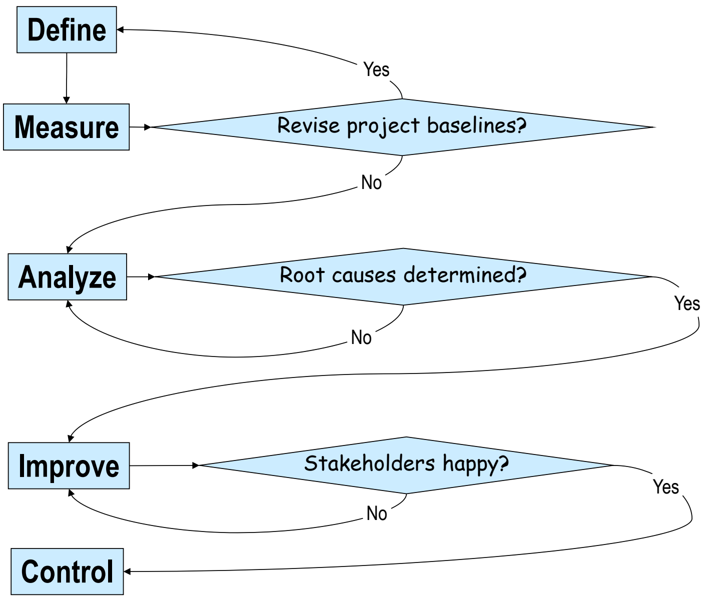
Measure
- Observe the current state
- Collect data on the current state
- Calculate baselines for project metrics
- Set quantitative project goals

Analyze
- Analyze current state data
- Use observations and analysis results to identify possible causes of the problem

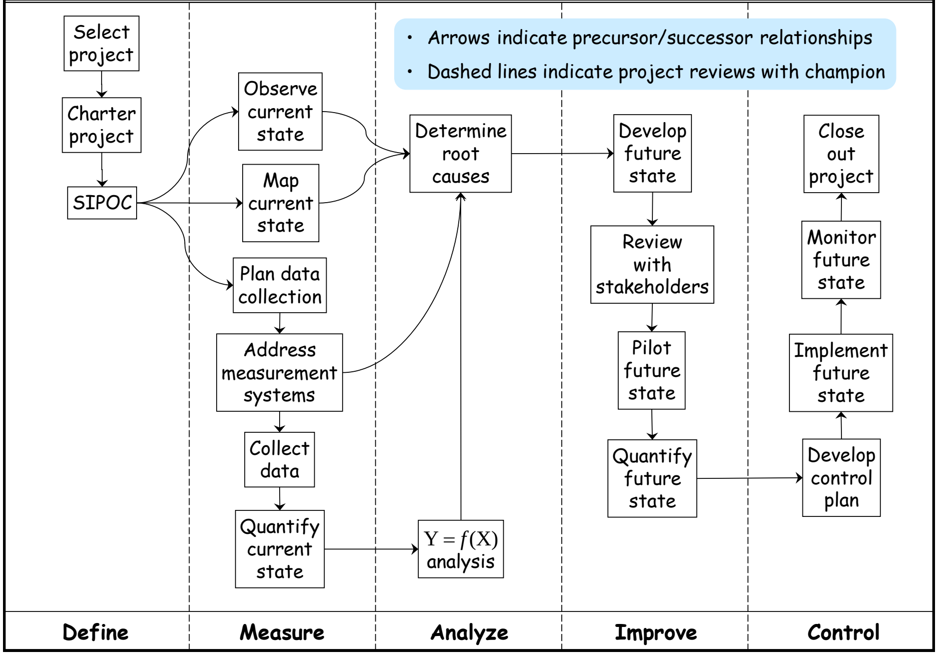
Improve
- Identify and prioritize possible solutions
- Review with stakeholders
- Pilot the selected solution(s)
- Analyze the results

Control
- Implement successful solutions
- Implement statistical monitoring to sustain the gains

Common DMAIC complications



The LSS project roadmap (detailed version of DMAIC)


- *Arrows indicate precursor/successor relationships*
- *Dashed lines indicate project reviews with champion*

Strengths of LSS projects

- Aligned with business priorities
- Clearly defined scope and boundaries
- Combination of process observation and data analysis
- Solve problems by understanding them
- Conclusions supported by statistical standards of evidence
- Improvements verified quantitatively
- Statistical monitoring used to sustain gains

Characteristics of LSS projects

- We want to improve a process (the way we do something) or product (a way for customers to do something)
- The current process or product falls measurably short of what is needed or desired
- The cause of the problem is not known, or there is lack of consensus as to what it is
- Process observation and data collection/analysis are required
- Root cause analysis is required
- Lean solutions may or may not be applicable

Examples of LSS projects

	Probability that Lean solutions will apply
• Reduce injection molding defects	Low
• Reduce injection molding setup time	High
• Reduce oxidation layer on titanium castings	Low
• Reduce unplanned downtime	Medium
• Reduce Request For Quote (RFQ) turnaround time	High
• Reduce repair shop turnaround time	High
• Reduce the cost of belt grinding	Low

Other types of projects (non-LSS)

- We know what needs to be done, and we want to do it
- It may be simple, quick, and cheap (a “just do it” project)
- It may be complex, time consuming, and/or expensive (a “project management” project)
- Both of these involve *implementing known solutions*
- These could be action items *resulting* from a LSS project, but they are not in themselves LSS projects

Examples of non-LSS projects

Automate a task that is currently done manually

Upgrade software to the latest revision

Revise outdated work instructions

Install a new piece of equipment

Obtain environmental permits

Replace outdated computers

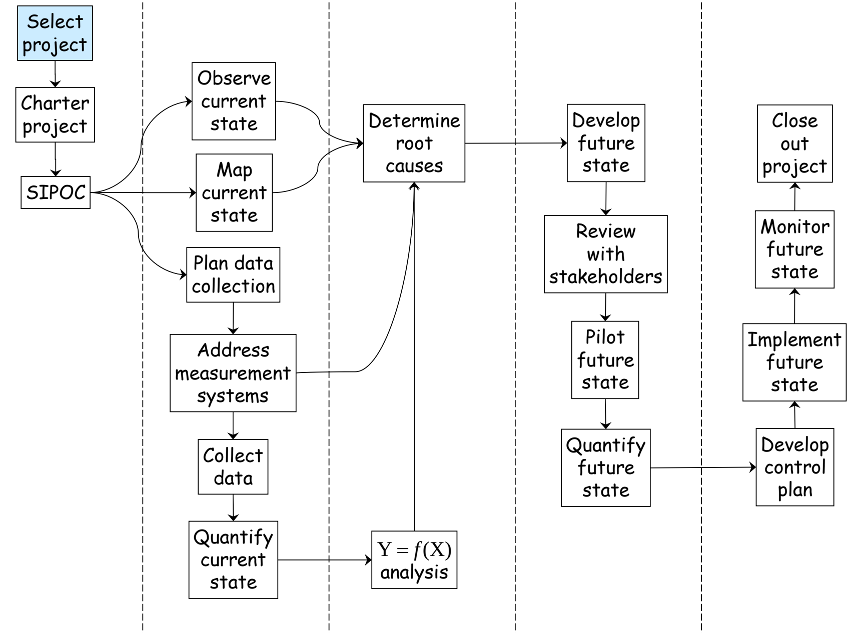
Install a bar coding system

Build a plant in China

Exercise 6.1

Classify these projects	**Lean**	**SS**	**Other**
Implement the new ERP system we have decided to use			
Reduce errors in processing purchase requisitions			
Reduce wave solder defects			
Open a new branch office in the next town			
Reduce billing lead time			
Install a web-based ordering system			
Reduce non-manufacturing time from order to sell			
Reduce scrap in the coiling department			
Eliminate cracking of molded housings			
Reduce installation & warranty costs			
Increase the percentage of quotes that produce a PO			

7 Identifying Candidate Projects



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

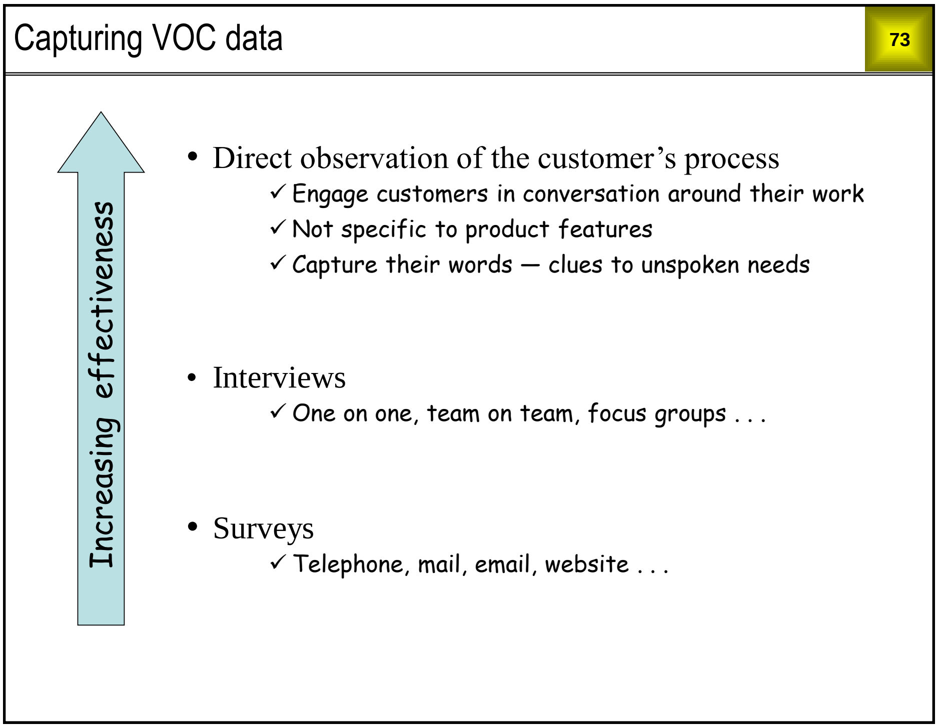
Implement future state

Develop control plan

Where do candidate projects come from?

- Benchmarking
  - ✓ If they can do it, why can't we?
- Vision of the future
- Demand expected to exceed current capacity
  - ✓ Seems to require capital expenditure
  - ✓ Better to reduce defects and lead times
- Voice of the customer (VOC)
  - ✓ Quality
  - ✓ Delivery
  - ✓ Cost
  - ✓ Service
- Cost of waste analysis
  - ✓ Follow the money

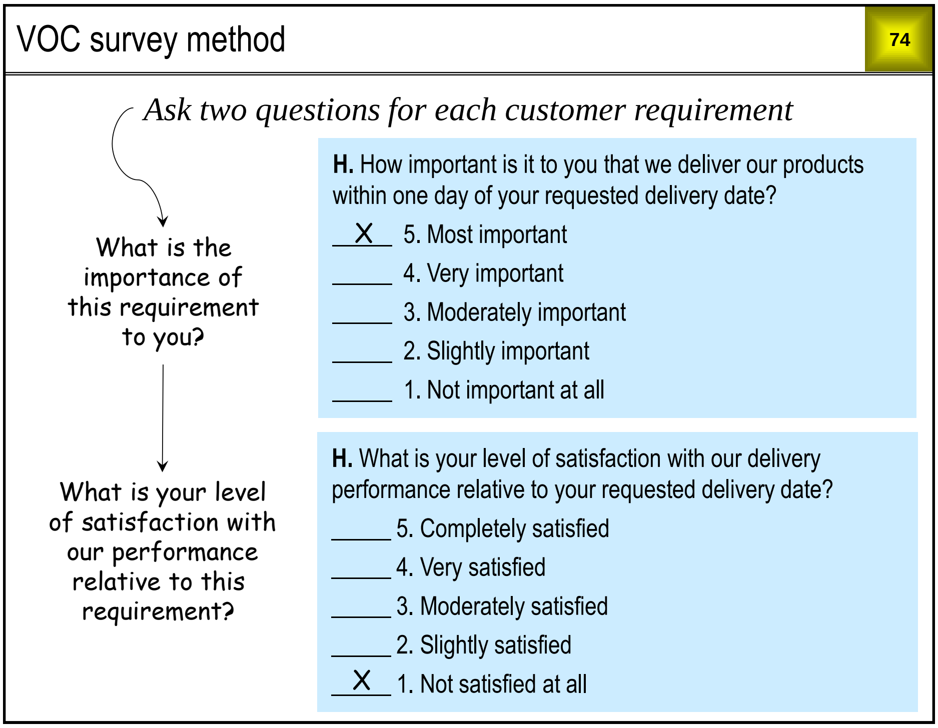
We will focus on these two



Capturing VOC data

Increasing effectiveness

- Direct observation of the customer's process
  - ✓ Engage customers in conversation around their work
  - ✓ Not specific to product features
  - ✓ Capture their words — clues to unspoken needs
- Interviews
  - ✓ One on one, team on team, focus groups . . .
- Surveys
  - ✓ Telephone, mail, email, website . . .



VOC survey method

Ask two questions for each customer requirement

What is the importance of this requirement to you?

H. How important is it to you that we deliver our products within one day of your requested delivery date?

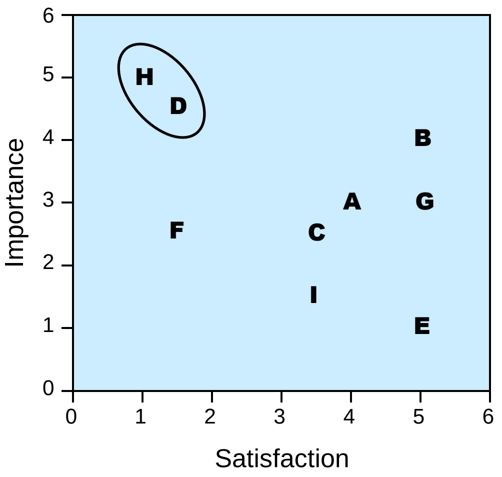
__X__ 5. Most important
_____ 4. Very important
_____ 3. Moderately important
_____ 2. Slightly important
_____ 1. Not important at all

What is your level of satisfaction with our performance relative to this requirement?

H. What is your level of satisfaction with our delivery performance relative to your requested delivery date?

_____ 5. Completely satisfied
_____ 4. Very satisfied
_____ 3. Moderately satisfied
_____ 2. Slightly satisfied
__X__ 1. Not satisfied at all

“Perceptual map” based on VOC data



- Average importance vs. average satisfaction for requirements A thru I
- Need improvement projects directed at requirements H and D
- The averages could represent multiple customers (smaller companies)
- They could also represent multiple individuals with different roles within a single customer (larger company)

Exercise 7.1

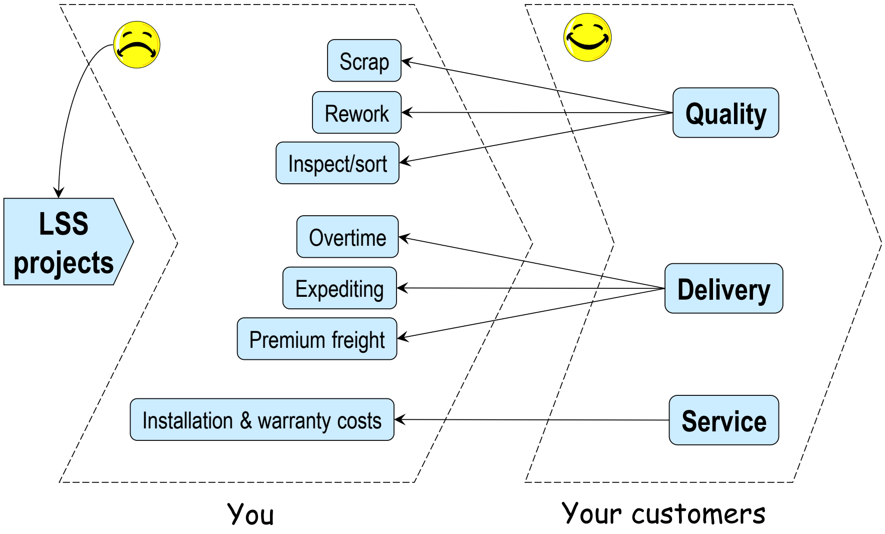
Think about and be prepared to discuss the following questions:

(a) What VOC information does your company receive, and how is it obtained?

(b) Give examples of decisions, actions, or improvement projects based on VOC information.

Often your customers are happy . . .

. . . but you're killing yourself to make it so



LSS projects

Scrap

Rework

Inspect/sort

Overtime

Expediting

Premium freight

Installation & warranty costs

Quality

Delivery

Service

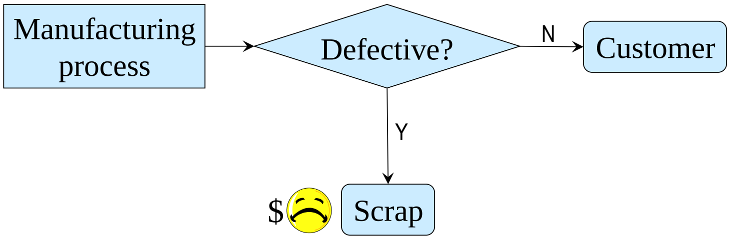
You

Your customers

Cost-of-waste analysis

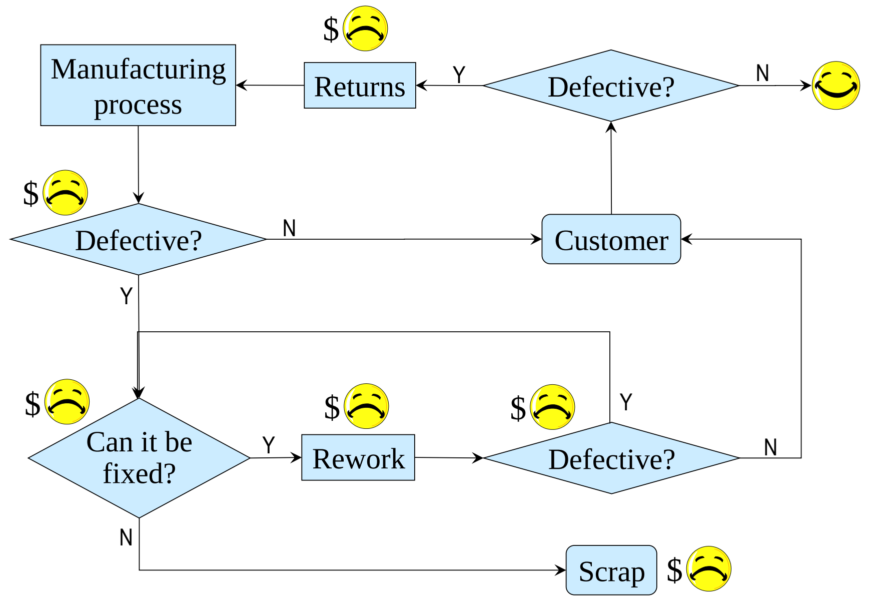
- Includes, but not limited to, cost of poor quality
- Assists in project selection and scoping
- Needed to establish project baselines
- Assists in defining project goals
- Needed to determine project benefits
- Money speaks loudest in many organizations

Apparent cost of poor quality



What is the real cost of poor quality?

The “hidden factory”



$

Manufacturing process

Returns

Y

Defective?

N

$

Defective?

N

Customer

Y

$

Can it be fixed?

Y

$

Rework

$

Defective?

Y

N

N

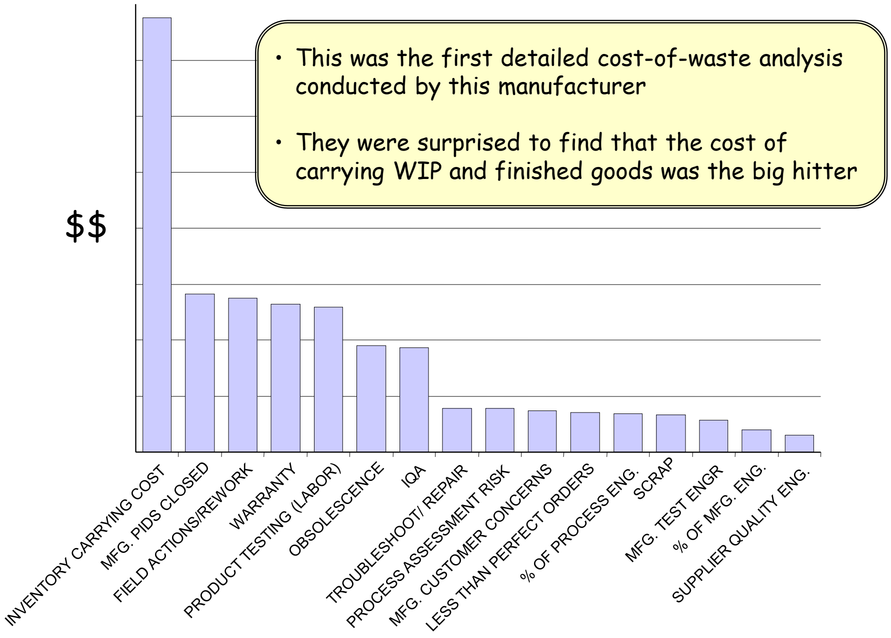
Scrap

$

Hidden factory (cont’d)

- Inspections to sort good parts from bad
- Efforts to determine causes of defects
- Inflating material orders and time/cost standards
- Returned goods
- Service activity under warranty
- Trips to placate unhappy customers
- Loss of business due to unhappy customers
- Reworking or scrapping defective parts
- Complicated inventory management
- Specialized training for rework processes
- Specialized rework equipment
- Capacity allocated to rework
- Special rework qualification processes

Example: cost-of-waste analysis

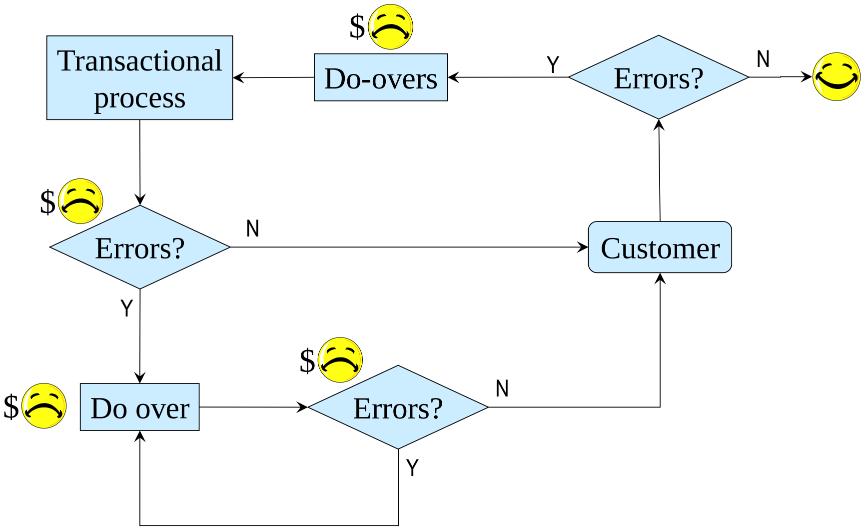


- This was the first detailed cost-of-waste analysis conducted by this manufacturer
- They were surprised to find that the cost of carrying WIP and finished goods was the big hitter

Costs of poor transactional quality

- Waste is harder to see in transactional processes
- The only quantifiable cost factor is the time people spend on NVA activities
- Even if this time is reduced, there will be no actual cost reduction (unless people are laid off)
- The real benefits are
  - ✓Reducing lead time,
  - ✓Increasing customer satisfaction, and
  - ✓Increasing capacity without additional resources

The “hidden office”



Hidden office (cont’d)

- Doing things over again due to errors or omissions
- Inspections to find errors and omissions
- Workarounds necessitated by root causes not being addressed
- Efforts to determine causes of errors and omissions
- Loss of business due to unhappy customers

Other costs of waste (from the Lean playbook)

D	Failure to meet expected standards of quality or delivery
O	Making or doing more than is needed at the time
W	People waiting to work, or things waiting to be worked on
N	Failure to integrate improvement cycles into the daily work of all employees
T	People or things being moved from one place to another
I	Supplies, WIP, or finished goods beyond what it is needed
M	Excessive motion in the completion of work activities
E	Producing or delivering to a higher standard than is required

Exercise 7.2

a) The current practice of a central pharmacy in a hospital is to prepare all IV piggybacks and syringes for each day at 7:00 am. Every day, some of this medication is wasted because patients are discharged, transferred, or have their medication orders changed. The anecdotal estimate of the annual cost of this waste is $100,000. Use the “hidden factory” data given below and a spread-sheet to get a better estimate of the annual cost of waste. (Assume 52 working weeks per year.)

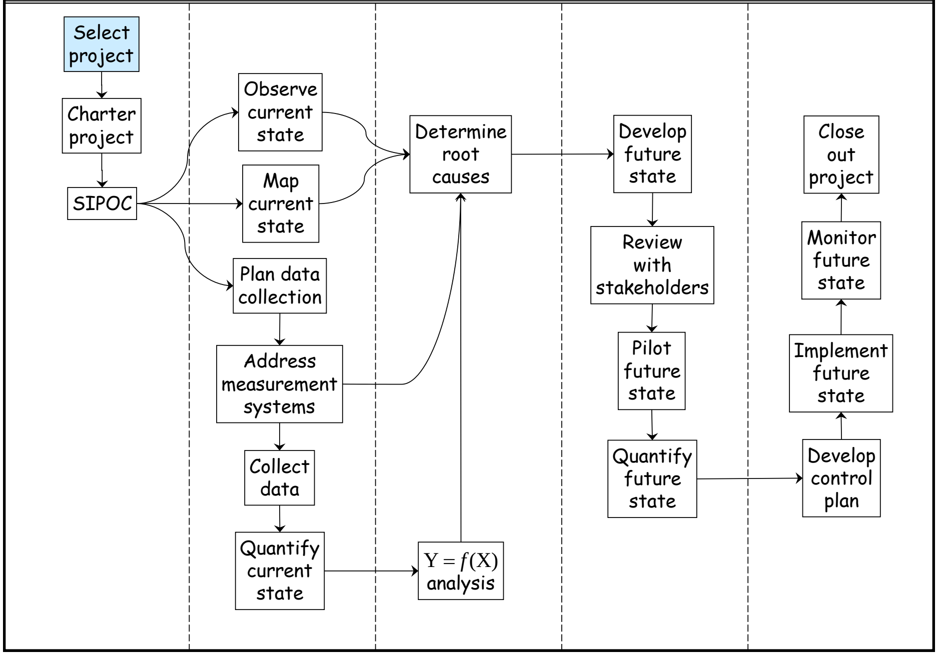
Weekly averages	
Number of doses wasted	657
Staff hours spent retrieving wasted doses	21
Staff hours spent disposing of wasted doses	10

Average rates	
Product cost per dose	$14
Disposal fee per dose	$42
Labor cost per hour	$23

b) Suggest a way to reduce the cost of waste in this example.

c) What other costs or impacts can you think of that might be occurring due to this practice?

8 Prioritizing Candidate Projects



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

Y = *f*(X) analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

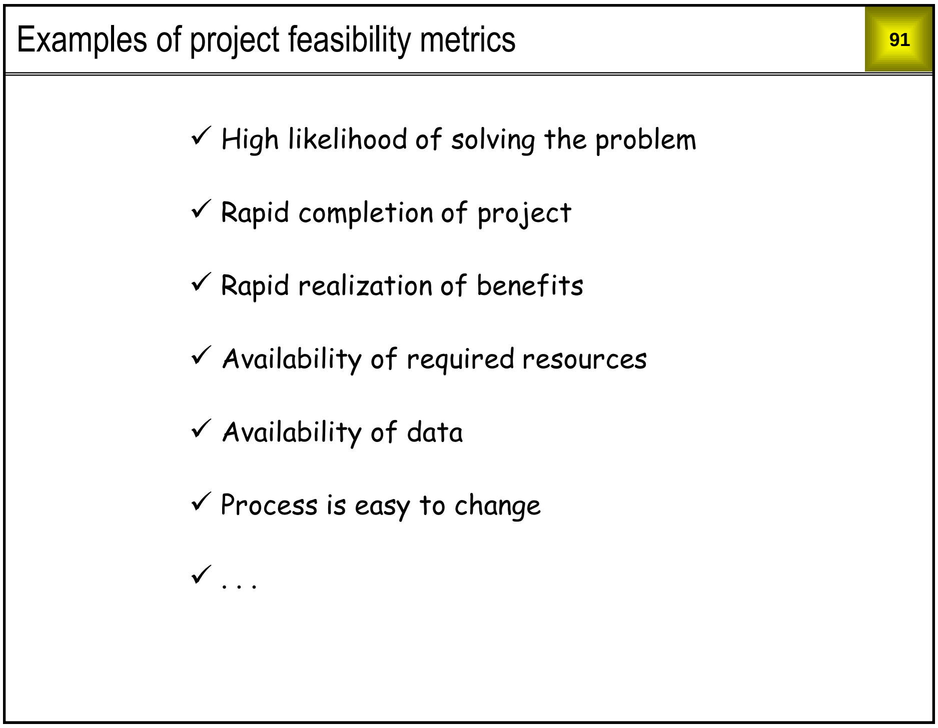
Monitor future state

Close out project

Qualitative description of a good improvement project

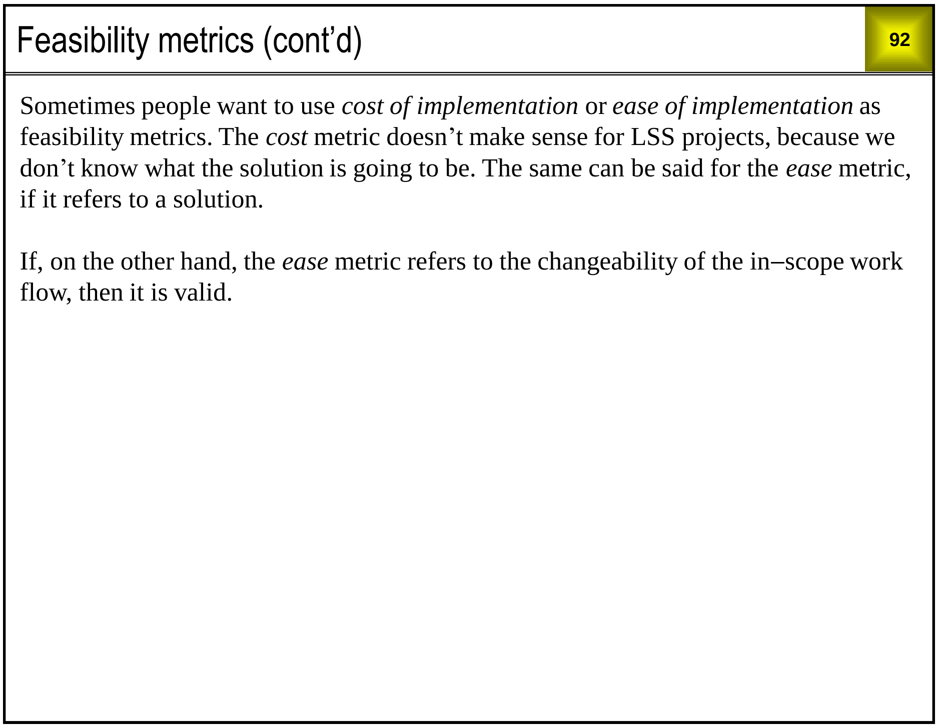
Clearly defined problem, scope, and boundaries	**S**pecific
Clearly defined project metrics with baselines and goals	**M**easurable
Resources available, good chance of success, rapid benefits	**A**chievable
Aligned with business priorities	**R**elevant
Can complete in a reasonable amount of time	**T**ime-bounded

How do we quantify these attributes?



Examples of project feasibility metrics

- ✓ High likelihood of solving the problem
- ✓ Rapid completion of project
- ✓ Rapid realization of benefits
- ✓ Availability of required resources
- ✓ Availability of data
- ✓ Process is easy to change
- ✓ . . .



Feasibility metrics (cont'd)

Sometimes people want to use *cost of implementation* or *ease of implementation* as feasibility metrics. The *cost* metric doesn't make sense for LSS projects, because we don't know what the solution is going to be. The same can be said for the *ease* metric, if it refers to a solution.

If, on the other hand, the *ease* metric refers to the changeability of the in–scope work flow, then it is valid.

Measures of project impact: KPIs

- ✓ Customer satisfaction — quality, delivery, service . . .
- ✓ Revenue, cash flow, cost of waste . . .
- ✓ Growth in existing markets
- ✓ New market penetration
- ✓ Lack of adverse safety impact
- ✓ Lack of adverse environmental impact
- ✓ . . .

KPIs (cont'd)

An organization should use its *key performance indicators* (KPIs) to measure the probable impact of proposed improvement projects. KPIs are often established during a strategic planning process.

If your organization has a balanced scorecard, it has already taken a step towards understanding what its KPIs are. If a KPI in a balanced scorecard is defined too broadly, it will need to be broken down further to be useful in project prioritization. An example would be breaking "customer satisfaction" into separate KPIs for quality, delivery, and service.

KPIs should be defined *before* they are used to prioritize projects. This helps people distinguish between the KPIs and the projects themselves, which in turn helps in scoping projects appropriately. For example, "reduce scrap and rework" is too broad for a project scope. A better project scope would be something like "reduce scrap and rework for product XYZ."

KPIs are supposed to reflect the priorities of the organization. As such, they should change when these priorities change, and only then.

Instructions for prioritizing projects

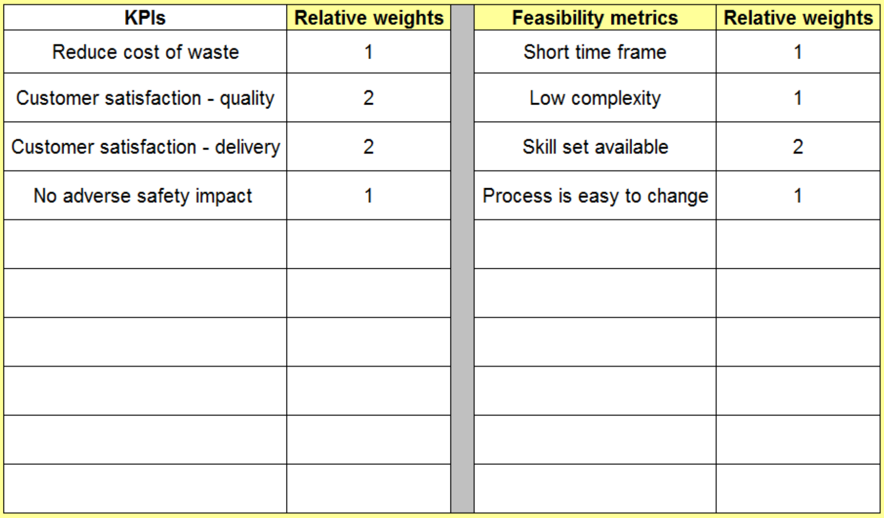
1. Open *Student Files* → *blank C&E matrix – impact & feasibility*.
2. In the *Metrics* sheet, change *Impact metrics* to *KPIs*. (Already done)
3. List your KPIs and relative weights.
4. List your feasibility metrics and relative weights.
5. Go to the *Impact ratings* sheet, change *Items to be ranked* to *Projects*.
6. List the candidate projects you wish to rank.
7. Rate each project for degree of positive impact on each KPI.

Prioritizing projects (cont'd)

8. Go to the *Feasibility ratings* sheet, rate each project for each feasibility metric.
9. Go to the sheet *Impact–feasibility plot* to evaluate the results.

Student Files \ prioritizing projects – example 1

Metrics tab



KPIs	Relative weights	Feasibility metrics	Relative weights
Reduce cost of waste	1	Short time frame	1
Customer satisfaction - quality	2	Low complexity	1
Customer satisfaction - delivery	2	Skill set available	2
No adverse safety impact	1	Process is easy to change	1

Metrics (cont'd)

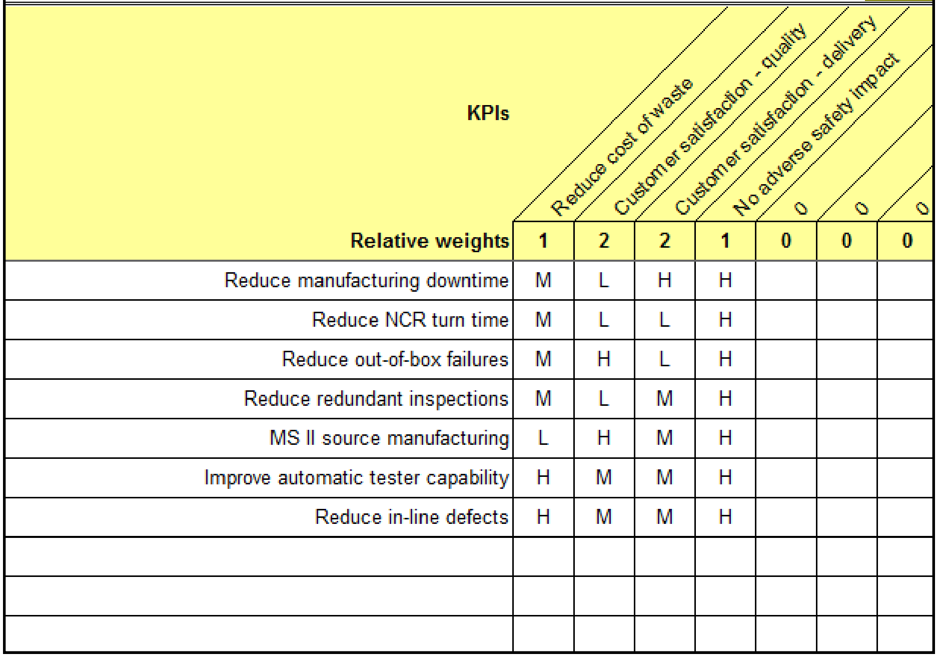
- Enter your KPIs in the *Metrics* sheet

- State KPIs in "higher is better" form — for example, use "reduce cost of waste" instead of "cost of waste"

- Enter relative weights (importance) for the KPIs. Here is a process for doing this:
    1. If the KPIs are equally important, weight them all as 1.
    2. If some KPIs are more important than others, split them into a more important group and a less important group.
    3. If some KPIs in a group are more important than others, split them into a more important subgroup and a less important subgroup.
    4. If necessary, split subgroups into sub-subgroups.
    5. If you end up with two homogeneous groups, use weights 1 and 2. If you end up with three homogeneous groups, use weights 1, 2, and 3. And so on.

- Everything said here applies as well to your feasibility metrics.

Impact ratings



KPIs	Reduce cost of waste	Customer satisfaction - quality	Customer satisfaction - delivery	No adverse safety impact	0	0	0
Relative weights	**1**	**2**	**2**	**1**	**0**	**0**	**0**
Reduce manufacturing downtime	M	L	H	H			
Reduce NCR turn time	M	L	L	H			
Reduce out-of-box failures	M	H	L	H			
Reduce redundant inspections	M	L	M	H			
MS II source manufacturing	L	H	M	H			
Improve automatic tester capability	H	M	M	H			
Reduce in-line defects	H	M	M	H			

Comments on impact and feasibility ratings

The slide above shows the *Impact ratings* sheet with some project titles entered. Our job is to rate each project as having high (H), medium (M), low (L), or no impact (blank) on each KPI. The numerical codings for H, M, and L are specified in the sheet *Impact calculations*.

Ideally, the team should assign the ratings *one KPI at a time*, because our goal is to prioritize the projects, not the KPIs. If you would rather assign the ratings one *project* at a time, just make sure to check that the resulting project rankings for each KPI make sense.

The next slide shows the *Feasibility ratings* sheet. Here we rate each project as high (H), medium (M), or low (L) for each feasibility metric. The numerical codings are specified in the *Feasibility calculations* sheet.

As for the impact ratings, it is best if the team assigns feasibility ratings one metric at a time. If you would rather assign the ratings one project at a time, just make sure to check that the resulting project rankings for each feasibility metric make sense.

Feasibility ratings

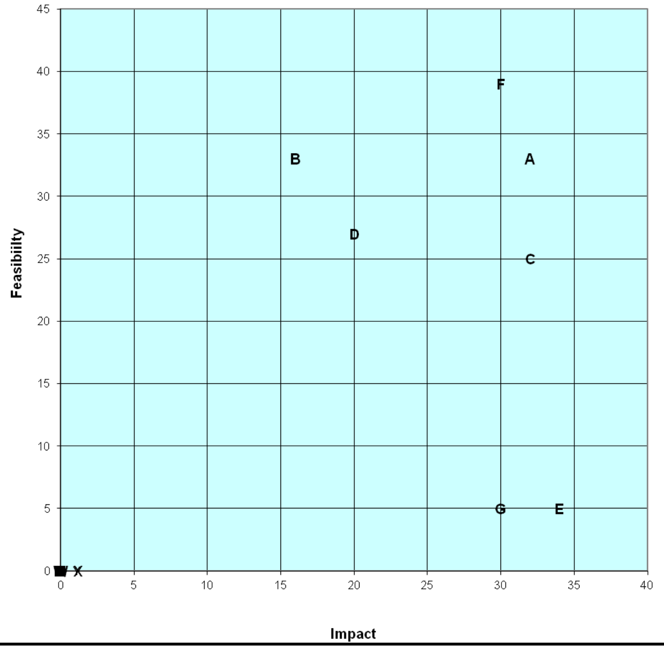
Feasibility metrics	Short time frame	Low complexity	Skill set available	Process is easy to change	0	0	
Relative weights	**1**	**1**	**2**	**1**	**0**	**0**	**0**
Reduce manufacturing downtime	M	M	H	H			
Reduce NCR turn time	H	M	H	M			
Reduce out-of-box failures	L	M	H	M			
Reduce redundant inspections	M	M	H	M			
MS II source manufacturing	L	L	L	L			
Improve automatic tester capability	H	M	H	H			
Reduce in-line defects	L	L	L	L			
0							
0							
0							

Impact-feasibility plot

Projects	Tag	Impact	Feasibility
Reduce manufacturing downtime	A	32	33
Reduce NCR turn time	B	16	33
Reduce out-of-box failures	C	32	25
Reduce redundant inspections	D	20	27
MS II source manufacturing	E	34	5
Improve automatic tester capability	F	30	39
Reduce in-line defects	G	30	5
0	H	0	0
0	I	0	0
0	J	0	0

- Project names and impact ratings are carried forward from the *Impact ratings* sheet
- Feasibility ratings are carried forward from the *Feasibility ratings* sheet

Impact-feasibility plot (cont'd)

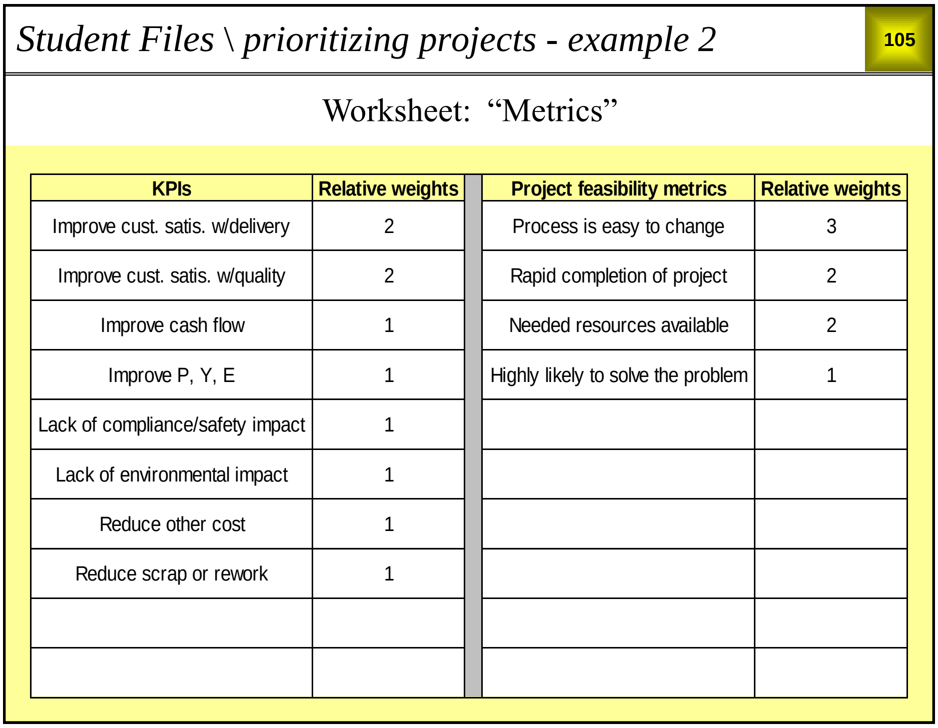


Impact-feasibility plot (cont'd)

This is a scatterplot of the overall impact and feasibility scores for the projects. The upper right hand corner is the "sweet spot." Projects that score highly for both impact and feasibility should be your first priority.

Based on the plot, projects A and F both have high priority based on the plot. Assuming you have resources for only one project, how should you choose between them?

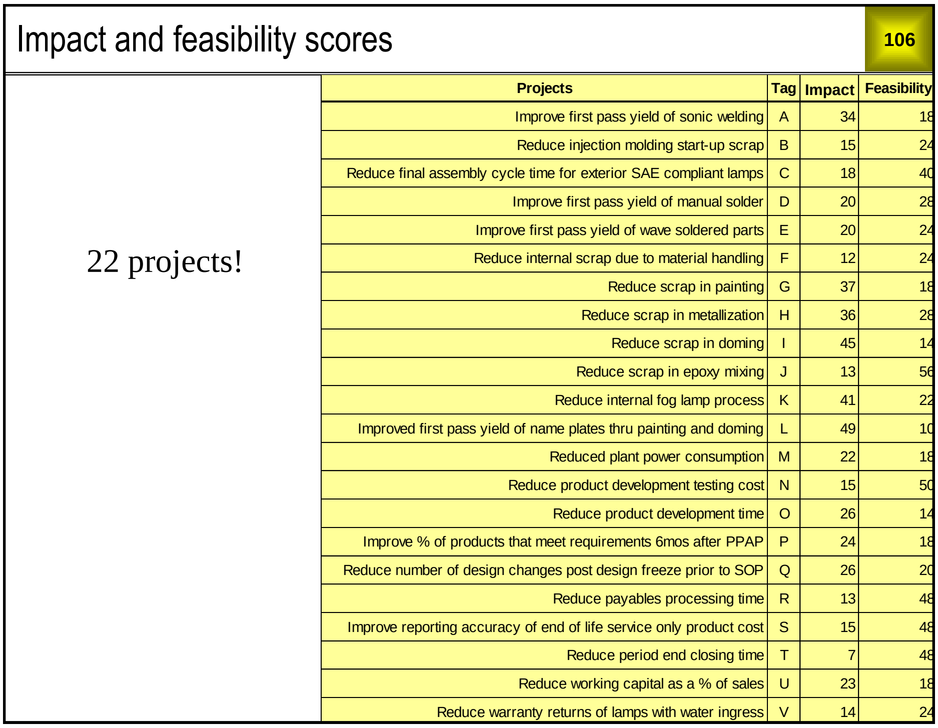
The answer to this question can be found by considering the maturity of your organization with respect to continuous improvement. If your organization is solidly committed to continuous improvement, and has been at it long enough to dispel any skepticism in the workforce, you should go with A (greater impact). On the other hand, if your organization has just started its continuous improvement journey, and you want a high probability success to win over the skeptics, you should go with F (greater feasibility).



Student Files \ prioritizing projects - example 2

Worksheet: “Metrics”

KPIs	Relative weights	Project feasibility metrics	Relative weights
Improve cust. satis. w/delivery	2	Process is easy to change	3
Improve cust. satis. w/quality	2	Rapid completion of project	2
Improve cash flow	1	Needed resources available	2
Improve P, Y, E	1	Highly likely to solve the problem	1
Lack of compliance/safety impact	1		
Lack of environmental impact	1		
Reduce other cost	1		
Reduce scrap or rework	1		

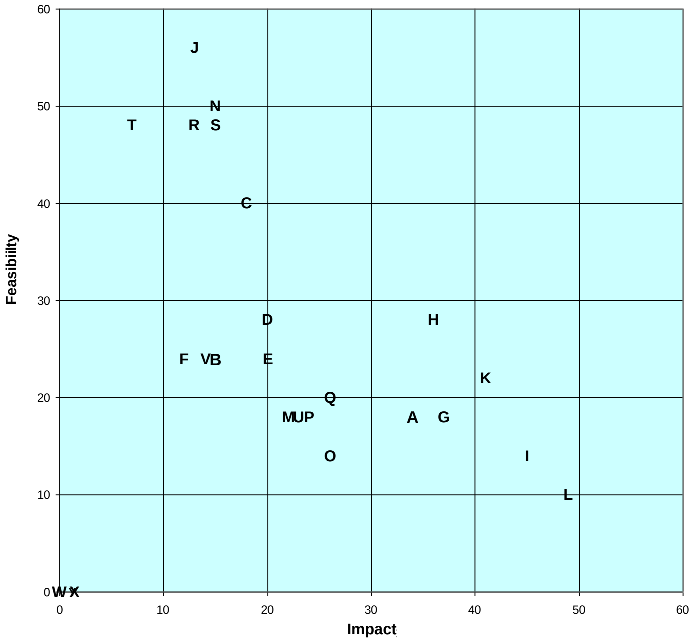


Impact and feasibility scores

22 projects!

Projects	Tag	Impact	Feasibility
Improve first pass yield of sonic welding	A	34	18
Reduce injection molding start-up scrap	B	15	24
Reduce final assembly cycle time for exterior SAE compliant lamps	C	18	40
Improve first pass yield of manual solder	D	20	28
Improve first pass yield of wave soldered parts	E	20	24
Reduce internal scrap due to material handling	F	12	24
Reduce scrap in painting	G	37	18
Reduce scrap in metallization	H	36	28
Reduce scrap in doming	I	45	14
Reduce scrap in epoxy mixing	J	13	56
Reduce internal fog lamp process	K	41	22
Improved first pass yield of name plates thru painting and doming	L	49	10
Reduced plant power consumption	M	22	18
Reduce product development testing cost	N	15	50
Reduce product development time	O	26	14
Improve % of products that meet requirements 6mos after PPAP	P	24	18
Reduce number of design changes post design freeze prior to SOP	Q	26	20
Reduce payables processing time	R	13	48
Improve reporting accuracy of end of life service only product cost	S	15	48
Reduce period end closing time	T	7	48
Reduce working capital as a % of sales	U	23	18
Reduce warranty returns of lamps with water ingress	V	14	24

Impact-feasibility plot



Impact-feasibility plot (cont'd)

- Nothing in the "sweet spot"
- Instead, an "efficient frontier" running from project J down to project L
- This company had been at it for a while, so they chose project L

Exercise 8.1

Open *Student Files* → *prioritizing projects –exercise*. Use your knowledge and experience to do the following tasks.

a) If the weights for the given KPIs and feasibility metrics don't fit your company, feel free to change them.

b) Rate the projects with respect to impact

c) Rate the projects with respect to feasibility.

d) Use the impact–feasibility plot to determine which of these projects your company would give top priority.

Exercise 8.2

This is "homework" to be done as a group activity involving Black Belt candidates and individuals likely to serve as Champions. It could also include other stakeholders. Do (a) and (b) first. Do (c) and (d) later in a separate session.

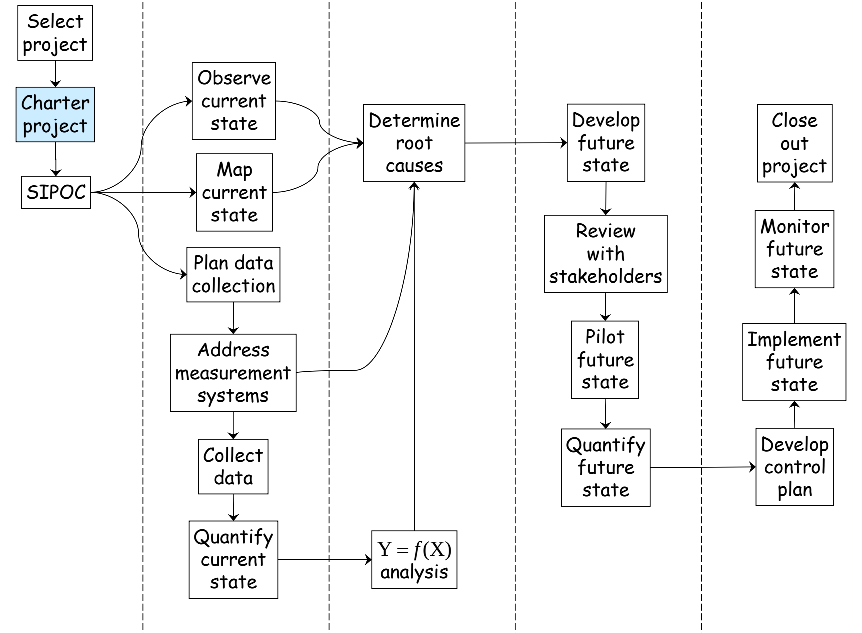
(a) Identify KPIs likely to be used by your organization to prioritize improvement projects.

(b) Identify feasibility metrics likely to be used by your organization to prioritize improvement projects.

(c) Compile a list of candidate improvement projects.

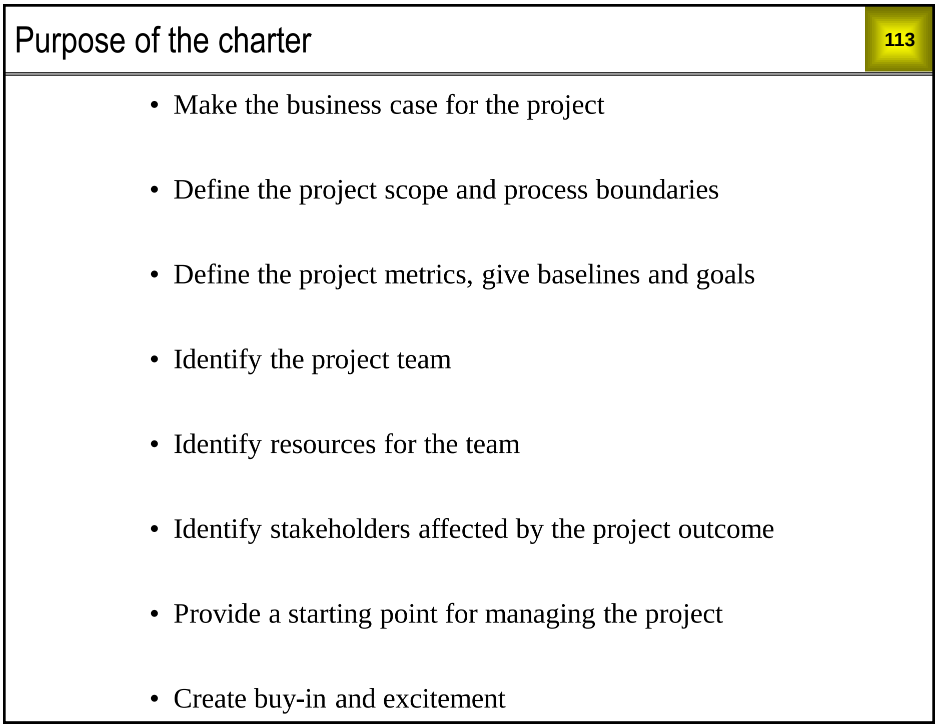
(d) Use the project prioritizer to rank these projects.

9 Chartering LSS Projects



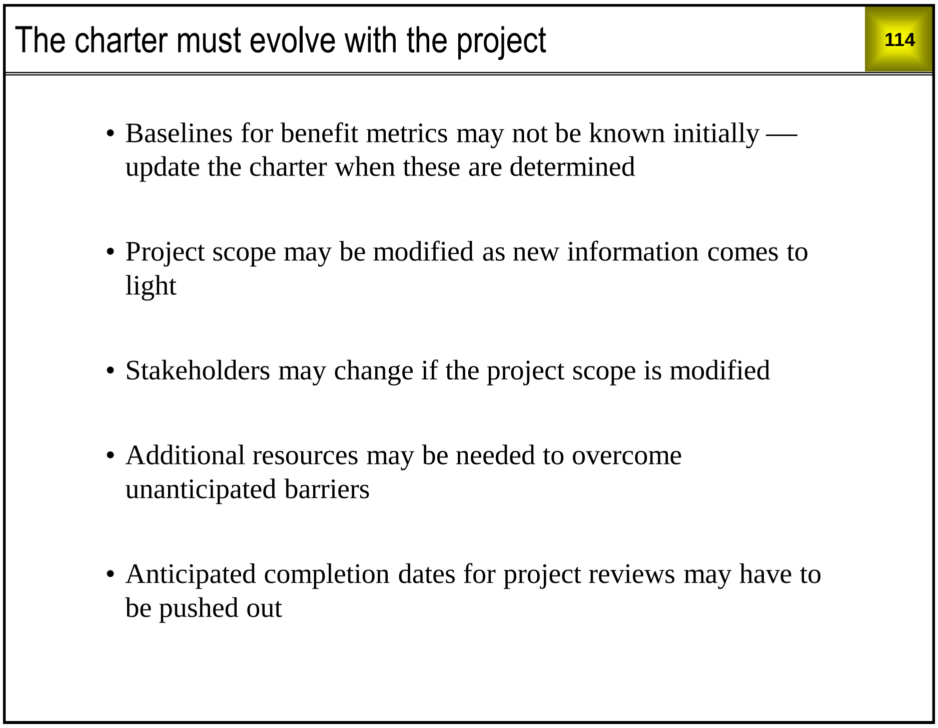
Elements of a project charter

- Project title
- Problem and goal statements
- Value stream scope
- Workflow scope
- Constraints, concerns, assumptions
- Primary project metrics, baseline values & goals, KPIs affected
- Secondary (“do no harm”) metrics, baseline values
- Team members and roles
- Resources and roles
- Stakeholders and their connection to the project
- Start and project review dates



Purpose of the charter

- Make the business case for the project
- Define the project scope and process boundaries
- Define the project metrics, give baselines and goals
- Identify the project team
- Identify resources for the team
- Identify stakeholders affected by the project outcome
- Provide a starting point for managing the project
- Create buy-in and excitement



The charter must evolve with the project

- Baselines for benefit metrics may not be known initially — update the charter when these are determined
- Project scope may be modified as new information comes to light
- Stakeholders may change if the project scope is modified
- Additional resources may be needed to overcome unanticipated barriers
- Anticipated completion dates for project reviews may have to be pushed out

Problem statement

- Describes the current situation in objective terms
- Does not suggest or imply solutions
- Locates the problem in time
- Can include baseline values of project metrics
- Gives enough information that people outside the team can understand what the project is about

What is

Problem statement guidelines

State the effect
Say who and what are affected, and how they are affected. Say what is wrong, not why it is wrong. Avoid "due to" or "because of" statements — they imply solutions.

Be specific
Avoid general terms like "morale," "productivity," "communication" and "training" — they tend to have a different meaning in each person's mind. Use specific, operationally defined terms to narrow the focus to the problem at hand.

Use positive statements
Avoid "lack of" statements (e.g., not enough, we need, we should). Negative statements imply solutions. Do not state a problem as a question — this implies that the answer to the question is the solution.

Quantify the problem
Say how much, how often, when, where. Use project metrics.

Focus on the "gaps"
Compare the current levels of the project metrics to previous levels, expected levels, or desired levels. These will also be presented in the *Project metrics* section.

Critiquing a problem statement

In 2008 there were 15 industrial accidents site wide. Previously, the annual average was 2.5 with at most 7 in a given year. This new level represents a significant decline in employee safety. If it continues, we will see a $200,000 increase in annual costs, and substantially decreased productivity.

Checklist for critiquing a problem statement

☐ Who is affected by the problem?

Employees directly, the company indirectly

☐ What is happening?

Industrial accidents

☐ What are the “gaps”?

2008 had 15, compared to previous average 2.5 and max of 7

☐ What are the consequences of not solving the problem?

Reduced employee safety, $200K cost impact, decreased productivity, OSHA intervention

☐ Where does the problem occur?

Site wide

☐ When does the problem occur?

☐ When did the problem start?

In 2008

Exercise 9.1

Critique this problem statement using the checklist below. Check the boxes for questions that are answered. The purpose of this process is to note which questions are *not* answered.

Customers are dissatisfied with telephone support wait times for calls handled through our call center in Uzbekistan. Our records show an average wait time of 8 minutes. 10% of wait times exceed 20 minutes.

Checklist for critiquing a problem statement

- ☐ What is happening?
- ☐ Who is affected by the problem?
- ☐ What are the “gaps”?
- ☐ What are the consequences of not solving the problem?
- ☐ Where does the problem occur?
- ☐ When does the problem occur?
- ☐ When did the problem start?

Evolution of problem statements

☹	😐	☺
We are unhappy with our customers because they don’t pay our invoices on time.	15% invoices submitted to customers are paid more than 60 days late.	20% of invoices submitted to Customer X last year were paid more than 60 days late. This compares to 5% for our other customers.
Due to lack of training in the ER, patients are waiting too long.	The average wait time for ER patients has increased from 1 hour to 2 hours.	In the last 6 months, the average wait time for ER patients during peak hours has increased from 2 hours to 4 hours.

Evolution of problem statements (cont’d)

☹	😐	☺
Regional account managers submit RFQs to business units on behalf of customers. The account managers say our customers are voicing dissatisfaction with our long quotation turnaround times (TATs). The business units don’t really think there is a problem. If there is a problem, it is most likely caused by the account managers.	Regional account managers submit RFQs to business units on behalf of customers. The expectation is to turn quotes within 3 days. According to the account managers, this expectation is not being met in many cases. This is causing customer dissatisfaction and lost orders.	Regional account managers submit RFQs to business units on behalf of customers. The expectation is to turn quotes in 3 days. Over the past 17 months, 27% have exceeded 3 days. The TATs have ranged from 1 to 29 days, with an average of 2.8 days. We suspect that long TATs are at least partially responsible for lost orders. (*Student Files \ quotation process charter*)

Student Files \ tool development charter

As our business has grown over the years, our tool development process has become a major problem. The primary customer complaint is that our order-to-sell time is too long. This is caused primarily by large numbers of tool rework cycles. Over the past year, the number of reworks per tool ranged from 0 to 18. The order-to-sell time ranged from 3 to 57 days. The rework cost per tool ranged from 0 to $32,400. We cannot compete on price with our Chinese competitors, so our only hope is to compete on quality and lead time.

A secondary problem is that many of the tools released to manufacturing from the current testing process require slow line speeds and high material weight.

Student Files \ Ti casting charter

"Alpha case" is an oxidation layer commonly found on titanium castings in the as-cast condition. It must be removed by chemical milling. Alpha case is measured by chemical analysis of coupons taken from the castings. The upper specification limit for O_2 is 200 PPM. Over the past six months, post-milling O_2 levels on large titanium castings have gradually trended upward. It has become common practice to send castings back for one or more extra chemical mills to bring the O_2 below 200. Each extra cycle reduces our profit margin by $TBD and adds TBD days to the lead time.

In the past two months, repeated chemical milling has failed to solve the O_2 problem for increasing numbers of castings. Instead, these castings are scrapped for dimensional nonconformance. This has resulted in scrap costs of about $400,000 per week, and has severely hindered our ability to meet delivery schedules.

Exercise 9.2

(a) Write a problem statement for the project you and your team currently have in mind. Leave blanks for metrics, as needed.

(b) Share your problem statement with another team.

(c) Write a critique of the problem statement you receive from another team.

(d) Share your critique with the other team and the class. (Start by saying something positive.)

(e) Revise your problem statement in light of the other team's comments.

Examples of goal statements

- Reduce the number of reworks per tool by 50%.
- Meet the 3-day turn-around-time (TAT) expectation 95% of the time.
- Achieve O_2 level of 200 PPM or less for all castings after first chemical milling.
- Complete all first project reviews within the 10-day expectation.

Project scope: the two dimensions

Value stream scope	Workflow scope
• Which customers?	• Starts with an RFQ from the customer, ends with an approved quote or a request to modify the RFQ.
• Which products?	• Starts with receipt of a CAD drawing from the customer, ends with an approved tool and run conditions released to Manufacturing.
• Which services?	• Starts with ceramic slurry make up, ends with a finished casting.
• Which locations?	• Billing, payment, adjustment, and collection.
• Which suppliers?	• Order processing, fulfillment, and costing.
• Which materials?	

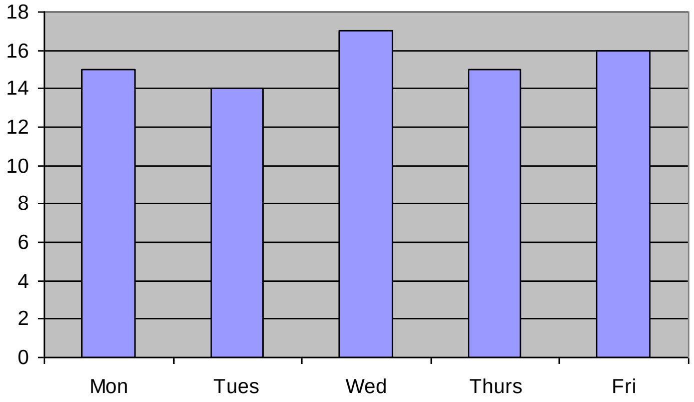
Examples of constraints and concerns

Constraints	Concerns
• Deadlines for project completion	• Several previous attempts to solve this problem were unsuccessful
• Types of solution excluded	• The low average TAT has created the impression there is no problem
• Limitations on availability of resources	• None of the process participants want to be on the team
• Limitations on availability of data	• Our yield is currently 0%, so we must move quickly to solve this problem
• . . .	• . . .

Examples of assumptions

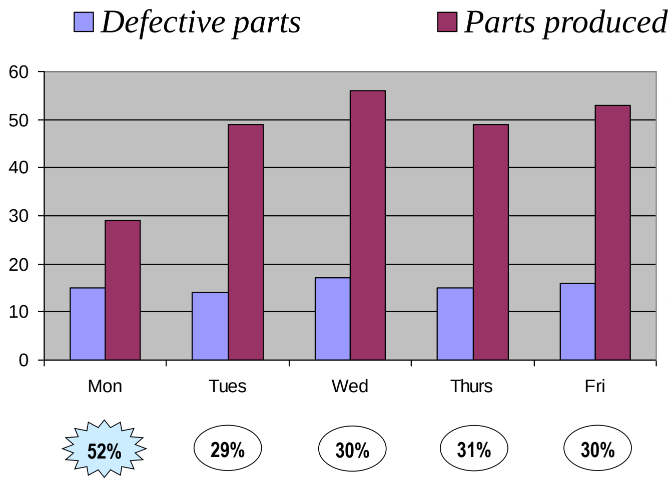
- How often the team will meet
- How long the meetings will be
- Time to be spent on the project by each team member
- Roles and responsibilities of the team members
- In scope solutions will apply to out of scope areas
- We will be able to get some process participants on the team
- We will engage stakeholders and convince them to support the project
- . . .

Project metrics



- Total number of defective parts last month, by day of week
- Can we conclude that Tuesdays are best and Wednesdays are worst?

Project metrics must be normalized!



- Part volume was lower on Mondays
- % Defective is much higher on Mondays
- The problem is worse on Mondays than on other days

Categories of Project Metrics

The three main categories of project metrics are quality, delivery and cost.

- It is recommended that your primary metric be a Quality or Delivery metric, in order to keep your project focused on the process.
- With process improvement, cost will follow.

If your primary metric is:	**Secondary metrics to consider are:**
Quality (defects, scrap, rework, etc.)	Delivery and Cost
Delivery (time to complete, on-time delivery, etc.)	Quality and Cost
Cost	Quality and Delivery

Examples of project metrics

a) Statistics calculated from current state data (must be *normalized*)

Statistic	**Data needed to calculate statistic**
Avg. number of reworks	Numbers of reworks for N tools
Avg. time order to sell	Order to sell times for N tools
PO hit rate	PO (yes or no) for N quotes
% TAT > 3	TAT > 3 (yes or no) for N quotes
Avg. TAT	Turnaround times for N quotes
% O_2 > 200	O_2 > 200 (yes or no) for N castings after first chem. mill
Avg. O_2	O_2 levels for N castings after first chem. mill

↑

Do you see a pattern here?

Project metrics (cont'd)

b) Validated financial calculations are needed to ensure your baseline costs (and benefits achieved) align with the financial methods used by your organization

- Cost of product rework
- Cost of product scrap
- Cost of tool rework
- Cost of lost orders
- Cash flow
- Revenue
- . . .

- Total $$ for a specified time period
- Annualized $$
- $$ as percent of COGS
- $$ as percent of sales
- . . .

Project metrics must be linked to KPIs

- ✓ Customer satisfaction — quality, delivery, service . . .
- ✓ Revenue, cash flow, cost of waste . . .
- ✓ Growth in existing markets
- ✓ New market penetration
- ✓ Lack of adverse safety impact
- ✓ Lack of adverse environmental impact
- ✓ . . .

Exercise 9.3

Define the primary metric for the project you currently have in mind. Describe the data that will be needed to calculate it and give the formula by which it will be calculated.

Exercise 9.4

Define secondary metrics for the project you currently have in mind. Describe the data that will be needed to calculate them, and give the formula by which it will be calculated.

Baselines for project metrics

- Should be calculated from data representative of the current state
- Use a long enough timeframe to get an adequate sample size
- Don’t go back so far that you lose relevance to the current state

Setting goals for project metrics

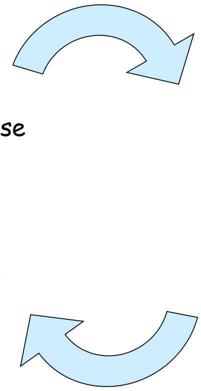
- From benchmarking
- From established business goals
- Performance prior to onset of the problem
- A percentage of the current state value (once this has been established)
- 50% reduction is a common goal*

*In many cases this is feasible and will have substantial business impact

LSS projects must be team projects

- They need to solve difficult problems
- They need expertise in diverse areas
- They require resources controlled by different parts of the organization
- They need internal customer/supplier participation
- They have to consider unintended consequences of proposed solutions
- They must create stakeholder support for proposed solutions

Iteration between team and individual work



Team work

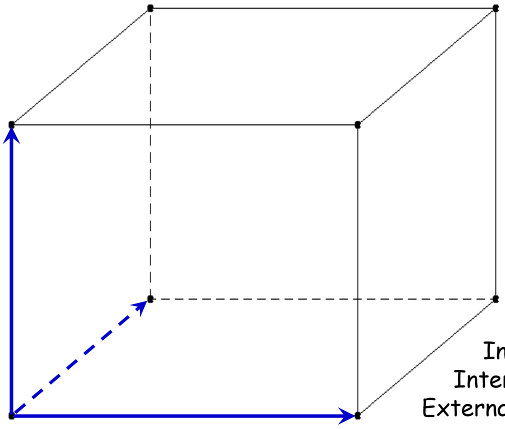
- ✓ Developing shared purpose
- ✓ Sharing information
- ✓ Combining, enhancing, improving, refining ideas

Individual work

- ✓ Following up on action items
- ✓ Gathering information
- ✓ Creating new ideas

Team member knowledge and experience

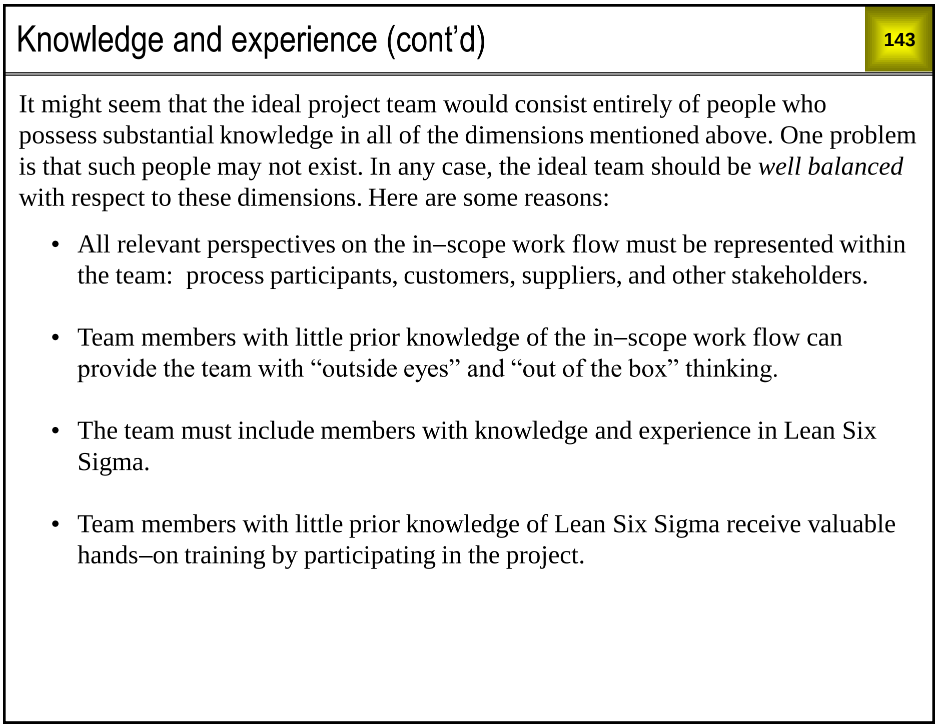
Multiple dimensions must be represented



Lean Six Sigma

External suppliers
Internal suppliers
Internal customers
External customers

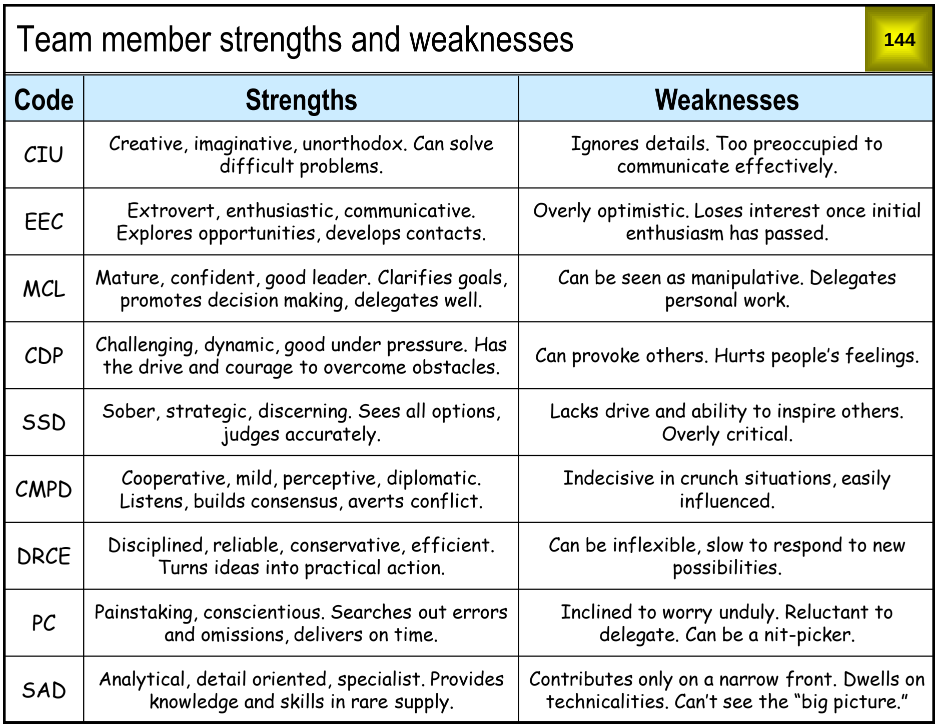
In scope workflow – operational
In scope workflow – technical



Knowledge and experience (cont'd)

It might seem that the ideal project team would consist entirely of people who possess substantial knowledge in all of the dimensions mentioned above. One problem is that such people may not exist. In any case, the ideal team should be *well balanced* with respect to these dimensions. Here are some reasons:

- All relevant perspectives on the in–scope work flow must be represented within the team: process participants, customers, suppliers, and other stakeholders.
- Team members with little prior knowledge of the in–scope work flow can provide the team with "outside eyes" and "out of the box" thinking.
- The team must include members with knowledge and experience in Lean Six Sigma.
- Team members with little prior knowledge of Lean Six Sigma receive valuable hands–on training by participating in the project.



Team member strengths and weaknesses

Code	Strengths	Weaknesses
CIU	Creative, imaginative, unorthodox. Can solve difficult problems.	Ignores details. Too preoccupied to communicate effectively.
EEC	Extrovert, enthusiastic, communicative. Explores opportunities, develops contacts.	Overly optimistic. Loses interest once initial enthusiasm has passed.
MCL	Mature, confident, good leader. Clarifies goals, promotes decision making, delegates well.	Can be seen as manipulative. Delegates personal work.
CDP	Challenging, dynamic, good under pressure. Has the drive and courage to overcome obstacles.	Can provoke others. Hurts people's feelings.
SSD	Sober, strategic, discerning. Sees all options, judges accurately.	Lacks drive and ability to inspire others. Overly critical.
CMPD	Cooperative, mild, perceptive, diplomatic. Listens, builds consensus, averts conflict.	Indecisive in crunch situations, easily influenced.
DRCE	Disciplined, reliable, conservative, efficient. Turns ideas into practical action.	Can be inflexible, slow to respond to new possibilities.
PC	Painstaking, conscientious. Searches out errors and omissions, delivers on time.	Inclined to worry unduly. Reluctant to delegate. Can be a nit-picker.
SAD	Analytical, detail oriented, specialist. Provides knowledge and skills in rare supply.	Contributes only on a narrow front. Dwells on technicalities. Can't see the "big picture."

Strengths and weaknesses (cont’d)

Optimal team composition has been researched from a personality point of view. The table above is adapted from the book *Team Roles at Work* by Meredith Belbin.

Successful teams need members with a variety of different strengths such as those described above. The strengths that a member brings to the team usually come with corresponding weaknesses. Team members make their greatest contributions when they are aware of their strengths and weaknesses. Team leaders are most successful when they are aware of the strengths and weaknesses of every team member.

The pairings of strengths and weaknesses shown above are based on statistical correlations. They do do not apply to all individuals. However, most people can find themselves somewhere on each list.

Which strengths do you possess? Which weaknesses?

Resources

People who provide the team with things they need

Master Black Belt

Project champion

Process owner

Facilities

Finance

HR

IT

.

.

.

Stakeholders

People with a vested interest in the project or its outcome

- May control critical resources
- May have concerns with proposed changes
- May have approval authority over proposed changes
- May own the in scope process
- Team must engage stakeholders to get support for the project

---

Stakeholder analysis

Student Files \ stakeholder analysis example

	1	2	3	4	5
Position with respect to the project	Strong support	Support	Indifference	Resistance	Strong resistance
Degree of Influence on the project or its outcome	Very low	Low	Medium	High	Very high
Degree affected by the project or its outcome	Very low	Low	Medium	High	Very high

Stakeholder analysis (cont'd)

Shown here is the *Criteria* sheet in *stakeholder analysis example*.

It is in the best interest of the team to determine the current levels of stakeholder support or resistance, and the levels of support needed for the project to succeed. The more strongly a stakeholder is affected by the project and its outcome, and the greater the influence he/she has on the project and its outcome, the stronger his/her support must be.

For each stakeholder, gather information (tactfully) and evaluate their level of support or resistance. Use this information to rate them with respect to the three criteria shown above.

A stakeholder analysis contains sensitive information and should remain confidential to the core team and champion.

Stakeholder analysis (cont'd)

Criteria →

Stakeholders	Current position w.r.t. project	Needed position w.r.t. project	Gap between current and needed	Degree of influence	Degree affected	Total rating
A	2	2	1	5	2	**20**
B	3	2	2	4	2	**48**
C	3	2	2	3	2	**36**
D	4	2	3	4	3	**144**
E	2	2	1	2	3	**12**
F	3	2	2	3	4	**72**
G	3	3	1	2	3	**18**
H	3	2	2	1	3	**18**
I	1	1	1	1	1	**1**
J	1	1	1	1	1	**1**

Stakeholder analysis (cont’d)

Shown here is the *Stakeholders* sheet in *stakeholder analysis example*.

A form of risk analysis is used to identify the stakeholders most in need of gentle persuasion. Your ratings should be entered into the white cells of the sheet shown above. The column *gap between current needed* is computed from the *current position* and *needed position* columns. For example, if the *current* and *needed* scores are the same, the *gap* is 1 — the lowest (best) possible value. If the *current* score is 5 and the *needed* score is 1, the *gap* is 5 — the largest (worst) possible value.

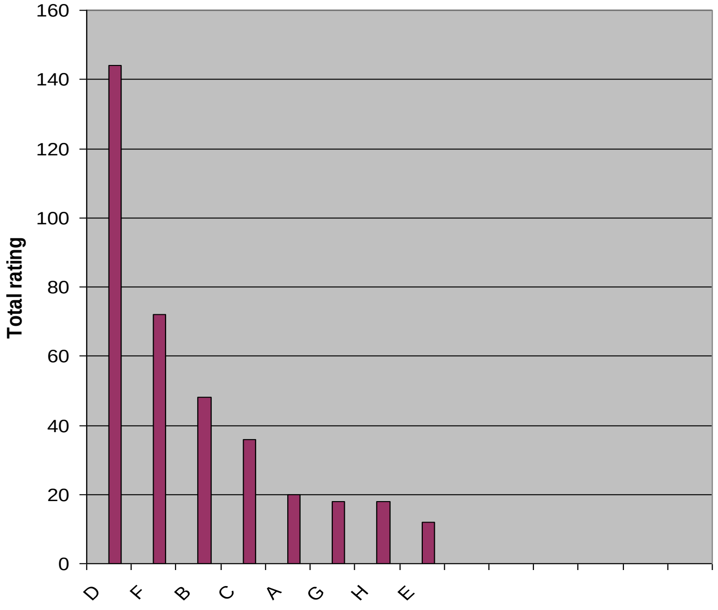
The total rating is the product of all columns, excluding the *needed position* column. The *needed position* is used only to compute the *gap*, the degree of increase in support required.

In the *Pareto* sheet, you should sort the stakeholders in decreasing order by total rating. (You may have to unprotect the sheet to do this.) The resulting chart is shown in the top slide on the next page.

You should focus your efforts to increase levels of support on the critical stakeholders — those with the highest total ratings.

A template for this analysis is in *Student Files \ blank stakeholder analysis*.

Stakeholder analysis (cont’d)



PAINT your way into stakeholder support

P	*Persuade* them by creating a compelling case using data, examples, what competitors are doing, links to strategic goals…
A	*Appeal* to their ideals, values, virtues, visibility, personal ambition…
I	*Involve* them in the project — perhaps not on the core team, but get them in the loop as soon as possible, avoid surprises.
N	*Negotiate* with them. Is there a *quid pro quo* for their support?
T	*Tell* them to cooperate. (This only works if you have the authority. Even so, use as a last resort.)

Notes

Lean Six Sigma Green Belt Training

Supplement:
Stages of Team Development

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Effective Teams

For teams to be effective, the members must work collectively to achieve desired outcomes.

- This does not happen automatically
- Initially, the team is just people assigned to work together
- The ability to work together effectively develops as the team works together. They:
  - get to know each other
  - learn what they can expect from each other
  - figure out how to divide labor and assign tasks
  - determine how to coordinate the work of the team

Stages of Team Development

Team Development is the process of learning to work together effectively.

In 1965, Bruce Tuckman published a widely adopted model of this process*

He proposed a development sequence consisting of four stages:

- Forming
- Storming
- Norming
- Performing

* Tuckman, B. W. (1965). Developmental sequence in small groups. Psychological Bulletin, 63(6), 384–399.

Forming

The Forming Stage is a period of orientation and getting acquainted with each other and the project

- Usually, the team is meeting for the first time
- Team members are polite and positive, and possibly anxious or excited
- Uncertainty is high
- Members strive to get to know each other
- People are looking for leadership and authority
- Questions they may have:
  - What does this team have to offer me?
  - Will I fit in?
  - What’s expected of me and others?

Storming

As the name indicates, the Storming Stage is marked by conflict, competition and polarization

- Energy is put into unproductive activities
- Members may disagree on team goals
- There is resistance to group influence and task requirements
- Subgroups can form around strong personalities or areas of agreement
- Individual personalities emerge
- Members may:
  - question boundaries established in the Forming Stage
  - think they are working harder than others on the team
  - be frustrated by the different working styles of other team members

Norming

The team becomes more cohesive and members have more in-group feeling as they enter the Norming Stage

- Members learn to cooperate and focus on team goals
- They appreciate each other’s strengths
- Consensus is reached on who the leader(s) are and the roles of individual members
- Members ask each other for help and provide constructive feedback
- The new-found harmony can be precarious, easily slide back into storming due to:
  - changes in team membership
  - disagreements re-emerging
  - the uncertainty surrounding new tasks

Performing

In the Performing Stage, the team is well-functioning and mature

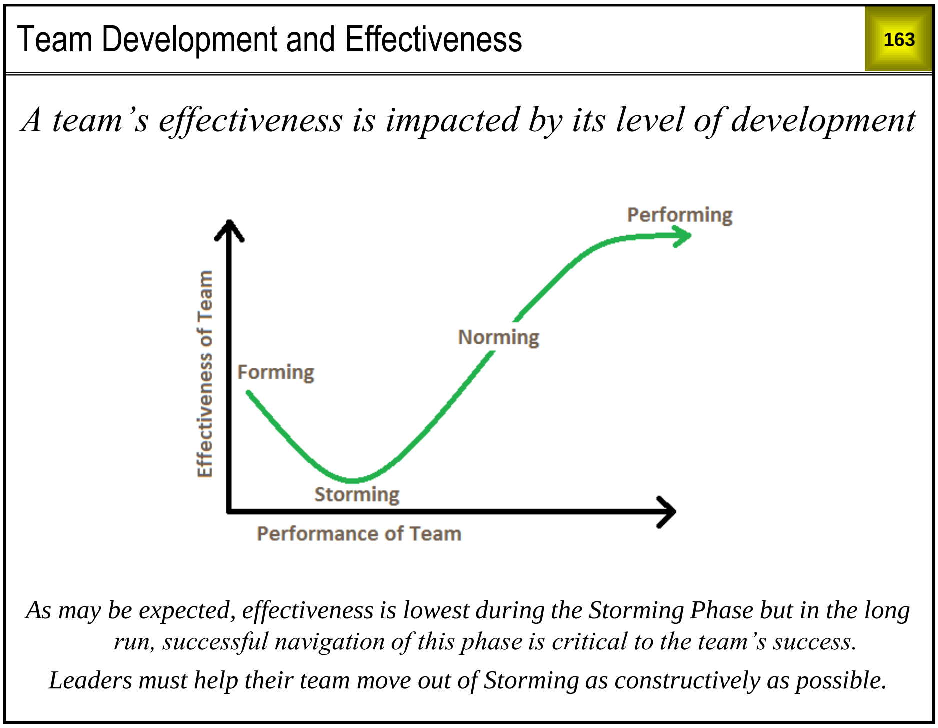
- Roles become flexible and functional
- Structural issues have been resolved
- Cooperation and consensus have been well established
- Problems and conflict are dealt with constructively
- Members are committed to the team's mission
- Group energy is channeled into the task

Adjourning

In 1977, Tuckman and Mary Ann Jensen updated the model, adding Adjourning, noting that "a perfect rhyme could not be found."

The Adjourning Phase involves team dissolution

- Most of the team's goals have been accomplished
- The focus is on wrapping of final tasks and documentation
- Some team members may move off the team, as the workload diminishes
- Working relationships that have developed come to an end
  - The process can be stressful, especially when the dissolution is unplanned or unexpected by the team
  - Some describe this stage as "mourning"
- Ceremonial recognition of the effort and success of the team is recommended!

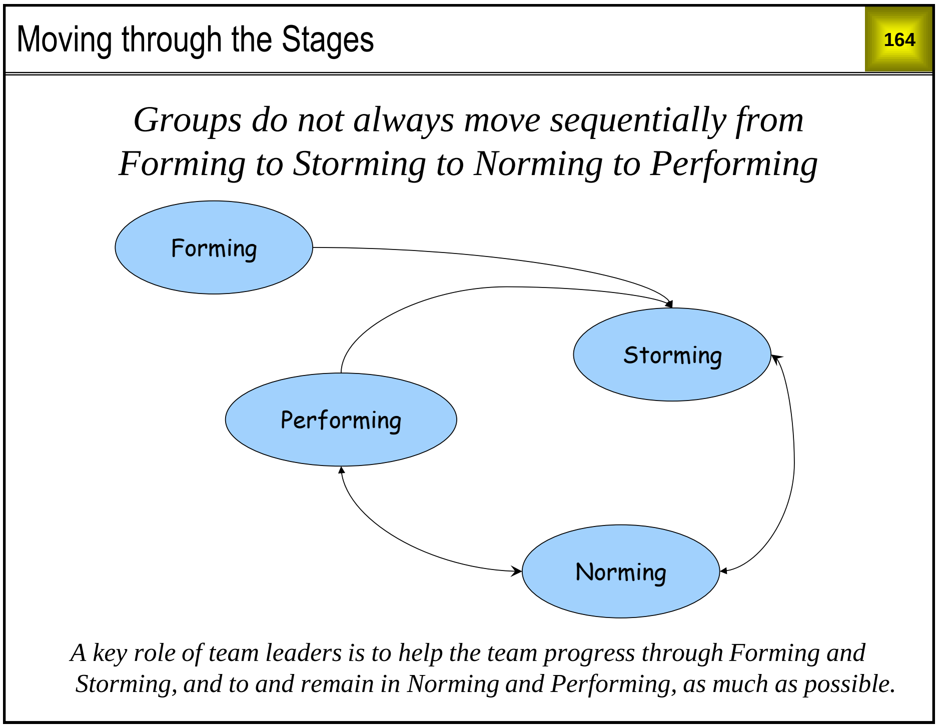


Team Development and Effectiveness

A team's effectiveness is impacted by its level of development

As may be expected, effectiveness is lowest during the Storming Phase but in the long run, successful navigation of this phase is critical to the team's success.

Leaders must help their team move out of Storming as constructively as possible.



Moving through the Stages

Groups do not always move sequentially from Forming to Storming to Norming to Performing

A key role of team leaders is to help the team progress through Forming and Storming, and to and remain in Norming and Performing, as much as possible.

Stages of Team Development Activity:

Your instructor will break you into groups. You will have 15 minutes in your group to complete this activity, for each phase assigned.

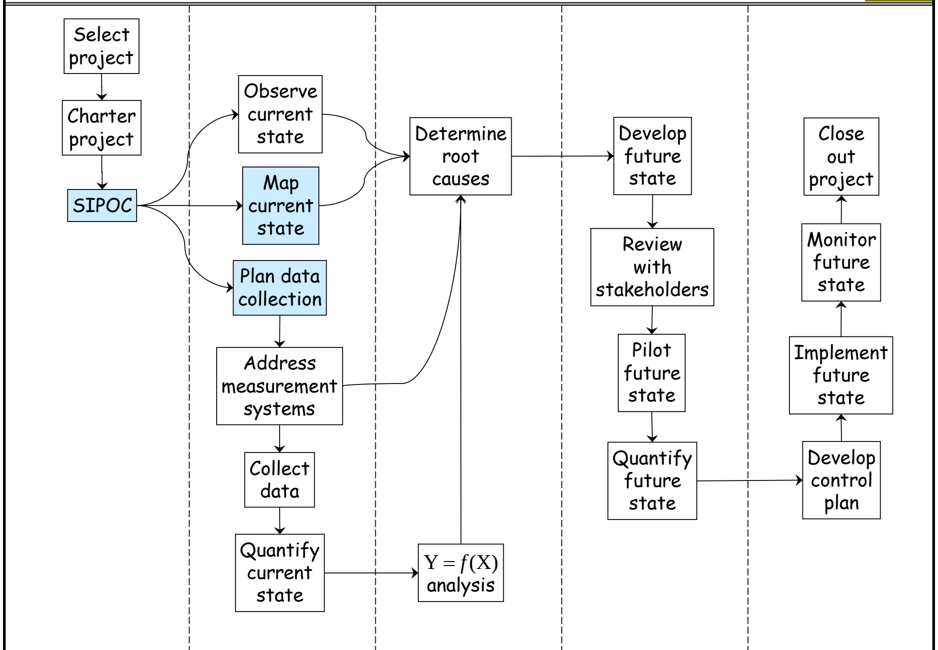
As a group:

- Quickly review the guidelines for brainstorming.
- Brainstorm specific ideas on the question for your assigned phase(s) [~ 10 min.] Consider the question from the team leader perspective.
- List all ideas on a white board or flipchart during the brainstorming session.
- Discuss the brainstormed list and make ideas more specific so they are actionable, as needed. Indicate all "good" ideas. [~ 5 min.]
- Choose someone to report out.
- Present all ideas deemed 'good' by your team.

Stages of Team Development Activity (cont'd)

Assigned Phase	**As the team leader, what specific things can you do in team meetings, or with individual members between meetings, to help your team work together effectively in this phase and . . .**
Forming	. . . move from Forming to Storming?
Storming	. . . move from Storming to Norming?
Norming	. . . move from Norming to Performing?
Performing	. . . remain in Performing?

10 Project Scope and SIPOC



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

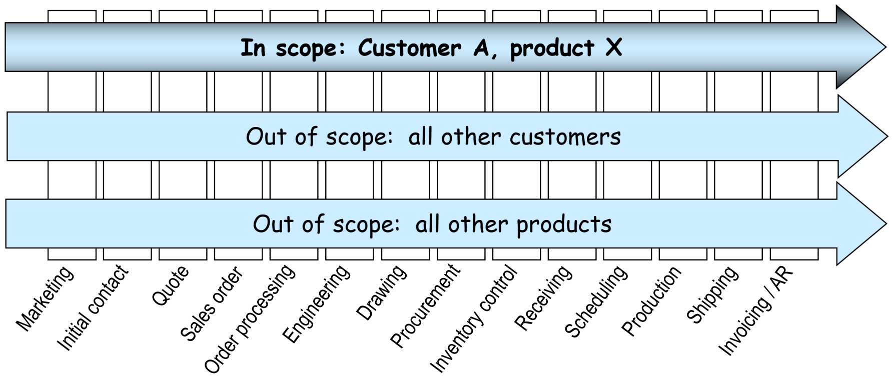
Value stream scope

Defines the project scope in terms of . . .

- ✓ Which customers?
- ✓ Which products?
- ✓ Which locations?
- ✓ Which materials?
- ✓ Which suppliers?
- ✓ . . .

Value stream	All activities needed to provide a specified family of products or services to customers

Value stream scope (cont'd)



Example of value stream scope

Project to reduce cost and lead time of extrusion tool development

In scope

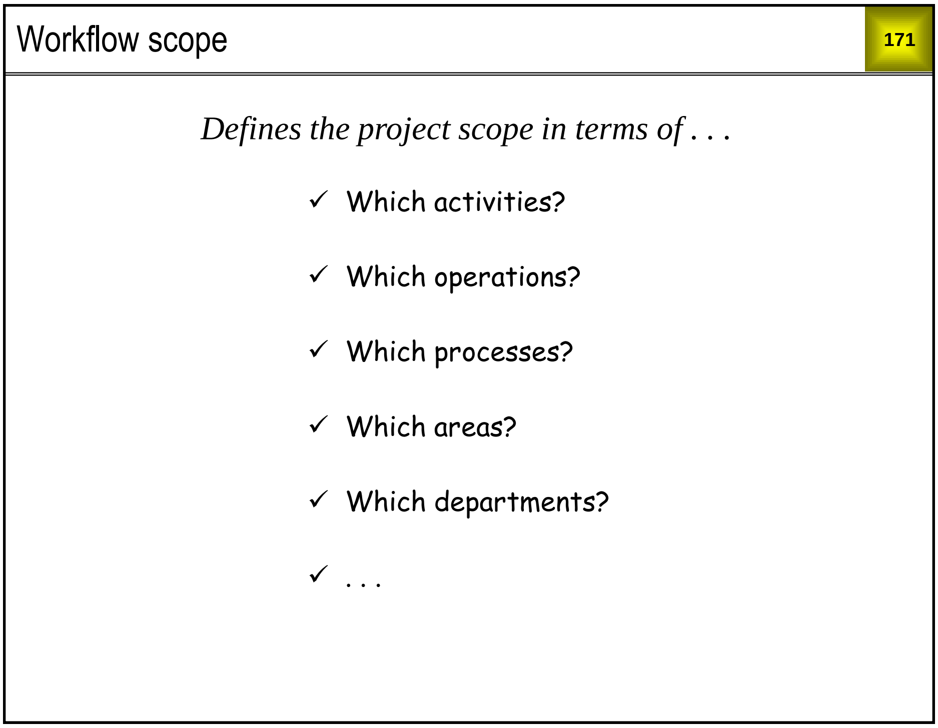
PVC products

Location A

Out of scope

Composite products

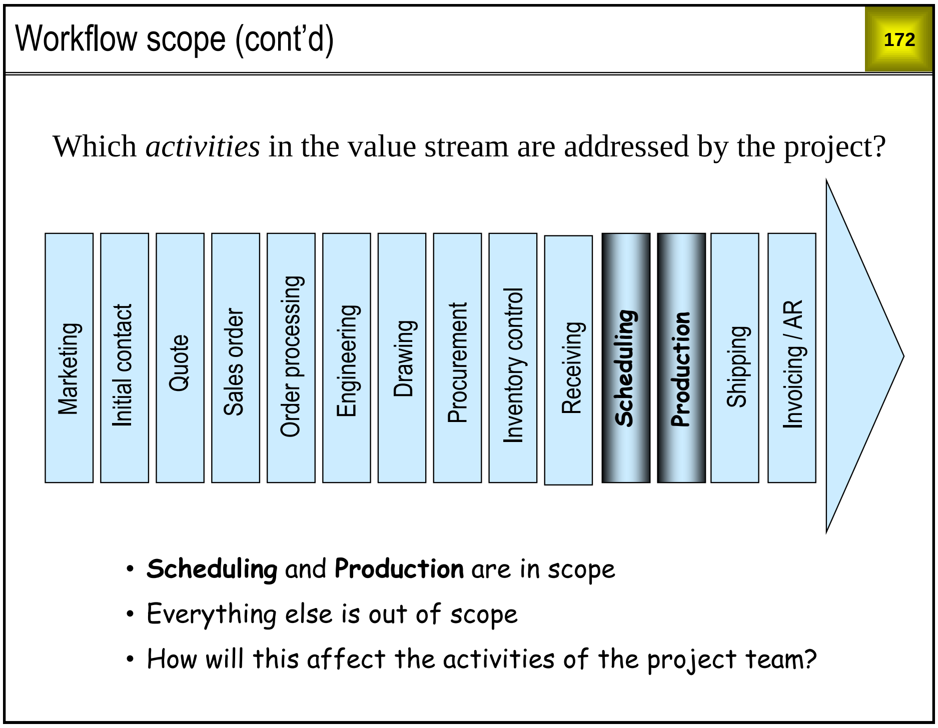
Locations B & C



Workflow scope

Defines the project scope in terms of . . .

- ✓ Which activities?
- ✓ Which operations?
- ✓ Which processes?
- ✓ Which areas?
- ✓ Which departments?
- ✓ . . .



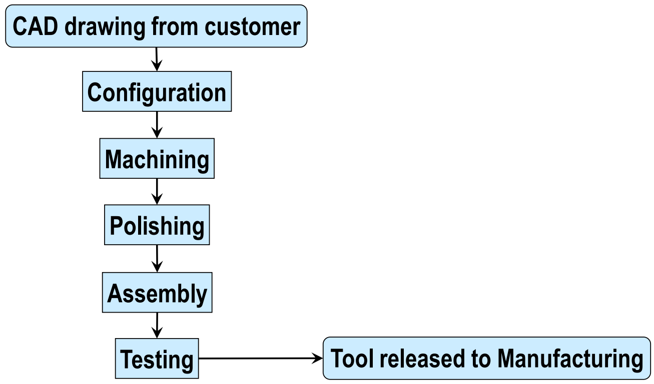
Workflow scope (cont'd)

Which *activities* in the value stream are addressed by the project?

- **Scheduling** and **Production** are in scope
- Everything else is out of scope
- How will this affect the activities of the project team?

Example of workflow scope

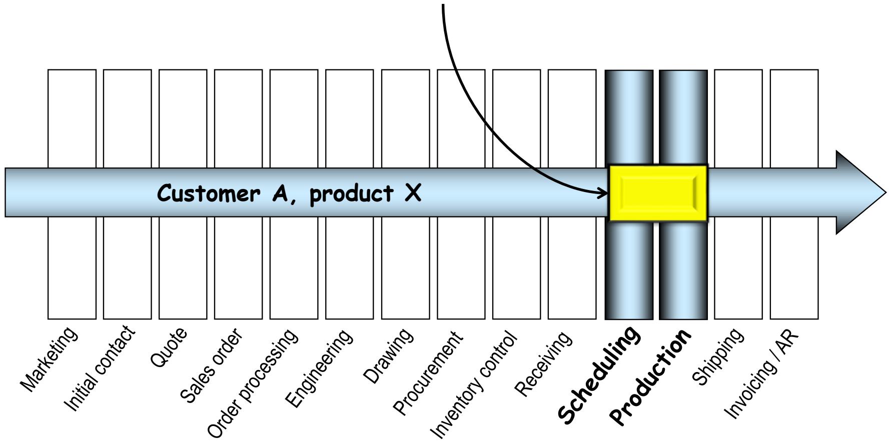
Project to reduce cost and lead time of extrusion tool development



- Manufacturing is out of scope
- The project is not chartered to analyze and improve Manufacturing
- What is the relationship between Manufacturing and the workflow scope?

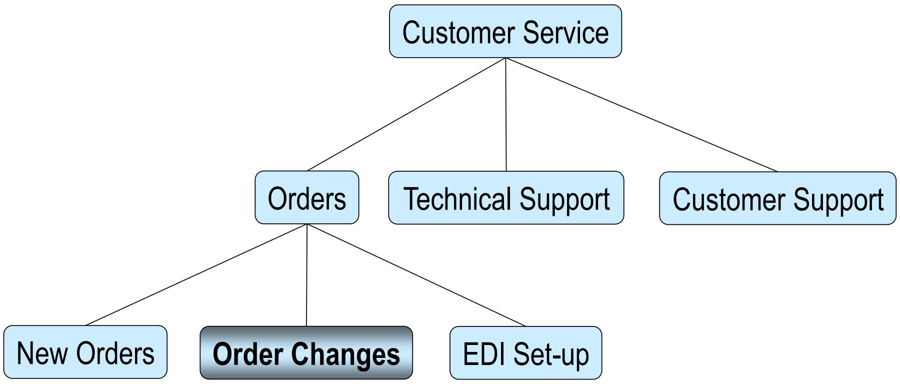
Project scope

The *intersection* of value stream and workflow scope



Another example of value stream scope

The project will address only *order changes*



Customer Service

Orders

Technical Support

Customer Support

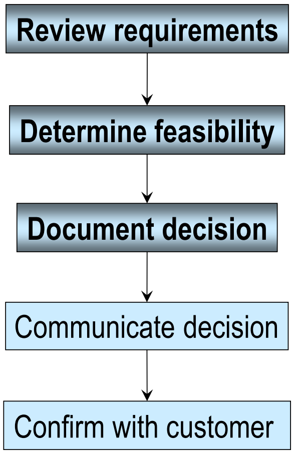
New Orders

Order Changes

EDI Set-up

Another example of workflow scope

The project will address only
the *first three steps* of the
order change process



Review requirements

Determine feasibility

Document decision

Communicate decision

Confirm with customer

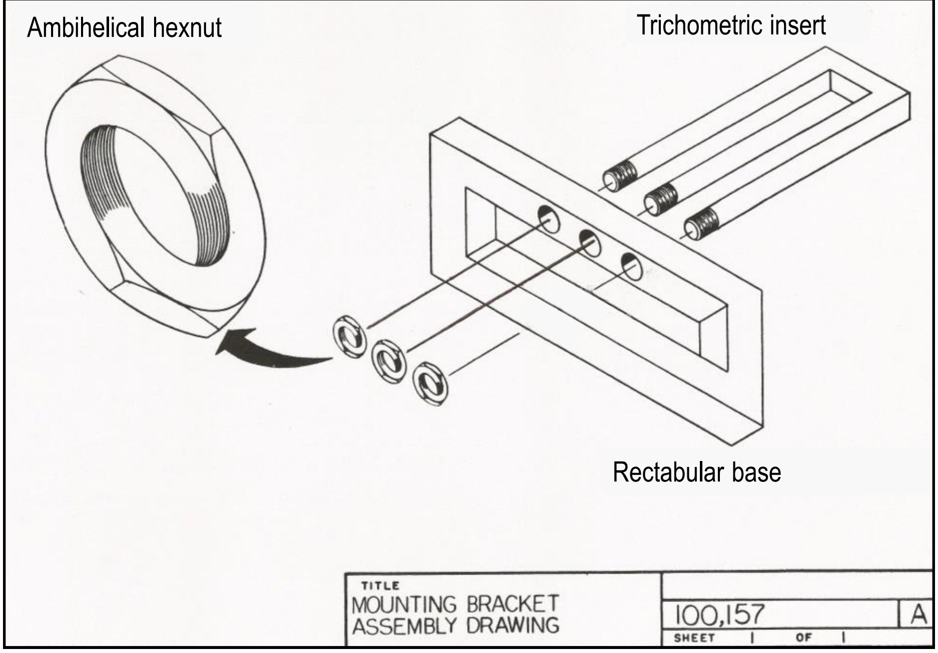
Exercise 10.1

Our company makes prototypes for various types of mounting brackets. These are classified as either standard or non-standard. A project has been launched to reduce the lead time for designing and building prototypes for non-standard brackets (see slide below for a typical example).

What is the value stream scope for this project?

What is the workflow scope for this project?

A non-standard mounting bracket



Introduction to SIPOC

- The project charter frames the project in the *business* space
- SIPOC is a separate document that frames the project in the *process* space:

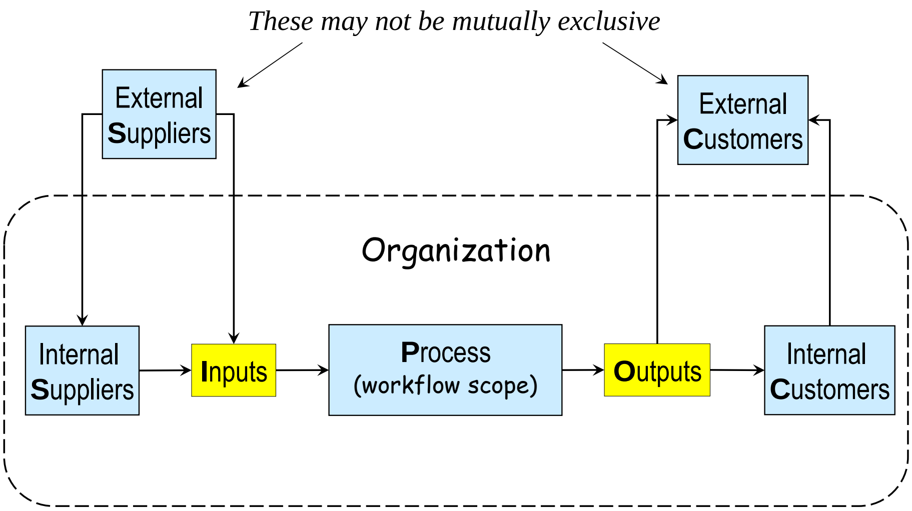
  Suppliers → **I**nputs → **P**rocess → **O**utputs → **C**ustomers
- SIPOC also documents the *data collection* needed for the project
- The five elements of SIPOC are defined on the slide below.
- The logical sequence for reading or creating a SIPOC:

  P → O → C → I → S

SIPOC definitions

5) Suppliers	Entities who provide necessary *inputs* to the workflow scope. Suppliers may be internal or external to the organization.
4) Inputs	Products, services, or information provided to the workflow scope by suppliers.
1) Process	The workflow scope: the activities to be analyzed and improved. A *high-level* description including first step, main intermediate steps, and last step.
2) Outputs	Products, services, or information provided by the workflow scope to customers.
3) Customers	Entities who receive *outputs* from the workflow scope. Customers may be internal or external to the organization.

Graphical presentation of SIPOC



Y variables

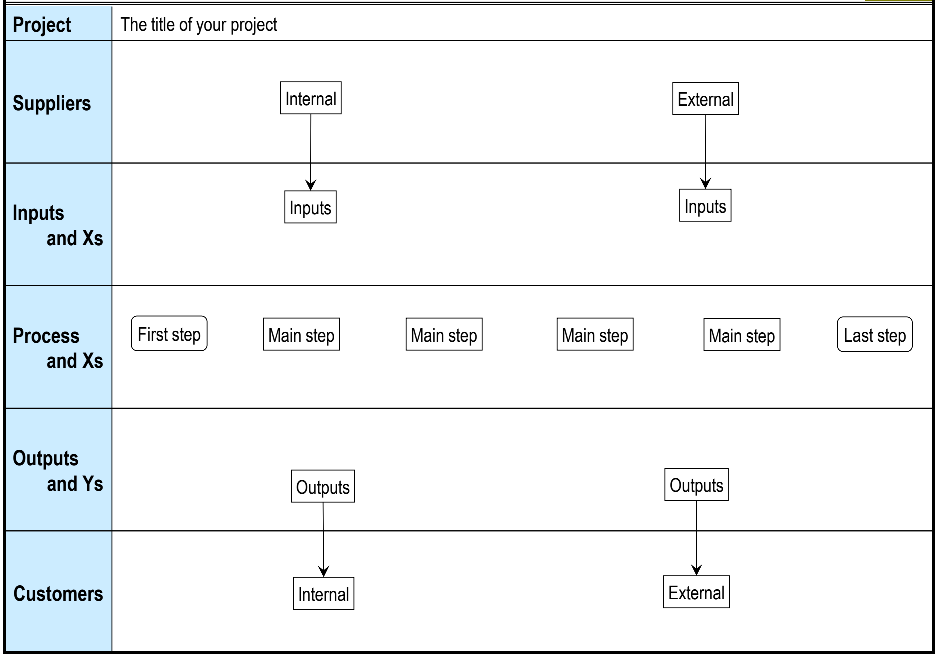
- A *data variable* is measurable characteristic defined for individual parts or transactions (What does "variable" mean?)
- *Y variables* are measurable characteristics of *outputs* from the workflow scope
- They are the data variables from which the statistical **project metrics,** such as average or percent defective, are calculated
- Examples: lead time, pass or fail, quantitative measures of poor quality
- The Y variables are the reason we are doing the project (Why?)

X variables

- Data variables that are possible causes of variation in the Ys are called *X variables*
- Examples: Who, What, Where, When, Which, . . .
- The greater the number of X variables identified, the greater the chance of solving the problem (Why?)
- The Fishbone Diagram will be used in the Measure Phase to identify and document the X variables

The SIPOC will contain only products, services, or information provided to the workflow scope by suppliers.

Blank SIPOC template



Project	The title of your project					
Suppliers	Internal			External		
Inputs and Xs	Inputs			Inputs		
Process and Xs	First step	Main step	Main step	Main step	Main step	Last step
Outputs and Ys	Outputs			Outputs		
Customers	Internal			External		

Blank SIPOC (cont’d)

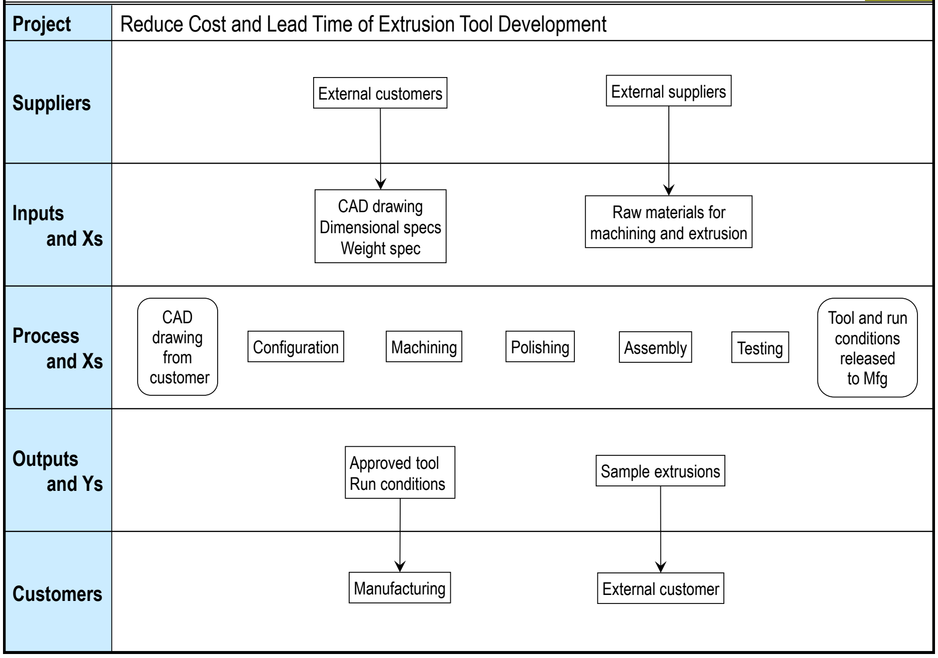
The slide shows a graphical SIPOC template. All you have to do is edit the various boxes and text. You can also add or delete boxes or text.

The following three slides show the graphical SIPOCs for three case studies.

Electronic versions can be found in the *Student Files* folder:

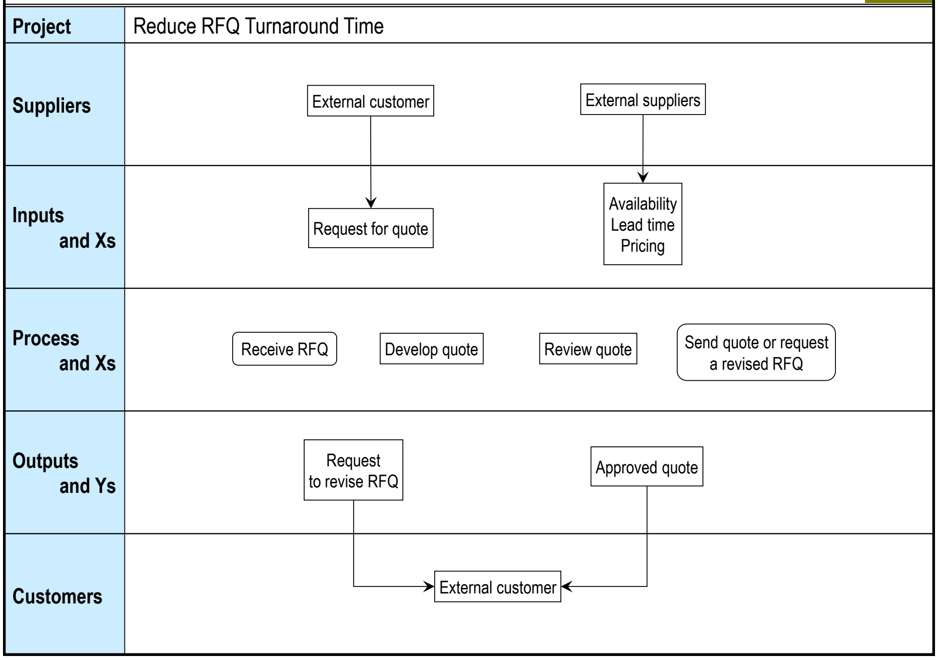
- *blank SIPOC*
- *quotation process SIPOC #1*
- *Ti casting SIPOC #1*
- *tool development SIPOC #1*

SIPOC example 1



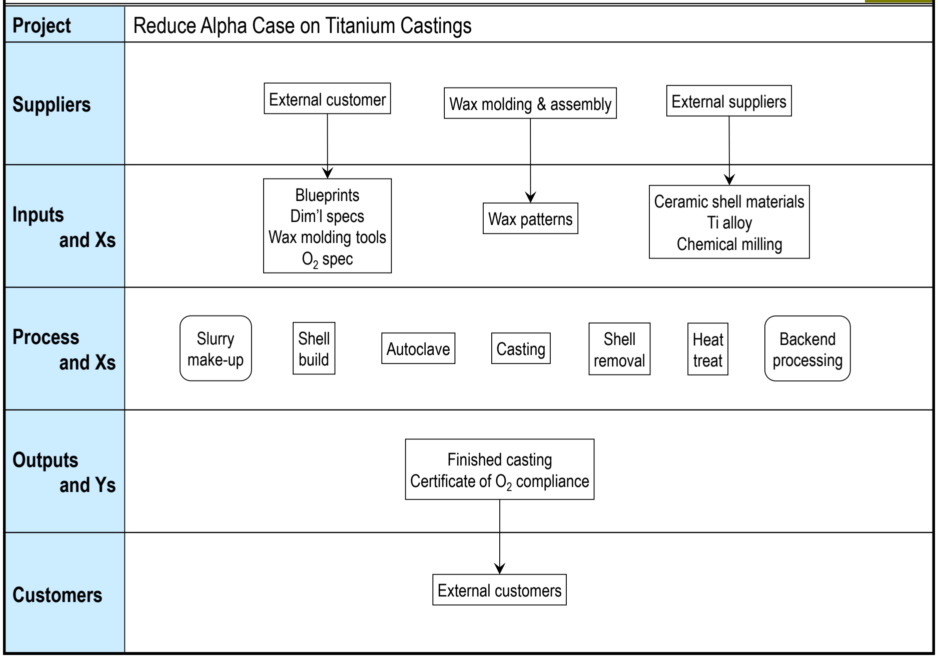
Project	Reduce Cost and Lead Time of Extrusion Tool Development
Suppliers	External customers External suppliers
Inputs and Xs	CAD drawing Dimensional specs Weight spec Raw materials for machining and extrusion
Process and Xs	CAD drawing from customer Configuration Machining Polishing Assembly Testing Tool and run conditions released to Mfg
Outputs and Ys	Approved tool Run conditions Sample extrusions
Customers	Manufacturing External customer

SIPOC example 2



Project	Reduce RFQ Turnaround Time
Suppliers	External customer External suppliers
Inputs and Xs	Request for quote Availability Lead time Pricing
Process and Xs	Receive RFQ Develop quote Review quote Send quote or request a revised RFQ
Outputs and Ys	Request to revise RFQ Approved quote
Customers	External customer

SIPOC example 3



Project	Reduce Alpha Case on Titanium Castings
Suppliers	External customer Wax molding & assembly External suppliers
Inputs and Xs	Blueprints Dim'l specs Wax molding tools O_2 spec Wax patterns Ceramic shell materials Ti alloy Chemical milling
Process and Xs	Slurry make-up Shell build Autoclave Casting Shell removal Heat treat Backend processing
Outputs and Ys	Finished casting Certificate of O_2 compliance
Customers	External customers

Exercise 10.2

Our company makes prototypes for various types of mounting brackets. The process of designing and building the prototypes is referred to as the Mounting Bracket Development Process (MBDP). A project has been launched to reduce the MBDP lead time for non-standard brackets (see below for an example). For background on the project and process, please refer to the following documents in the *Student Files* folder:

MBDP charter

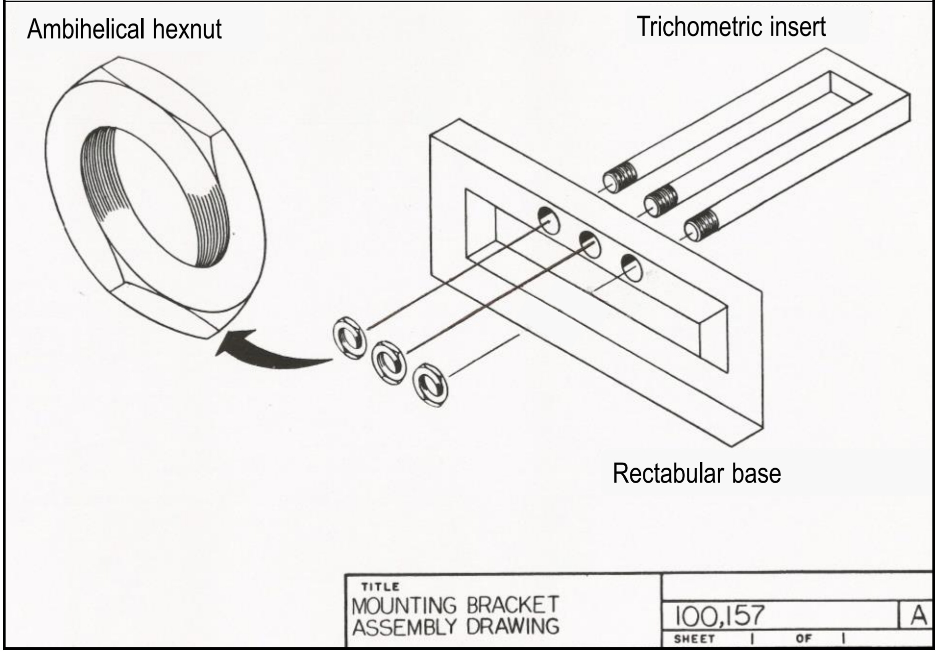
MBDP description for SIPOC

Based on the information in these documents, create a SIPOC for this project using the template in *Student Files \ blank SIPOC*. (Don't worry about X and Y variables. We will not use this feature yet.)

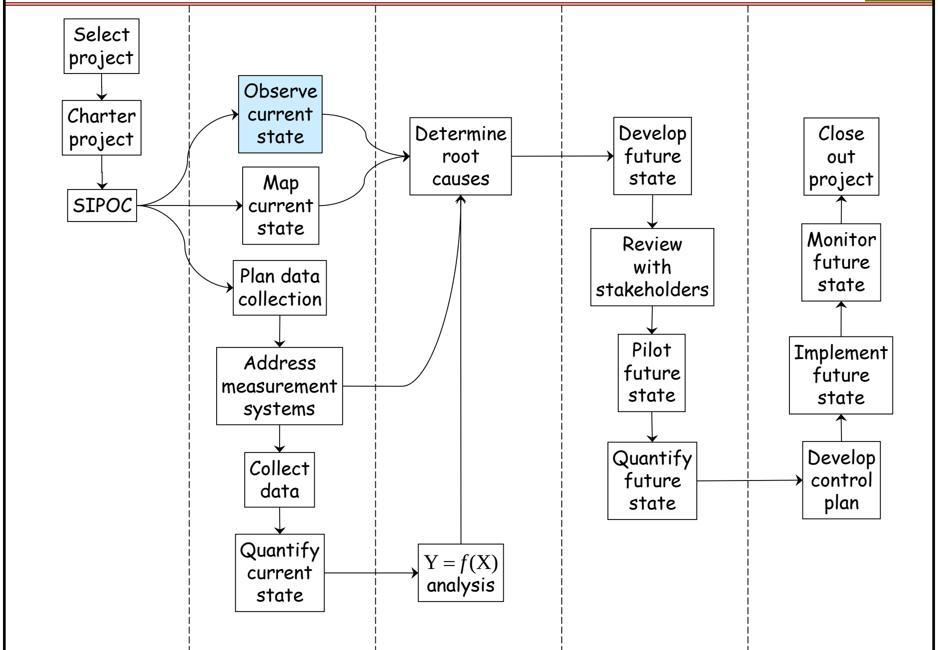
Update the MBDP charter by entering your description of the workflow scope.

Save the charter and your SIPOC.

A non-standard mounting bracket



11 Observing the Current State



Select project
Charter project
SIPOC

Observe current state
Map current state
Plan data collection
Address measurement systems
Collect data
Quantify current state

Determine root causes
$Y = f(X)$ analysis

Develop future state
Review with stakeholders
Pilot future state
Quantify future state

Close out project
Monitor future state
Implement future state
Develop control plan

Guidelines

- The purpose is to improve the process, not to audit work performance
- Workflow observation periods should be scheduled in advance with appropriate supervisors and/or managers
- Workflow participants must be briefed on the project charter
- Participants must have adequate advance notice of observation periods
- Observations should be limited to the value stream and workflow scopes for the project

Guidelines (cont’d)

- Don’t “gang up” on a few participants or process steps— deploy team members effectively to get as many perspectives as possible
- Ask permission to take notes, photographs or videos — this helps team members get the information they need without having to repeat questions later
- Observations should begin with introductions and guided tours, in some cases
- This should be done on all relevant shifts
- Subsequent “unguided” observations are often needed

Typical elements of workflow observation

- Interview workflow participants within the project scope
- Identify data variables and inspection points for inputs provided by internal suppliers
- Interview internal suppliers and customers of the workflow scope
- Identify data variables and inspection points for outputs provided to internal customers
- Identify NVA activities — these may be opportunities for improvement within the project scope
- Confirm or revise process map(s)

Team roles & responsibilities

	Bob	Carol	Ted	Alice	Moe	Larry	Curly
Interview workflow participants	✓			✓			
Observe and record changes to process map		✓			✓		
Identify workflow data variables and inspection points			✓			✓	
Identify data variables and inspection points for workflow inputs				✓			✓
Interview internal customers	✓				✓		
Identify data variables and inspection points for workflow outputs		✓				✓	
Focus on measurement systems			✓				✓

Asking questions

- The *way* you ask questions can affect the usefulness of the answers you get
- *Closed* questions can be answered with "yes" or "no" — if the person is reluctant to talk to you, closed questions will not get you anywhere
- *Open* questions start with words like *what, why, when, where, who, which, how,* etc.
- Open questions are much better for eliciting information, ideas, opinions, etc.

Asking questions (cont'd)

Open questions	Closed questions
"How do you do that?" "Why is it done this way? "How do you think that would help?" "When you say ___ , what do you mean?" "What would be an example of that?" "What are some possible causes of ___ ?" "Why do think that could be a cause?" "Why do you think that happens?"	"Can you see from where you're sitting?" "Can you hear me in the back?" "So, you agree with the schedule change?" "Have we decided to meet on Fridays?" "We covered that earlier, didn't we?"
	• *Closed questions are useful for moving a conversation along* • *Try to phrase them so that the answer you want is "yes"*

Correcting bad listening habits

Concentrate . . . . on what is being said.

Observe . . . . .facial expressions and body language.

Respond . . . . with eyes, voice, gestures, and posture to communicate empathy and understanding.

Reflect . . . . information by paraphrasing.

Elicit . . . . information by asking questions.

Control . . . . the urge to interrupt, judge, or change the subject.

Take . . . . advantage of lags between question and answer to record observations or further questions.

Lean checklist

☐ Are there opportunities for reducing batch size?

☐ Where is the greatest amount of work-in-process (WIP)?

☐ What are the most common do-overs?

☐ Is the physical layout causing excessive movement of people or material?

☐ Is there unnecessary complexity?

☐ Where are the most time-consuming changeovers?

☐ Are there opportunities for mistake proofing?

Lean checklist (cont'd)

☐ Are there serial activities that could be parallel?

☐ Are there separate steps that should be combined into a single step?

☐ Are there single steps that should be split into separate steps?

☐ Are work instructions missing, outdated, or not visible?

☐ Are there problems with availability of equipment or material?

☐ . . .

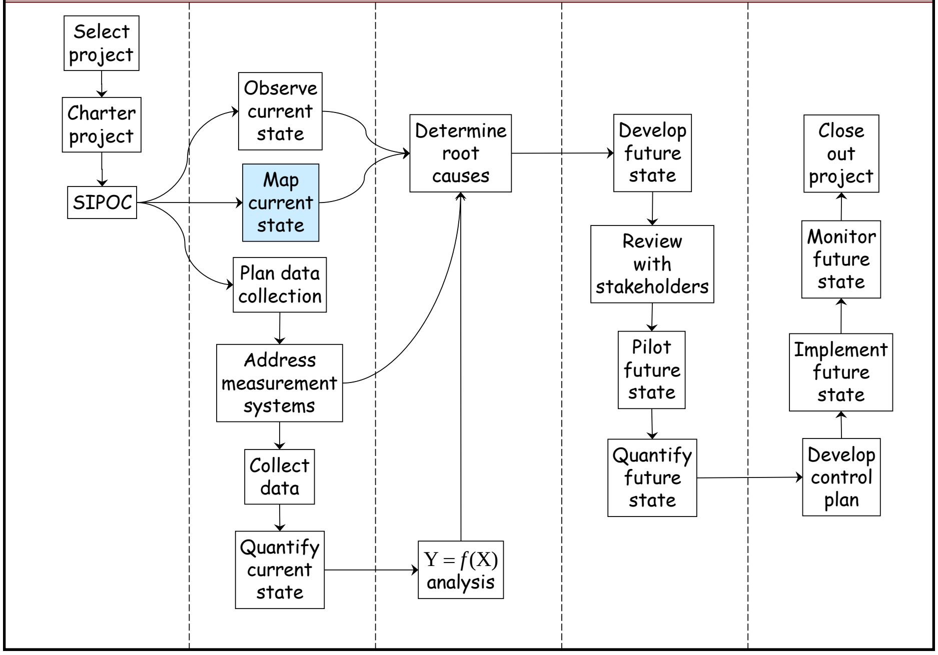
Observation log

- Team members may see possible causes of problems and solutions as soon as they start observing and mapping the current state
- These observations should *not* be publicized until the appropriate point in the project roadmap
- These observations *should* be logged as they arise, preferably in Excel (facilitates categorization and prioritization)
- The possible causes will be reviewed in the *Analyze* phase, along with data analysis results, to determine root causes
- The possible solutions will be reviewed in the *Improve* phase to develop the future state

Observation log (cont'd)

Team member	Date	Location	Possible cause	Possible solution

12 Basic Process Mapping



Basic process mapping (cont'd)

Process mapping is easy to learn and produces useful documentation of the current state. It is also a great team building activity.

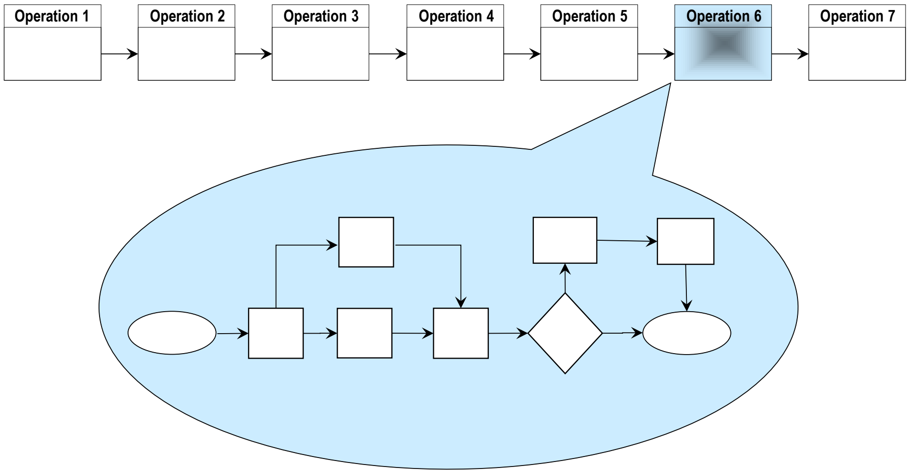
The key to successful application of any mapping technique is to focus on the appropriate *level of activity* for your project. In SIPOC we identify the first, last, and main intermediate steps of the in-scope workflow. This gives you a high-level process map.

A high-level map is a good starting point for more detailed mapping. A basic process map, discussed in this section, shows individual tasks and decision points within the main steps. A cross functional or swimlane maps shows who is responsible for each task and decision. This and other common mapping formats are discussed in the next section.

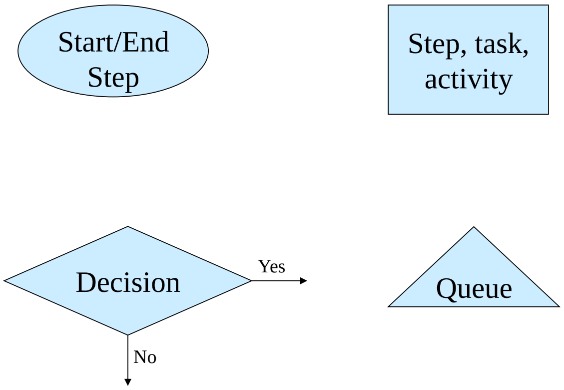
A high-level map is also the usual starting point for value stream mapping (VSM). VSM combines visualization of what is happening with certain forms of data analysis. VSM will be discussed later in the program.

Basic process mapping (cont'd)

Often, we want to create detailed maps for some or all of the main steps given in the SIPOC



Standard (basic) process mapping symbols



Mapping as a team activity

Suspend your disbelief	Map the process the way it really is, not the way you think it should be.
Don't make assumptions	If you don't know what happens at a certain point, or can't agree on what happens, put a question mark there. Then, go ask someone who does know.
Solicit feedback	Ask participants of the in scope workflow, and their internal customers, to review the map for accuracy and clarity.
Document your work	Use mapping software to create an electronic version of the map.

Writing good narrative

✓ Use active voice, not passive voice
    ☹ Order is entered
    ☺ Enter the order

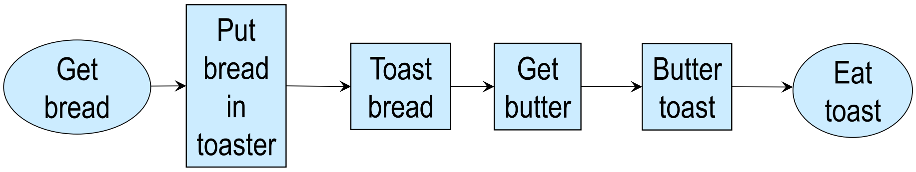
✓ Use verb/object, not name of activity
    ☹ Order Entry
    ☺ Enter the order

✓ Use short sentences with familiar words
    ☹ Twilight's last gleaming
    ☺ Dusk

✓ Use present tense

✓ Use logical, consistent layout

A high-level map for making toast



Get bread

Put bread in toaster

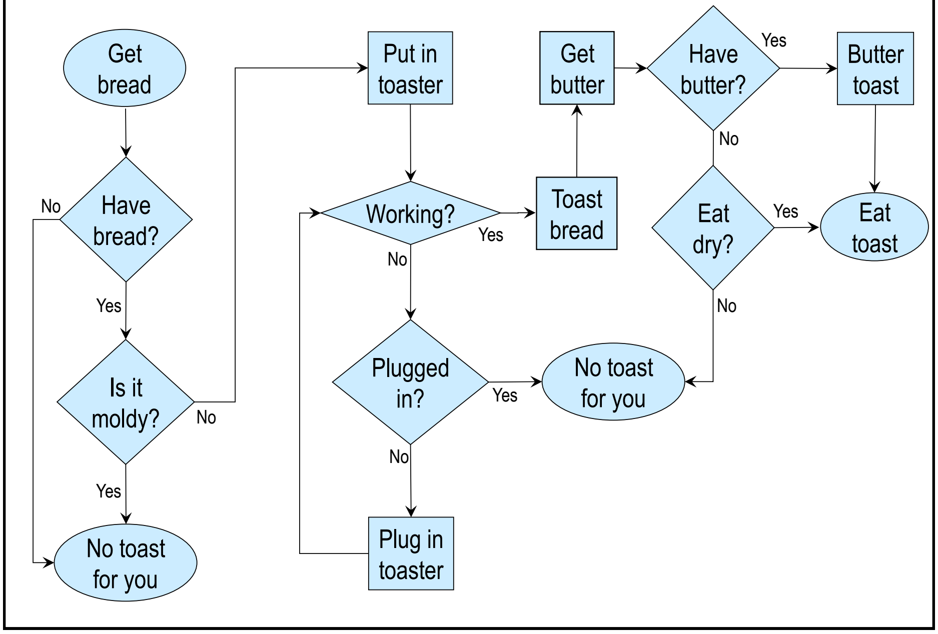
Toast bread

Get butter

Butter toast

Eat toast

Decision steps show what really happens



Get bread

Have bread?

No

Yes

Is it moldy?

No

Yes

No toast for you

Put in toaster

Working?

Yes

No

Toast bread

Plugged in?

Yes

No

No toast for you

Plug in toaster

Get butter

Have butter?

Yes

No

Butter toast

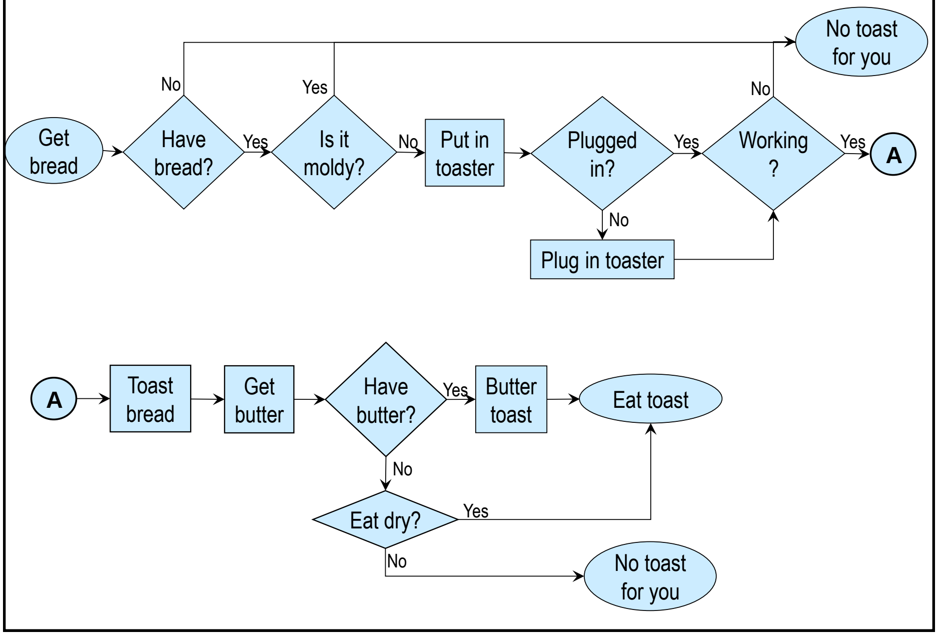
Eat dry?

Yes

No

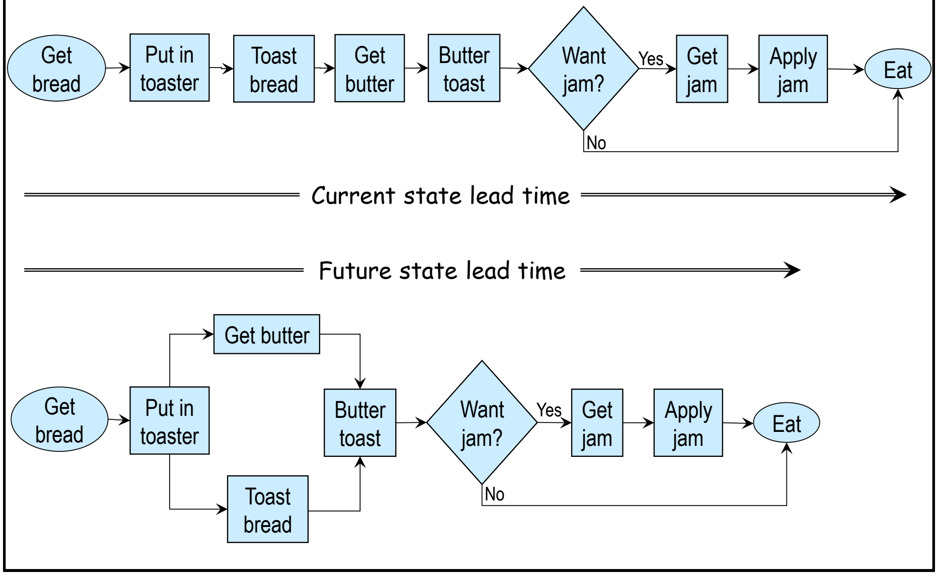
Eat toast

Best practice: follow a qualitative timeline



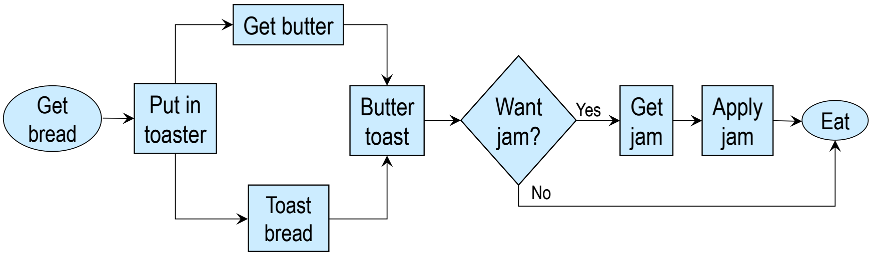
Parallel activities

Common technique for reducing lead time: convert *serial* to *parallel*



Exercise 12.1

How would you modify the toast-making process to further reduce the lead time?



Exercise 12.2

You are to create a process map based on the information given on the slide below. It will be beneficial to work on this in small groups.

This is not *your* process. Someone else is describing *their* process to you. Do not make unwarranted assumptions!

Use a separate sheet of paper to draw your map. Use a qualitative timeline!

Exercise 12.2 (cont'd)

There are two types of material, A and B. The material must be processed before it can be used. There are two steps in this process. For Process 1, the A and B materials must be processed in separate Type 1 machines. If two Type 1 machines are available, load the A material into one machine, the B material into the other, and run the two machines at the same time. If there is only one Type 1 machine available, run the two loads sequentially in that machine.

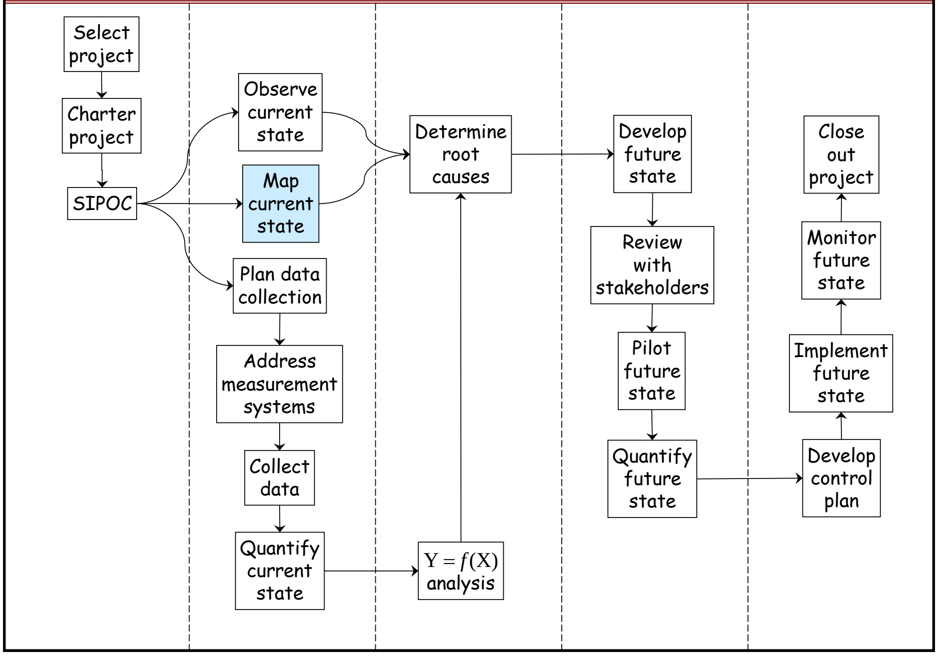
When Process 1 is completed, unload the material, and move on to Process 2. Process 2 requires Type 2 machines. If two Type 2 machines are available, load the A material into one machine, the B material into another, and run the two machines at the same time.

Unlike the Type 1 machines, the A and B material can be processed together in the same Type 2 machine. If there is only one Type 2 machine available, load both the A and B material into that machine for processing. This will take longer than processing the A and B materials in separate machines, but not as long as running two loads sequentially.

When Process 2 is completed, unload the material, separate the A and B materials if necessary, then store them for subsequent use.

Notes

13 Other Common Mapping Formats



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

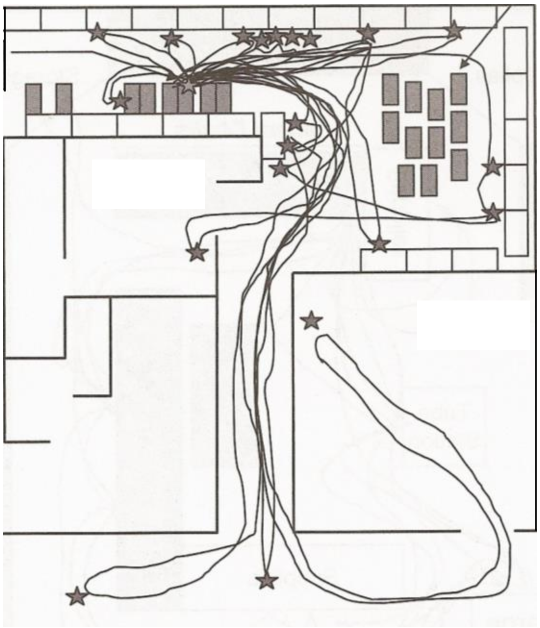
Implement future state

Develop control plan

Other common process mapping formats

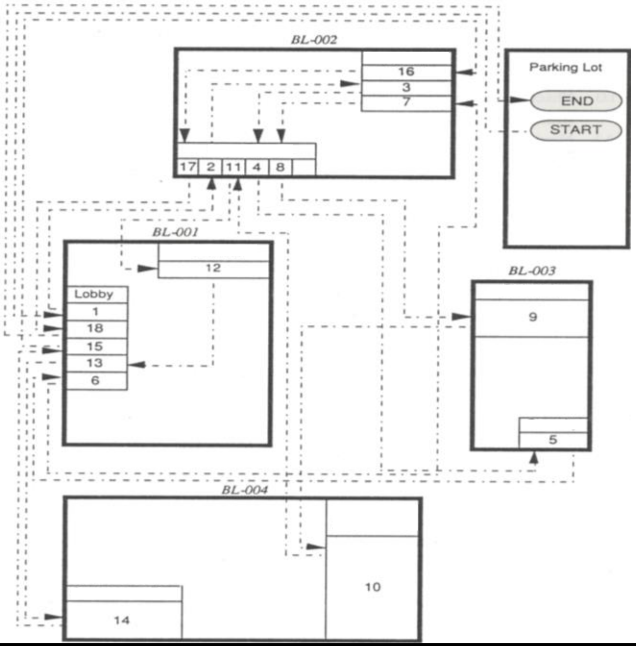
- Geographic (aka Spaghetti) Diagram
- Swimlane Diagram
- Topological Map

Spaghetti Diagram

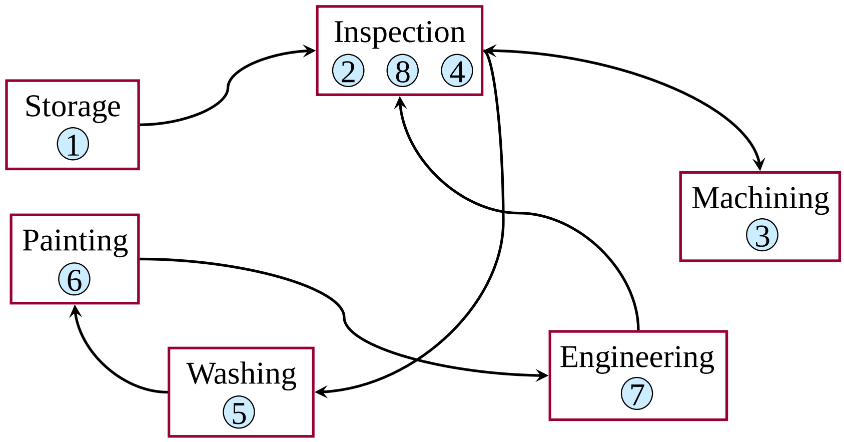


- Most useful in the Analyze Phase
- Requires a floor plan or scale drawing
- Shows typical travel patterns
- Quantify distance travelled
- Also known as a *geographic map*

Large scale spaghetti diagram

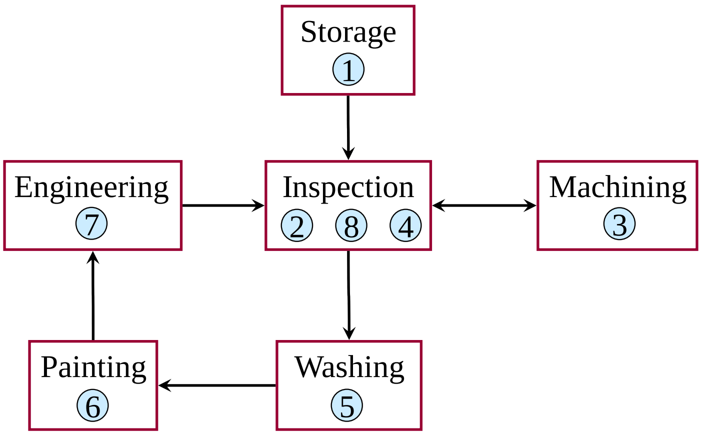


Spaghetti Diagram: current state

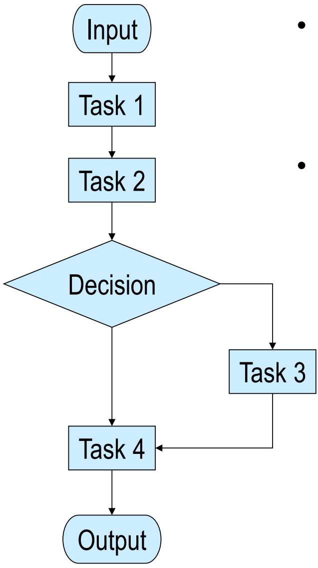


- Should rearrange to minimize transport
- Good opportunity for a Kaizen event

Spaghetti Diagram: future state



Basic process map revisited



- Often it is important to document who is responsible for each activity and decision in a process
- How do we do this?

Basic process map (cont'd)

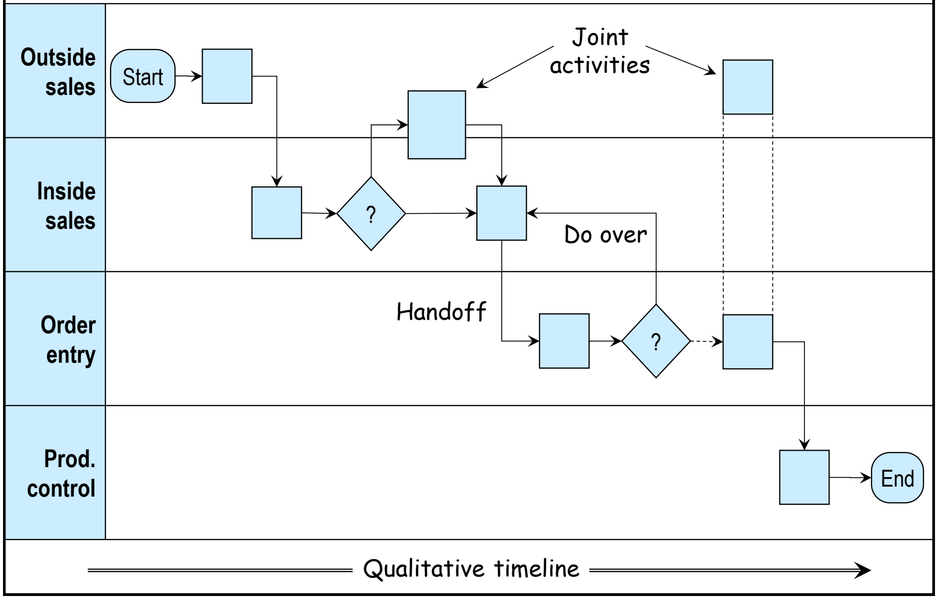
We could make a table like the one shown here . . .

. . . but there is a better way!

	Responsibility
Input	
Task 1	
Task 2	
Decision	
Task 3	
Task 4	
Output	

Swimlane Diagram

Also known as *cross-functional map*



Outside sales

Inside sales

Order entry

Prod. control

Start

Joint activities

?

Do over

Handoff

?

End

Qualitative timeline

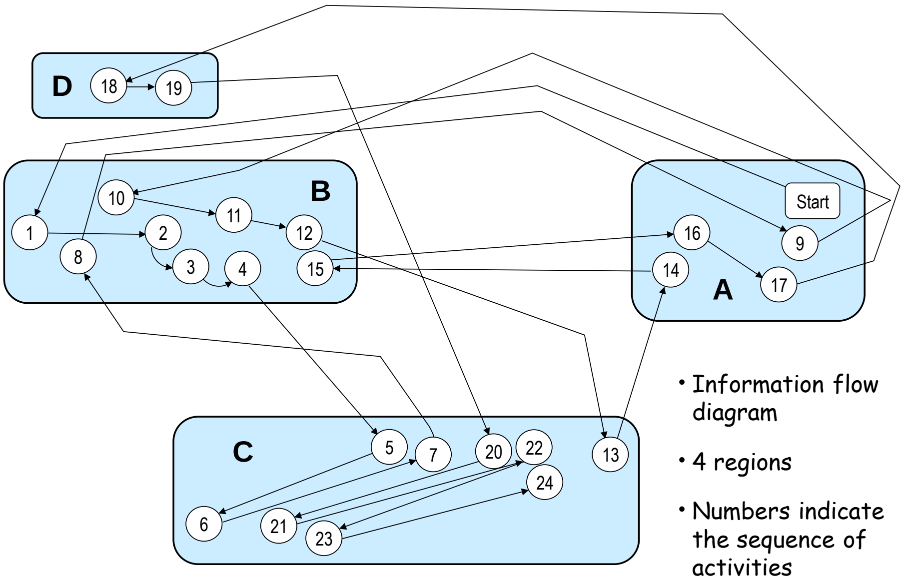
Swimlane Diagram (cont'd)

A swimlane diagram visually portrays the responsibilities for all process activities and decisions. In addition to showing responsibilities, swimlane diagrams are much better than simple maps for identifying opportunities for improvement.

To create a swimlane diagram, first determine all the departments or functions involved in the activities and decisions you want to map. Enter swimlanes for departments or functions from top to bottom in the order they are first called for in the sequence of activities and decisions. Also, you should follow a qualitative timeline in placing activities and decisions on the map.

With this method, the general flow of the activities and decisions will be from top left to bottom right on the map. This usually leads to the simplest and easiest to read depiction of the process.

Topological map



- Information flow diagram
- 4 regions
- Numbers indicate the sequence of activities

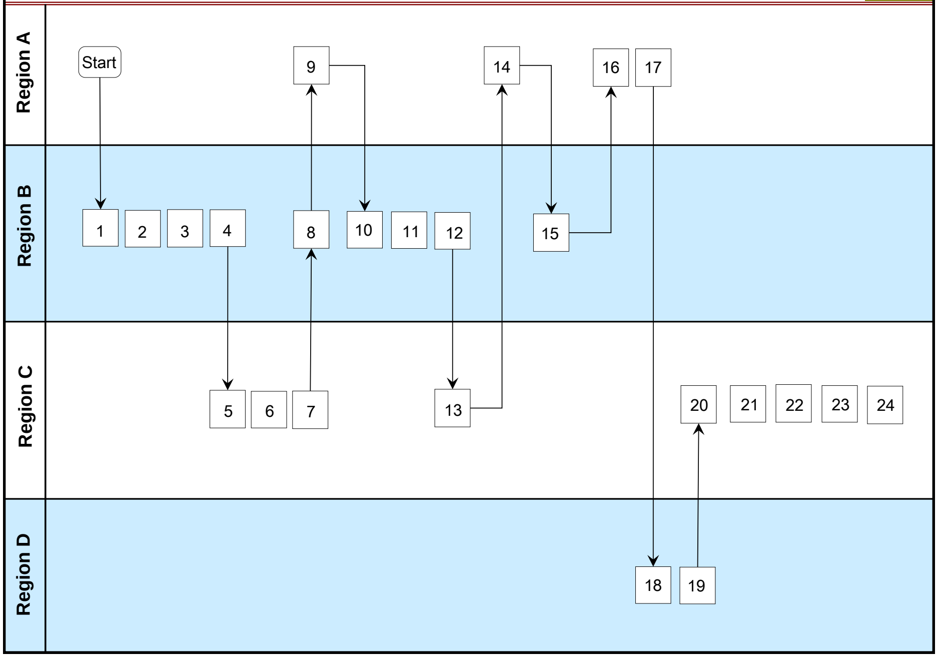
Topological map (cont'd)

topological *adj* **:** concerned with relations between objects abstracted from exact quantitative measurement

A topological map is similar to a spaghetti diagram, but without the geography/scale. It shows connections, but not distances. It may or may not indicate a time or process sequence. The routing diagrams in the London Underground are famous examples of topological maps.

An example of a topological map is shown above. It shows the information flow among several departments, organizations, or regions. It makes no attempt to depict location or distance. The numbers in the circles indicate the process sequence.

Information flow in swimlane format



Swimlane format (cont'd)

- Swimlane diagram of the same information flow
- Shows the back and forth among regions
- Gives a visual representation of the time sequence
- Easy to follow

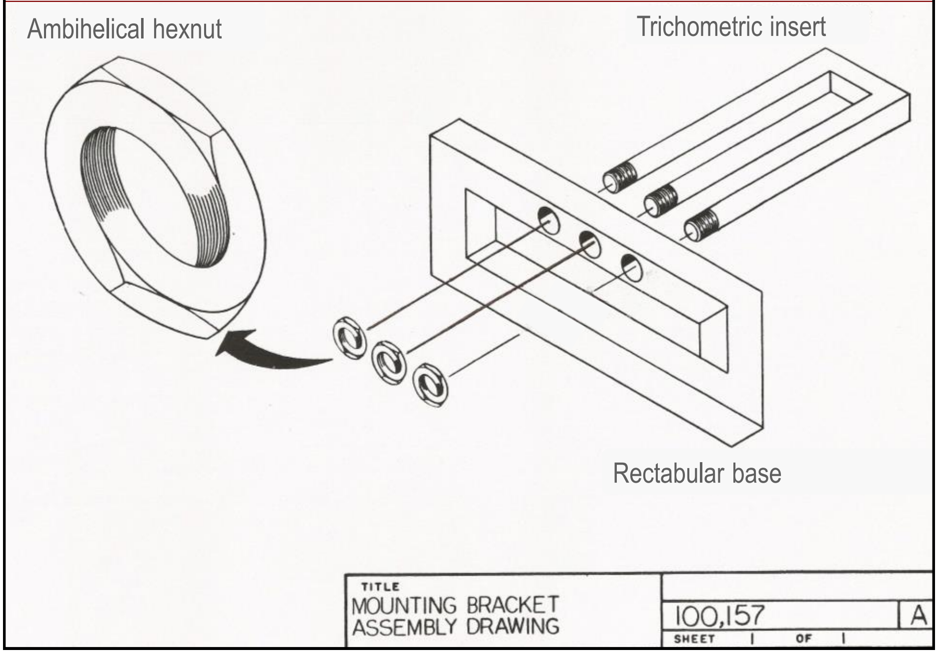
Exercise 13.1

Each team (same teams as for the SIPOC) will create a cross functional process map for the current state mounting bracket development process (MBDP). Use the information in the following file:

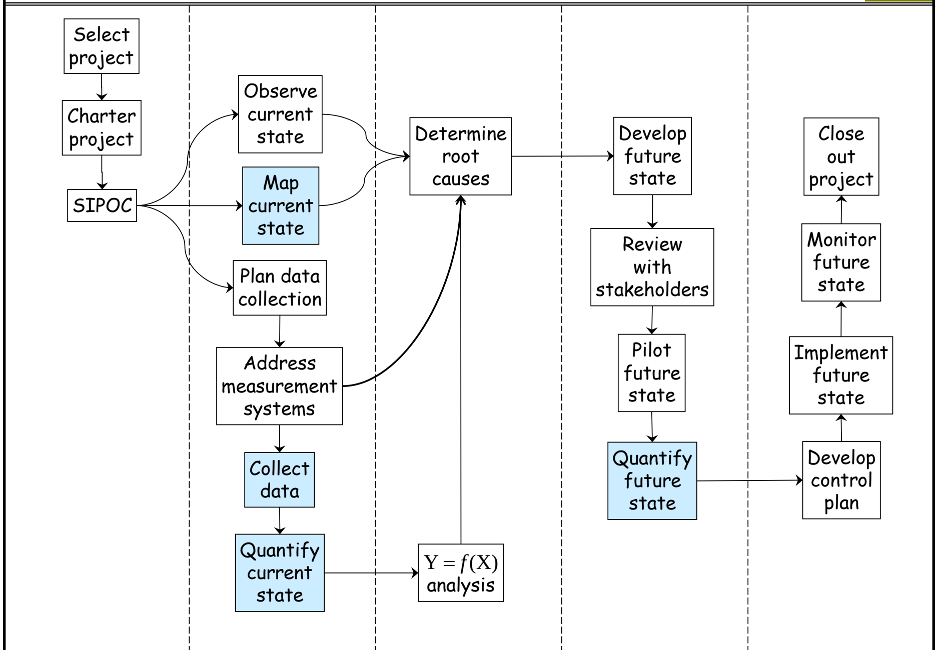
Student Files \ MBDP description for process map

The instructor will provide paper. Enter swimlanes (departments) as they occur in the narrative. (Make the swimlanes at least two sticky notes wide.) Add a sticky note for each step or decision in the process. Use marker for the text. Use masking tape to attach additional paper if needed. Add flow lines in pencil as you go. Trace flow lines with marker once your map is finished.

A non-standard mounting bracket



14 Value Stream Mapping



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

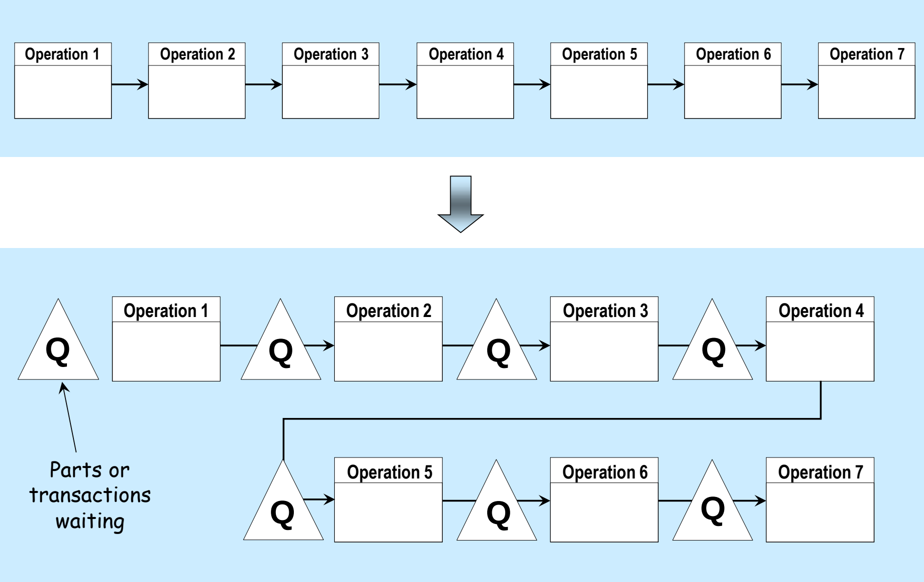
Develop control plan

The nature of Value Stream Mapping

- Value stream mapping (VSM) combines several things:
  - ✓Visualization of the current state
  - ✓Documentation of the current state
  - ✓Certain types of data collection and analysis
- VSM is an effective way to identify improvement opportunities
  - ✓Especially in projects involving WIP, capacity, and lead time reduction
  - ✓Also used to document the future state

From SIPOC to VSM

High-level map from SIPOC

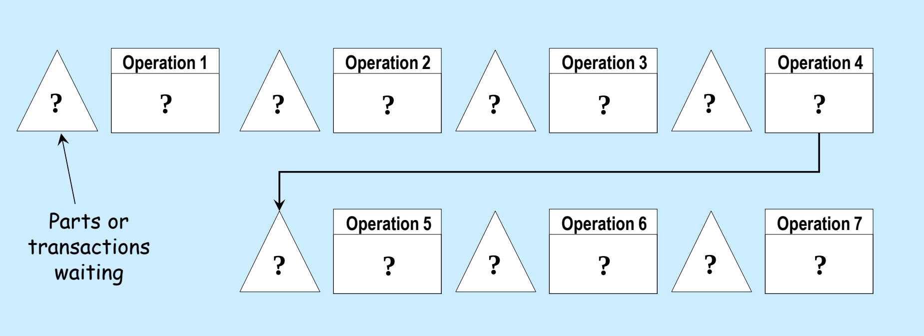


VSM, no data yet

What is the average lead time?

How much time is spent in each box or triangle?

How do we get this information?



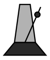
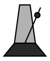
Definitions

Available Working Time (AWT)	• The time a process is available to conduct work • AWT excludes time when work isn’t occurring such as time for breaks, meetings, lunch, preventative maintenance, estimates of unplanned downtime, change overs, etc.
Throughput (Tput)	• The average number of good parts or transactions completed over a period of time • Typically measured as average over at least several days • Throughput, lead time, and WIP are related through Little’s Law

Definitions (cont’d)

Lead time (LT)	• The total elapsed time to produce one defect free product or transaction • The time difference between when a part or transaction enters and leaves a process
Customer Demand Rate (CDR)	• The number of parts or transactions that the customer desires over a period of time (usually a day, week, or month)

Definitions (cont'd)

Takt time (TT)	• The pace at which an operation should complete products or transactions in order to meet customer demand during the Available Working Time.  • Available working time during a period divided by the number of products or transactions *required* during that same period
Cycle time (CT)	• The fastest repeatable time between part or transaction completions using the current processes and resources • Shows how a process is capable of performing  • Combines with AWT to determine capacity

Definitions (cont'd)

Process Cycle Efficiency (PCE)	• The percentage of time that WIP is being transformed by VA activities. In other words, the percentage of lead time that is value added.
Work In Progress (WIP)	• Includes items waiting to be worked on and items actively being worked on. WIP includes all of the inventory in the production system.

Example 1

Available Working Time per day = 480 min – 90 min breaks, lunch, meetings

= 390 min

Avg. daily Customer Demand Rate = 32 units

$$\text{Takt time} = \frac{\text{390 minutes}}{\text{32 units}} = \text{12.2 mins}$$

During a study of this process, parts were completed at the following times:

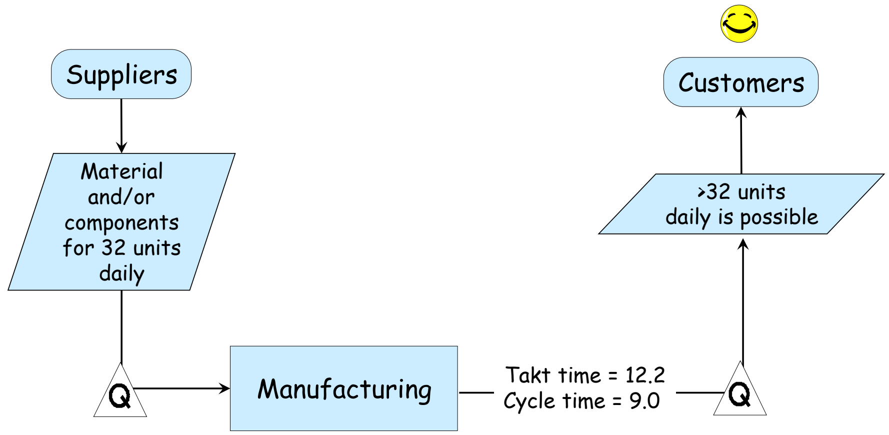
9:00, 9:09, 9:17, 9:28, 9:37, 9:46, 9:58, 10:07, 10:16, 10:24, 10:33, 10:42

Based on this, the elapsed time in minutes between completed units was:

9, 8, 11, 9, 9, 12, 9, 9, 8, 9, 9

Cycle Time = 9 minutes (the fastest repeatable value)

Example 1 (cont'd)



Getting used to takt time and cycle time

- Units of takt and cycle time: time divided by quantity
  - Shorter cycle time → more output
  - Longer cycle time → less output
- Cycle time *longer* than takt time
  - **Cannot** meet customer demand with current processes and resources
- Cycle time *shorter* than takt time
  - **Can** meet customer demand with current processes and resources, but may need to eliminate process variation

---

We may not want to operate as fast as possible

- Takt time longer than cycle time
- Downstream operations constrained to cycle time of upstream bottleneck
- Upstream operations pace themselves to cycle time of downstream bottleneck (pull system)

Exercise 14.1

Using the information provided in Example 1, consider the scenario where the customer wants to increase their purchases from 32 to 42 units per day.

a) What is the new takt time?

b) What is the cycle time and is the new takt time faster or slower than the cycle time?

c) Can you accommodate this demand increase?

d) What problems might need to be solved?

e) Why should cycle time measurements not typically be taken from process output data in an ERP system?

How do we get lead time data?

Method	Drawbacks
Download accurate, time stamped records from database	• The best scenario, if such data exists • Make sure WIP time is accounted for properly
Shadow parts or transactions	• Tedious • Logistically difficult • Time consuming for team members
Tag documentation	• Anything identified as “special” is likely to be expedited • Data will not represent reality
Enter “file cabinet data” into Excel	• Tedious and time consuming • Likelihood of data entry errors • May not exist
Little’s Law	• Allows calculation of LT from WIP and T’put

Little’s law

Lead Time = (WIP) / (Throughput)

- WIP is easy to count during process observation
- If WIP varies, count multiple times and use average or min/max to show range in lead time
- Throughput is the quantity completed during an observation period. Period should be at least several days.
- Lead time = amount of time that passes between when a piece enters and leaves a process or processes
- These values can be calculated for individual processes or for an entire production process chain

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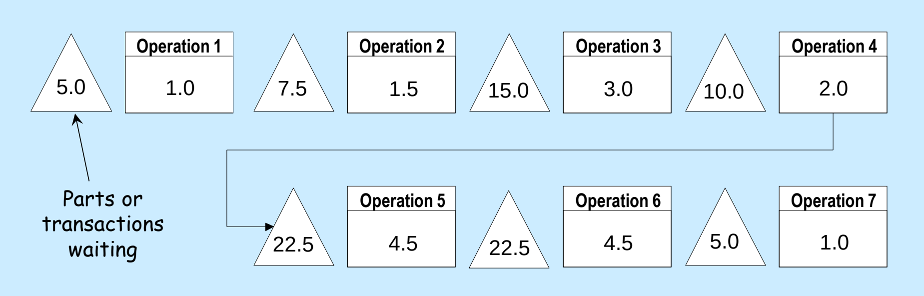
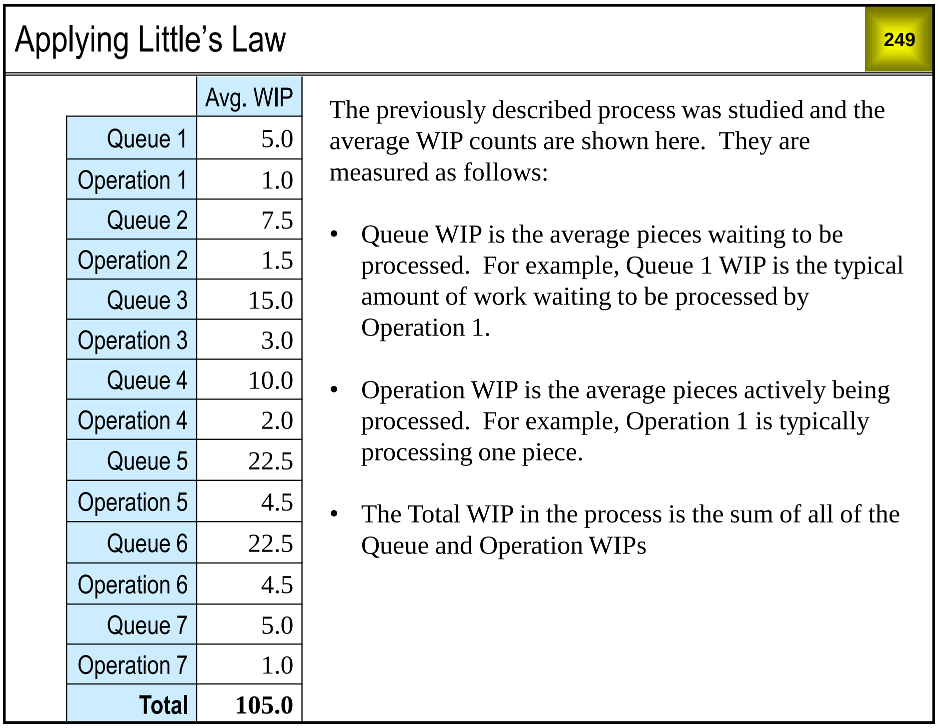
VSM with WIP data

Average WIP for each box and triangle during an observation period



- Suppose in the system shown above, each operation has a throughput of 6 pieces per hour, so the entire production process is also making 6 pieces per hour
- We can use Little’s Law to calculate the overall lead time for the process, for individual processes, or for subsets of processes

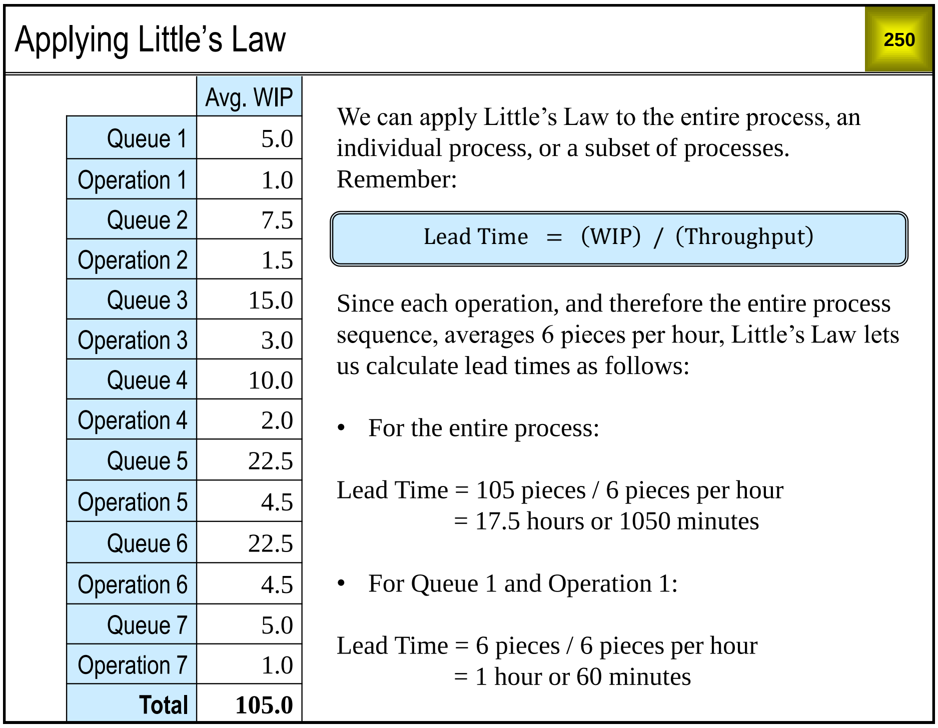


Applying Little's Law

	Avg. WIP
Queue 1	5.0
Operation 1	1.0
Queue 2	7.5
Operation 2	1.5
Queue 3	15.0
Operation 3	3.0
Queue 4	10.0
Operation 4	2.0
Queue 5	22.5
Operation 5	4.5
Queue 6	22.5
Operation 6	4.5
Queue 7	5.0
Operation 7	1.0
Total	**105.0**

The previously described process was studied and the average WIP counts are shown here. They are measured as follows:

- Queue WIP is the average pieces waiting to be processed. For example, Queue 1 WIP is the typical amount of work waiting to be processed by Operation 1.
- Operation WIP is the average pieces actively being processed. For example, Operation 1 is typically processing one piece.
- The Total WIP in the process is the sum of all of the Queue and Operation WIPs



Applying Little's Law

	Avg. WIP
Queue 1	5.0
Operation 1	1.0
Queue 2	7.5
Operation 2	1.5
Queue 3	15.0
Operation 3	3.0
Queue 4	10.0
Operation 4	2.0
Queue 5	22.5
Operation 5	4.5
Queue 6	22.5
Operation 6	4.5
Queue 7	5.0
Operation 7	1.0
Total	**105.0**

We can apply Little's Law to the entire process, an individual process, or a subset of processes. Remember:

Lead Time = (WIP) / (Throughput)

Since each operation, and therefore the entire process sequence, averages 6 pieces per hour, Little's Law lets us calculate lead times as follows:

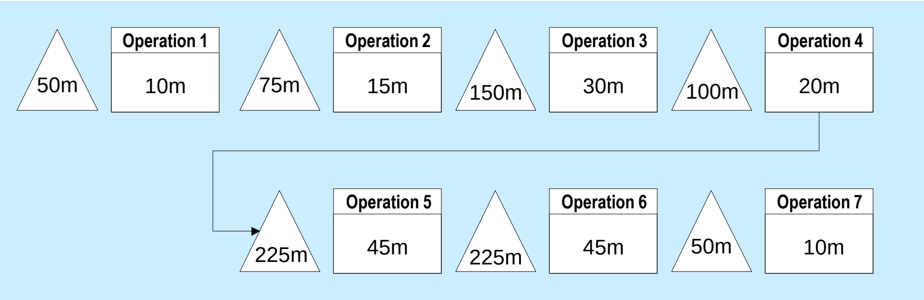
- For the entire process:

Lead Time = 105 pieces / 6 pieces per hour
= 17.5 hours or 1050 minutes

- For Queue 1 and Operation 1:

Lead Time = 6 pieces / 6 pieces per hour
= 1 hour or 60 minutes

VSM with waiting and process times



50m

Operation 1

10m

75m

Operation 2

15m

150m

Operation 3

30m

100m

Operation 4

20m

225m

Operation 5

45m

225m

Operation 6

45m

50m

Operation 7

10m

Lead time = 1050 minutes or 17.5 hours

Waiting time = Sum of time in queue
= 50 + 75 + 150 + 100 + 225 + 225 + 50 + 10 = 875 minutes

Process time = Sum of time the pieces are being worked on
= 10 + 15 + 30 + 20 + 45 + 45 + 10 = 175 minutes

Process Cycle Efficiency = The percent of lead time that a part is being worked on
= (175 / 1050)*100 = 16.7%

Exercise 14.2

a) A manufacturing process completes an average of 45 defect-free parts each day. The average WIP is 15 parts. Calculate the average lead time in hours.

b) Suppose in the example above, the company works one 8-hour shift per day. Under what conditions would this impact the lead time calculations and when would it not?

c) A manufacturing operation runs 365 days a year. They produce about 416 defect-free units of a particular product per year. The average WIP for this product is 40. Calculate the average lead time in days.

d) Should raw materials be counted as WIP?

Exercise 14.3

Open *Data Sets* → *MBDP VSM*. Average WIP and estimates of process times (in hours and days) are given for the six main steps in this process. The quantity completed in 260 work days is also given. Use Excel formulas to calculate the following:

a) Throughput, total process time in days, total WIP.

b) PO-PD (lead time) for the six main steps individually and the overall process?

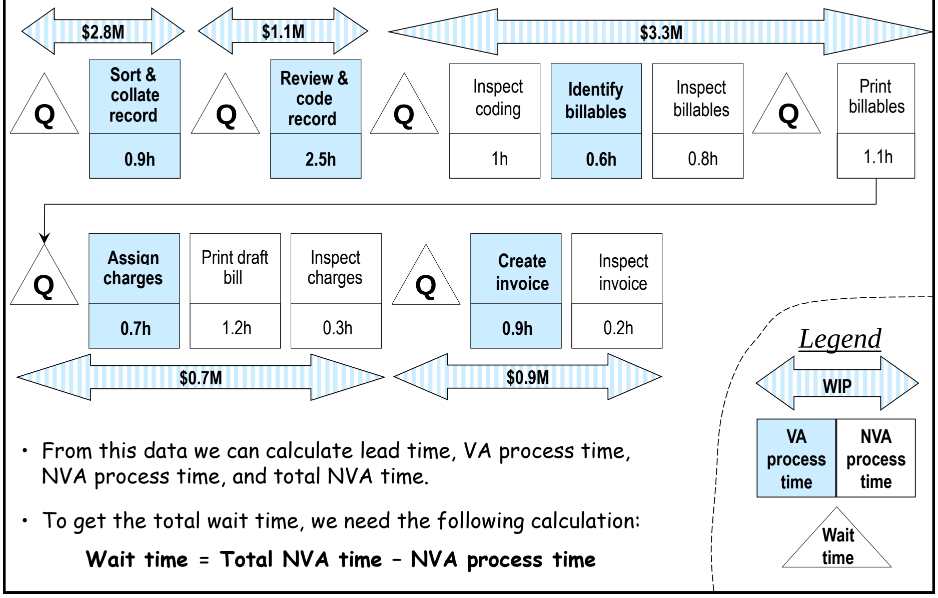
c) Where are the bottlenecks? Do these steps have anything in common?

d) What would the overall lead time be if all transactions were handled immediately upon receipt at each step?

e) Save your work.

Exercise 14.4

Billing process VSM with process times and WIP



- From this data we can calculate lead time, VA process time, NVA process time, and total NVA time.
- To get the total wait time, we need the following calculation:

  Wait time = Total NVA time – NVA process time

Exercise 14.4 (cont'd)

The average annual revenue of the company whose billing process is shown in the previous slide is $300M. Its average dollars in accounts receivable (AR) is $60M. Consider the following translations:

- AR is a process
- Dollars in AR is the WIP quantity
- Annual revenue is the quantity completed in 365 days
- Average days in AR is the average lead time of this process

Use Little's law to calculate the average days in AR.

The result will explain why the Accounts Receivable (billing) process was targeted for improvement.

Exercise 14.4 (cont'd)

Open *Data Sets* → *billing process VSM*. Use Excel formulas to calculate the following in units of $M (dollars in millions) and days (use a 24-hour day):

a) Throughput, total VA process time, and total WIP.

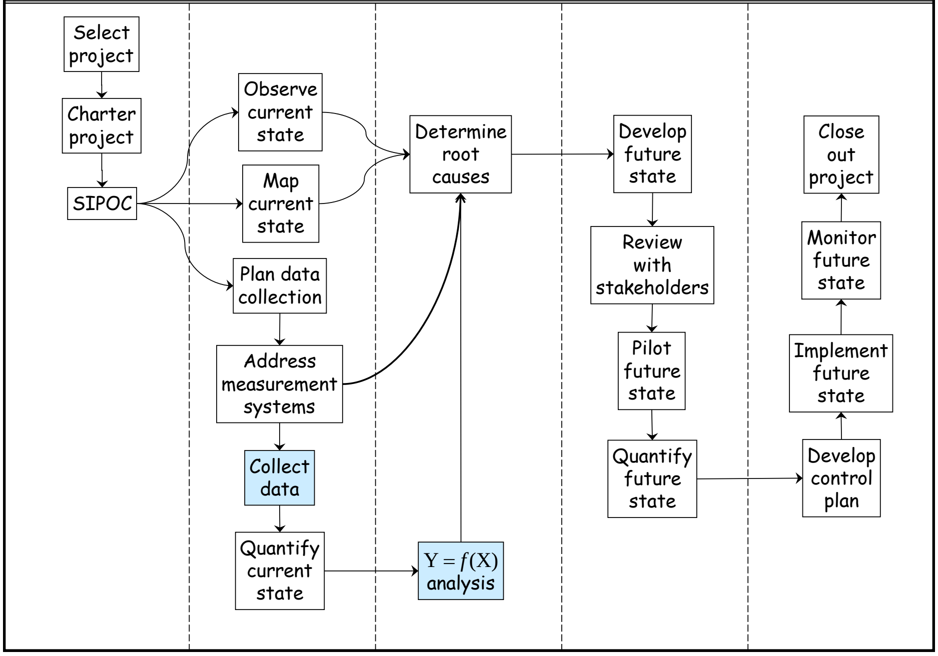
b) Lead time for the five main process steps, and overall.

c) Total NVA Lead Time, NVA Process Time and Process Cycle Efficiency.

d) Wait time and Wait time as a percentage of total NVA time.

e) Where does WIP indicate a capacity constraint? If each process had the same resources and AWT, where would the constraint be? Why might there be little WIP in front of a constraint?

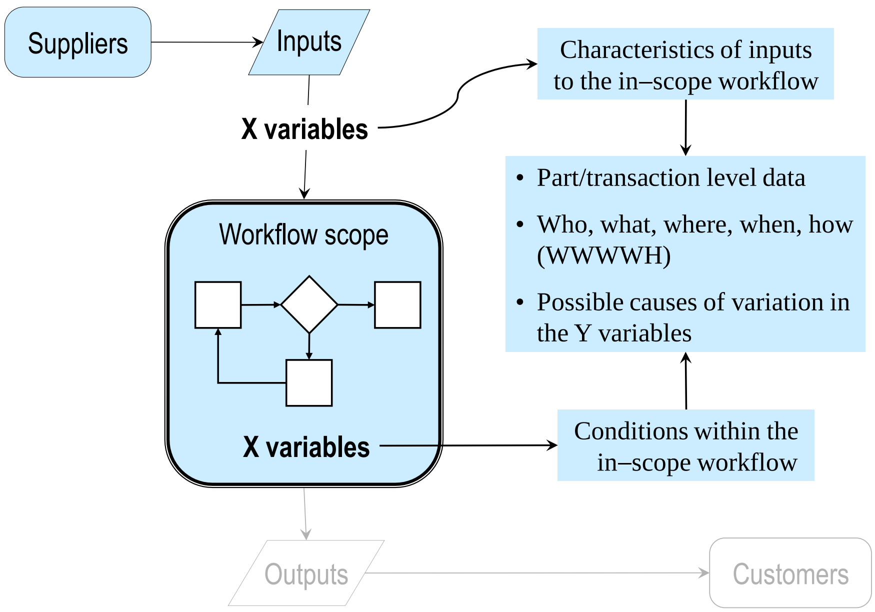
15 X and Y Variables



Topics

- X variables
- Fishbone Diagram
- Prioritizing X variables
- Y variables
- Operational definitions for data variables
- “Big Y” and “little y”

X variables



Characteristics of inputs to the in–scope workflow

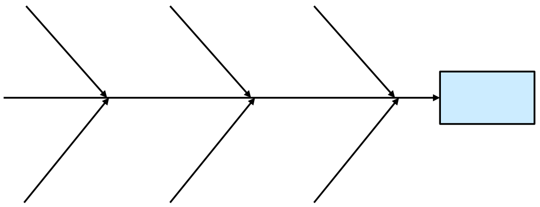
- Part/transaction level data
- Who, what, where, when, how (WWWWH)
- Possible causes of variation in the Y variables

Conditions within the in–scope workflow

Fishbone Diagram

The Fishbone Diagram is:

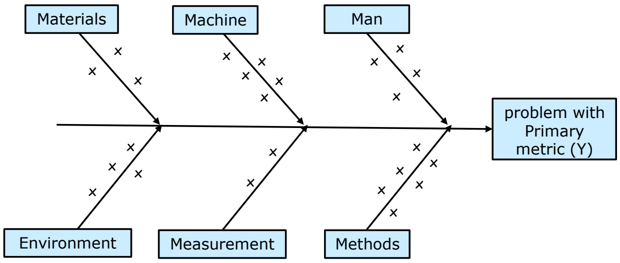
- used to identify all potential causes (X's or inputs) of the effect (output or problem of interest), usually the primary metric.
- part of identifying process inputs during the Measure Phase
- most often associated with root cause analysis
- also known as Cause-and-Effect Diagram and Ishikawa Diagram



Fishbone Diagram (cont.)

The Fishbone Diagram is created with the project team.

- It focuses the team on the particular effect, shown in the "head of the fish"
- All ideas for potential causes (critical x's) are collected using brainstorming
- Categories on the main "bones" help trigger ideas
  - Standard categories are Man, Machine, Materials, Methods, Measurement and Environment ("5 M's and an E")
  - The team can choose to use different categories
  - Standard categories (with minor modifications) are recommended for your first uses

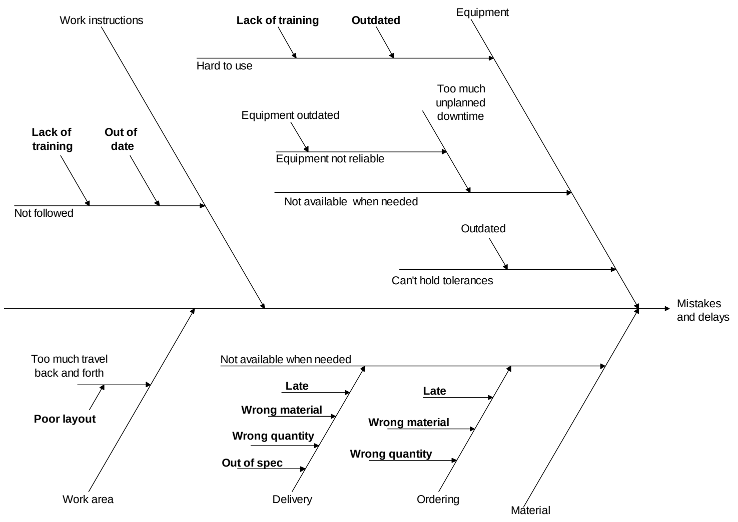


Steps for Creating a Fishbone Diagram

The Fishbone Diagram must be visible to the entire team during the brainstorming (creation) session.

1. Put output of interest (usually primary metric) in the "head of the fish."
2. Choose categories for "bones"
   - Standard Categories: Man, Machine, Materials, Methods, Measurement, Environment
   - The team can choose to use other categories
3. Brainstorm all possible inputs (x's) that could cause the problem seen in the output (primary metric—Y)
   - Rules for Brainstorming: Accept all stated ideas and add to diagram; No ideas are evaluated or rejected during the brainstorming session
4. Break broad categorical x's into more useful, more measurable features
   - Measurable features can be verified as causes of performance issues in the primary metric during the Analyze Phase
   - We can act upon them to improve the process
   - They need to be identified early in the project
   - Example: Work instructions not followed—out of date; lack of training
5. Highlight those x's deemed most important by the team

Fishbone Diagram Example (non-standard categories)



Exercise 15.1

A project has been launched to improve the mounting bracket development process (MBDP) in a company that makes mounting brackets. Background on the project and process may be found in the following files in the *Student Files* folder:

MBDP charter

MBDP description for process map

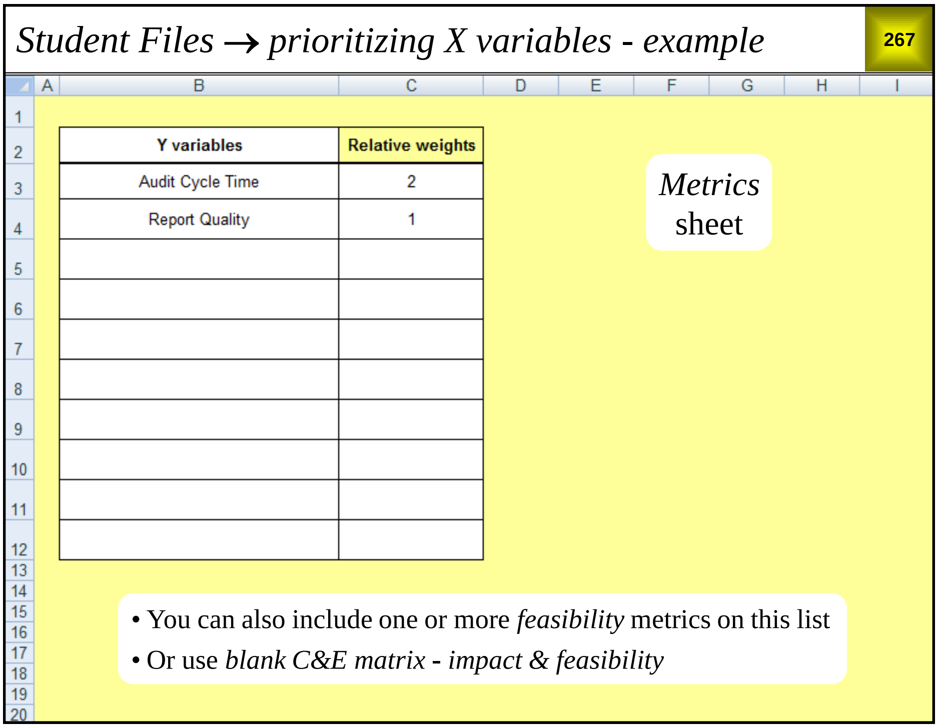
Based on the information in these documents and the process map you created earlier, create a Fishbone Diagram for this project.

Prioritizing X variables for data collection

- X’s are measurable characteristics of process inputs
- Who/what/where/when/how within the workflow scope
- These are shown on your fishbone diagram
- It may not be feasible to collect data on all X variables of interest
- You may need to prioritize them

Instructions for prioritizing X variables

1. Open *Student Files* → *blank C&E matrix - Pareto method*
2. In the *Metrics* sheet, change *Metrics* to *Y variables*
3. List your Y variables and relative weights
4. In the *Items to be ranked* sheet, change *Items to be ranked* to *X variables*
5. List the X variables you wish to rank
6. Rate each X variable for degree of correlation with each Y variable: none (blank), low (L), medium (M), high (H)
7. Copy your X variable list, paste it into the *Pareto* sheet under *Paste items to be ranked*
8. Copy your overall rankings, *Paste Special* → *Values* into the *Pareto* sheet under *Paste overall rankings*
9. Select the range B3:C27, select *Data* → *Sort*, uncheck *My data has headers*, sort by column C, largest to smallest

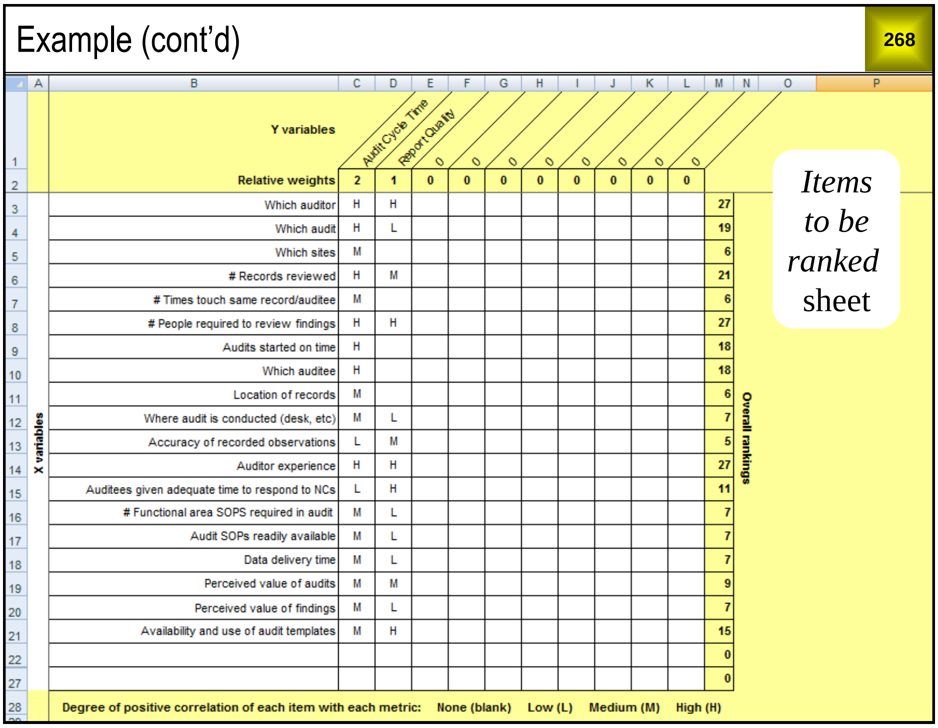


Student Files → prioritizing X variables - example

Y variables	Relative weights
Audit Cycle Time	2
Report Quality	1

Metrics sheet

- You can also include one or more *feasibility* metrics on this list
- Or use *blank C&E matrix - impact & feasibility*



Example (cont'd)

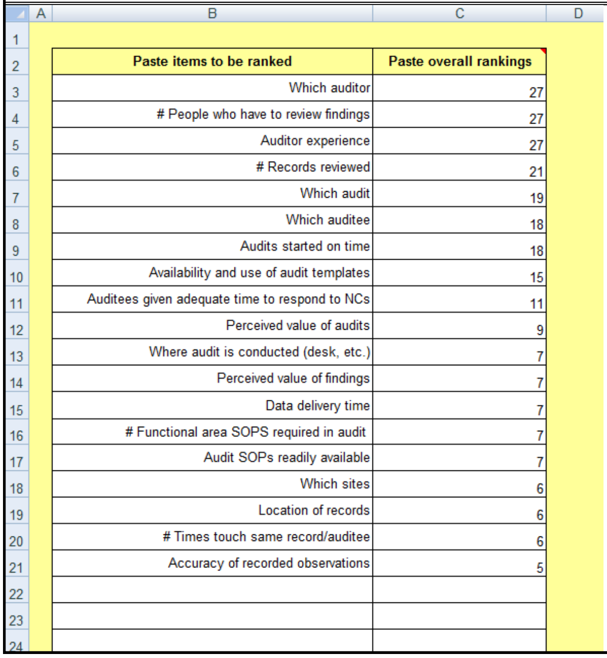
X variables

Y variables	Audit Cycle Time	Report Quality	0	0	0	0	0	0	0	0	**Overall rankings**
Relative weights	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Which auditor	H	H									**27**
Which audit	H	L									**19**
Which sites	M										**6**
# Records reviewed	H	M									**21**
# Times touch same record/auditee	M										**6**
# People required to review findings	H	H									**27**
Audits started on time	H										**18**
Which auditee	H										**18**
Location of records	M										**6**
Where audit is conducted (desk, etc)	M	L									**7**
Accuracy of recorded observations	L	M									**5**
Auditor experience	H	H									**27**
Auditees given adequate time to respond to NCs	L	H									**11**
# Functional area SOPS required in audit	M	L									**7**
Audit SOPs readily available	M	L									**7**
Data delivery time	M	L									**7**
Perceived value of audits	M	M									**9**
Perceived value of findings	M	L									**7**
Availability and use of audit templates	M	H									**15**
											0
											0

Degree of positive correlation of each item with each metric: None (blank) Low (L) Medium (M) High (H)

Items to be ranked sheet

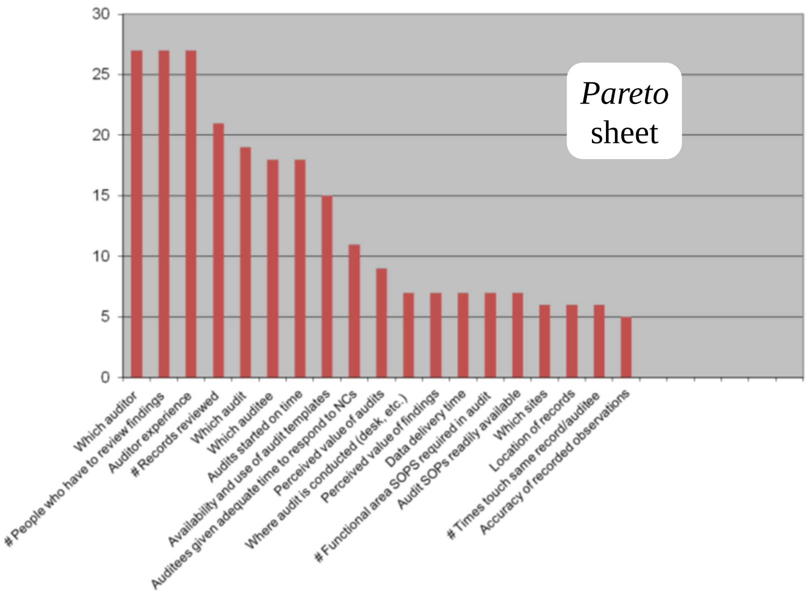
Example (cont'd)



Paste items to be ranked	Paste overall rankings
Which auditor	27
# People who have to review findings	27
Auditor experience	27
# Records reviewed	21
Which audit	19
Which auditee	18
Audits started on time	18
Availability and use of audit templates	15
Auditees given adequate time to respond to NCs	11
Perceived value of audits	9
Where audit is conducted (desk, etc.)	7
Perceived value of findings	7
Data delivery time	7
# Functional area SOPS required in audit	7
Audit SOPs readily available	7
Which sites	6
Location of records	6
# Times touch same record/auditee	6
Accuracy of recorded observations	5

Pareto sheet

Example (cont'd)



Pareto sheet

Exercise 15.2

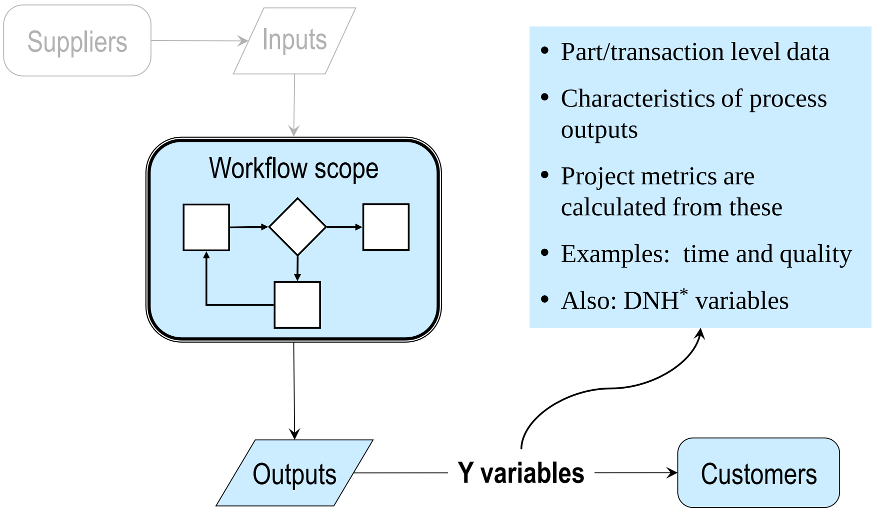
Open *Student Files* → *MBDP X variable prioritizer*. Y variables and X variables are given. Use your knowledge and experience to rate the X variables for correlation with the Y variables and produce the Pareto Chart.

Prioritizing X's using Multi-voting

Another method for prioritizing X's for data collection is to use multi-voting:

1. Count the number of X's
2. Divide the total number of X's by 3. Each team member gets that many "votes"
3. Each team member decides how they will apply their votes, giving one vote to each X they think is a most likely main contributor to the problem
   - Give a marker to each team member and have them write their votes on the fishbone diagram or list
   - Use a *secret ballot* if there are concerns of undo influence among team members
4. Focus data collection on those X's that rise to the top

Y variables



- Part/transaction level data
- Characteristics of process outputs
- Project metrics are calculated from these
- Examples: time and quality
- Also: DNH* variables

*Do No Harm — not trying to improve them, just don't want to make them worse. These are your secondary project metrics.

Operational definition for a Y variable

Examples of questions to be answered

- How, and from what basic quantities, will Y be calculated?
- What measurement system will be used?
- If Y is a lead time, what are the starting and stopping points?
- If Y is pass/fail, what are the possible defects?
- If you are going to count defects per opportunity, how are the opportunities defined?
- If Y is unplanned downtime, how will you record your data: hourly/daily/weekly summaries or event log?
- If there is existing data, can you use it with minor modifications to your operational definition(s)? (Data readily available will jump start your project. Use it whenever possible, even if minor adjustments to the project scope are needed.)

Exercise 15.3

Working with one or two others from your company, if possible:

1. Give an operational definition for PO-PD in the Mounting Bracket Development Process (MBDP) project. Your definition should address the relevant questions on the previous slide.
2. Give an operational definition for one of the Y variables for your project. Your definition should address the relevant questions on the previous slide.

"Big Y" and "little y"

Often, we collect data based on a high-level breakdown of the in-scope workflow

- Sort & collate
- Code
- Identify billables
- Assign charges
- Prepare bill

A billing process:
by main steps

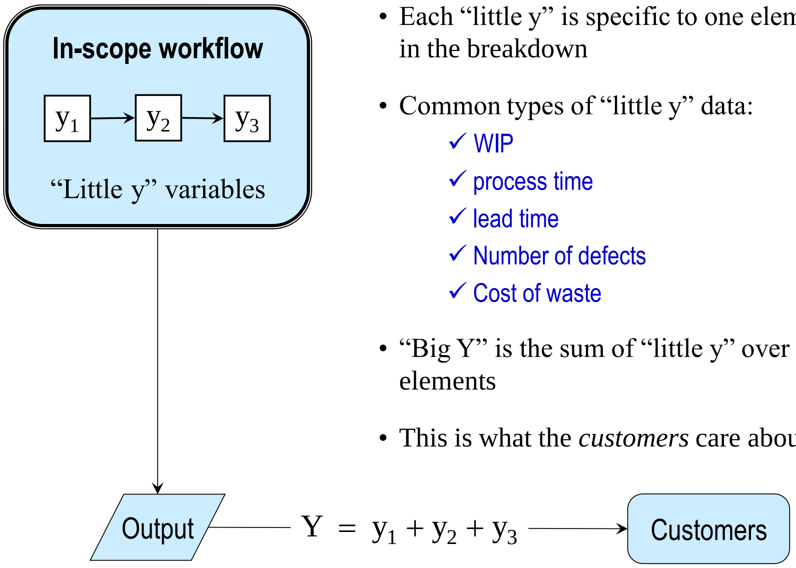
- Regional Sales
- Technical Sales Coordinator
- Business Unit Sales
- Business Unit Engineering
- Service
- Finance
- Legal

A quotation process:
by functional roles

- PO: Sales/PE
- Design Spec: PE
- Design Spec: ME/QE
- Drawing: Drafting/PE
- Drawing: ME/QE
- Proto

The MBDP:
by main steps ***and***
functional roles

"Big Y" and "little y" (cont'd)

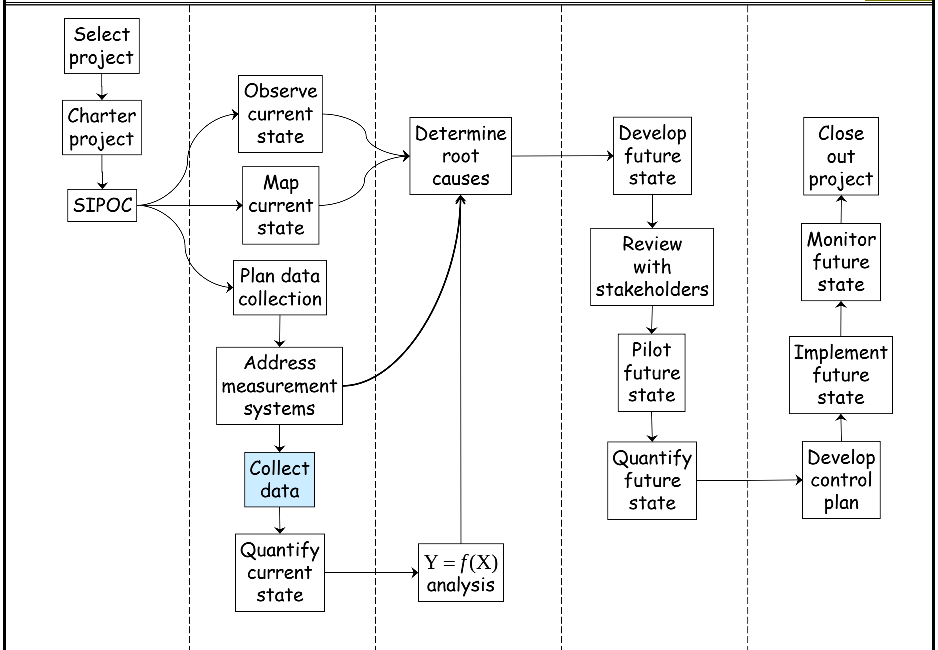


- Each "little y" is specific to one element in the breakdown
- Common types of "little y" data:
    - ✓ WIP
    - ✓ process time
    - ✓ lead time
    - ✓ Number of defects
    - ✓ Cost of waste
- "Big Y" is the sum of "little y" over all elements
- This is what the *customers* care about

Pitfall: setting goals for each "little y"

- Suppose $Y = y_1 + y_2 + y_3$
- Suppose we have a 50% reduction goal for Y
- One way to achieve this is to reduce each of y_1, y_2, and y_3 by 50% . . .
- . . . but we should *not* set separate 50% reduction goals for y_1, y_2, and y_3
- Why?

16 Data Collection



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Purposes of data collection

- Calculate project metrics for the current state
- Pareto analysis of defect types, error types, failure reasons, etc.
- Comparisons within the current state (stratification analysis)
- Correlation of X and Y variables
- Use analysis results to help identify root causes

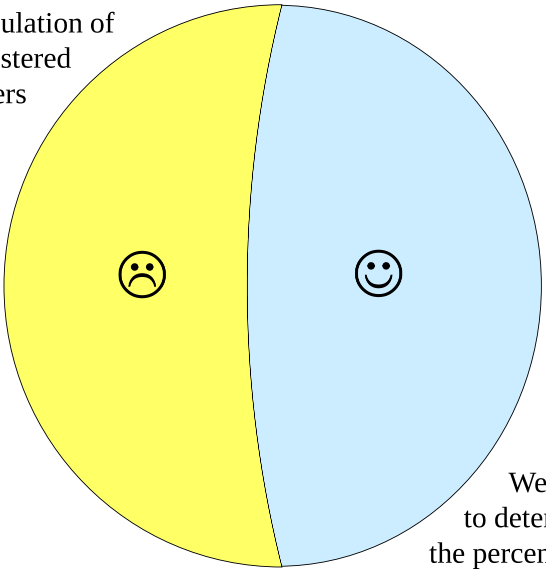
Population sampling

Population	• A specified collection of people or things
Sample	• A subset of a population • Usually relatively small • Intended to represent the population

Example: opinion poll

Population of
registered
voters

"Do you support
the President's
policy on _____ ?"



We want
to determine
the percentages

The sample must be representative

"Do you support the President's policy on _____?"

Representative sampling (cont'd)

- Examples of obvious biases: sample includes only
  - ✓ Democrats
  - ✓ Republicans
  - ✓ Men
  - ✓ Women
  - ✓ Residents of Wyoming
  - ✓ Convicted white collar criminals
  - ✓ Relatives of elected government officials
- Standard survey sampling technique
  - ✓ All counties are categorized into something like 30 groups ("strata") according to population density
  - ✓ Each stratum (group of counties with similar population density) is randomly sampled in proportion to its population
- This is an example of *stratified random sampling*

Exercise 16.1

Decide whether or not the proposed sample in each case below will be representative of the population. If not, note obvious or possible biases on the slide below.

Population	Purpose	Proposed sample
(a) Former Enron employees	Opinion on culpability of top Enron executives	Those with the largest retirement accounts, comprising 85% of lost value
(b) A year, make, and model of car	Surreptitiously determine % with a given defect	Offer a free _____ until 100 cars have been inspected at each US dealership
(c) ER patients at a hospital last year	Customer satisfaction survey	Those whose last names begin with the letter M
(d) Lambs born in New Zealand last year	Determine % with "mad lamb" disease	Random sample of each ranch in NZ, proportional to # of lambs
(e) Registered voters	Opinion on presidential candidate	Generate telephone numbers at random, call those people

Exercise 16.1 (cont'd)

(a)

(b)

(c)

(d)

(e)

Incorrect interpretation of survey data

"Do you support the President's policy on _____?"

☐ 51% of the people responding to the survey say "yes"

Infotainment Nightly "News"

"According to a recent survey, the majority of registered voters support the President's policy."

Interpretation of survey data (cont'd)

- Suppose the sampling plan was perfectly representative of the population
- Still, we cannot say that what is true in the sample is true in the population
- The sample data does *not* prove that 51% of registered voters agree with the President's policy

Must quantify the uncertainty

"Do you support
the President's
policy on _____?"

Rational Public Radio

"51% of sampled voters supported the President's policy. The margin of error is ±3 percentage points, so the survey is inconclusive."

Quantifying uncertainty (cont'd)

- "Margin of error" (MOE) is how we quantify our uncertainty about the population in light of the sample data
- The most we can say: "The percentage of registered voters agreeing with the President's policy is between 48% and 54%"
- The data fails to demonstrate a majority on *either* side of the question

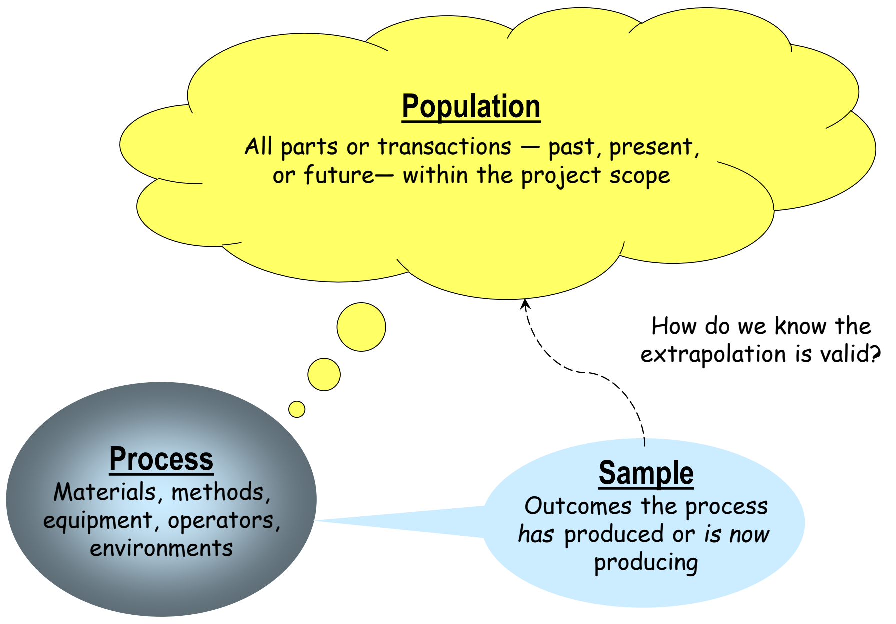
Process sampling

Process A predetermined sequence of actions and decisions intended to produce a desired outcome. (A way of doing something.)

- ✓ Manufacturing process
- ✓ Service process
- ✓ Business process
- ✓ Transactional process
- ✓ Decision process
- ✓ Design process

For any process, there is an associated *population*

Process sampling (cont'd)



Population
All parts or transactions — past, present, or future— within the project scope

How do we know the extrapolation is valid?

Process
Materials, methods, equipment, operators, environments

Sample
Outcomes the process *has* produced or *is now* producing

Process sampling for LSS projects

- 100% sampling for a period of time, is the most common method
- What are some situations where 100% sampling is not possible?
- The sample must cover a representative time period
- The sample must capture all *typical sources of variation* (see slide below)

Typical sources of variation

Process participants

“Identical” pieces of equipment

Time of day, week or month

Batches or lots of raw material

Different suppliers

Production lots, work orders, . . .

Different locations

Changing environmental conditions

Multiple measurement systems

.
.
.

“Less than 100%” sampling methods

Random	Items are selected by a random number generator
Systematic	Items are selected at regular intervals
Stratified random[*]	Items are sampled from homogeneous subpopulations, in proportion to subpopulation size
Judgment	Items are selected using knowledge of the process
Convenience	Items are selected based on cost or ease of access

[*] Usually considered to be the most representative sampling method.

Exercise 16.2

Check the sampling methods that apply in each case based on the given information.

	Random	Systematic	Stratified	Judgment	Convenience
Pulled 10 parts off the high volume production line at the top of each hour					
Reviewed Enron electricity trades during periods of highest demand					
Used random numbers to select 10% of patient charts for the past year					
Monitored every 1000th customer service call					
Downloaded invoices with numbers ending in 0 or 5					
Inspected the first 3 parts from each production lot					
Took a sample from the top of each barrel on the top layer of the stack					

Sample size

- Amount of data: more is better than less
- Time period: longer is better than shorter*
- Capturing all typical sources of variation usually gives an adequate sample size
- You should do a sample size calculation just to make sure

---

*But beware of old data that is no longer relevant to your current state.

Sample size calculation: opinion poll example

ϕ	The fraction (proportion) of people in the population who would say yes to the survey question if asked. We don't know, and will never know, the exact value of ϕ. However, we can get an accurate estimate of ϕ if we collect enough data.
Sample	The people who respond to the survey. Usually, this is a very small subset of the population.
ϕ_{sample}	The fraction (proportion) of the respondents who say yes to the survey question. This is our estimate of ϕ. We don't know this now, but we will after we get the data.
MOE	Margin of error: the amount by which ϕ_{sample} could differ from ϕ, based on an established statistical standard of evidence. The most common standard of evidence is called "95% confidence."
N	The number of people who respond to the survey — the *sample size*. The required sample size depends on ϕ_{sample} and the desired MOE.

Sample size (cont'd)

In most opinion polls, ϕ_{sample} is assumed to be close to 0.5 when determining sample size. This gives the largest sample size needed to achieve the desired margin of error (MOE). If ϕ_{sample} is not 0.5, the MOE will be smaller, which is desireable. The approximate formula for the MOE (with 95% confidence) is:

$$\text{MOE} = 1.96\sqrt{\frac{\phi_{sample}\left(1-\phi_{sample}\right)}{N}} = 1.96\sqrt{\frac{0.5\,(0.5)}{N}} = \frac{0.98}{\sqrt{N}}$$

We can solve this equation for N:

$$N = (0.98 / \text{MOE})^2$$

MOE	N
0.05	384
0.04	600
0.03	1067
0.02	2401
0.01	9604

Sample size calculation: process applications

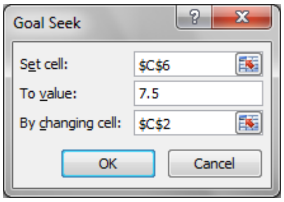
- In process applications, ϕ represents the fraction defective
- In this case, the margin of error on the high side is of greatest interest:

$$\phi_{sample} + \text{MOE}_{upper} = \text{Upper bound on } \phi \text{ (with 95\% confidence)}$$

- To do a sample size calculation, we must provide two inputs:
  - a) A guess for ϕ_{sample}
  - b) An acceptable upper bound on ϕ (giving the desired MOE, which is the difference between this upper bound and ϕ_{sample})
- Open *Student Files* → *calculator - sample size* → *% Defective*

Example

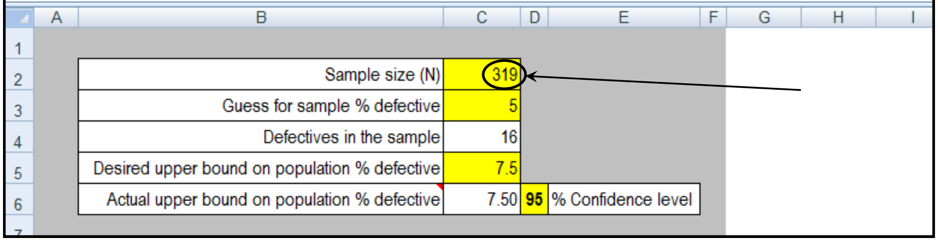
- We think ϕ_{sample} will be close to 0.05 (5% defective)
- If this turns out to be true, we want to be able to say (with 95% confidence) that ϕ is no larger than 0.075 (7.5% defective)
- Enter 1 in cell C2, 5 in C3, and 7.5 in C5
- We want to set cell C6 to 7.5 by changing cell C2
- Select *Data* → *What If Analysis* → *Goal Seek* → set up as shown to the right → click OK



Set cell: $C$6

To value: 7.5

By changing cell: $C$2



Sample size (N)	319		
Guess for sample % defective	5		
Defectives in the sample	16		
Desired upper bound on population % defective	7.5		
Actual upper bound on population % defective	7.50	95	% Confidence level

---

Exercise 16.3

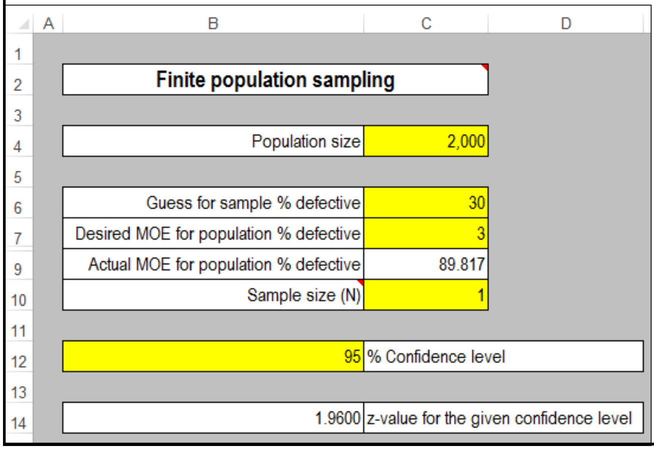
We want to get an accurate estimate of the population % defective. Find the required sample size in the following scenarios.

	Guess for sample % defective	Desired upper bound on population % defective	Sample size
(a)	10	20	
(b)	10	15	
(c)	10	13	
(d)	1	4	
(e)	1	3	
(f)	1	2	

Finite population sampling

Open *Student Files → calculator - sample size → Finite population sampling*

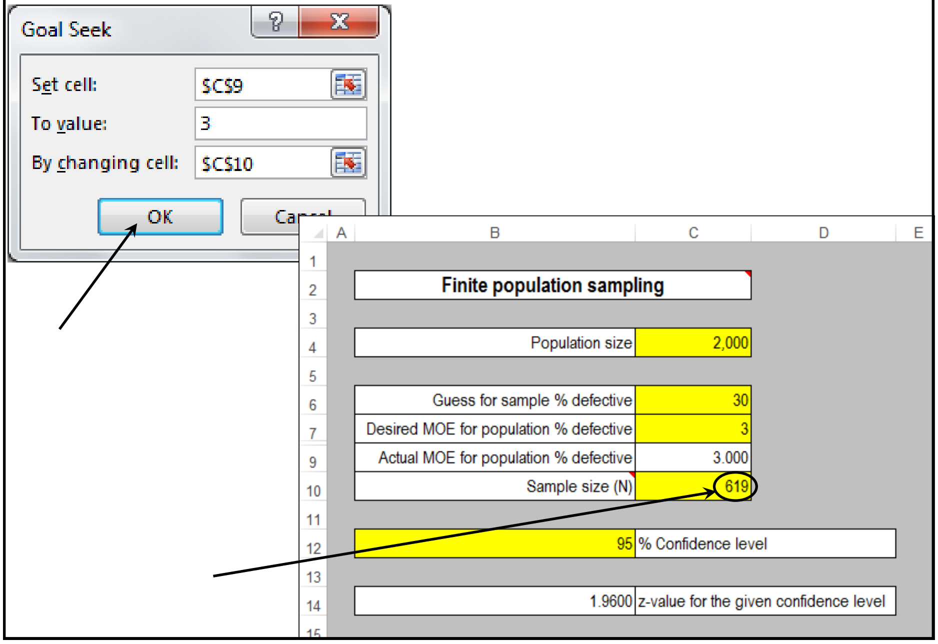
- We want to determine the % defective in a finite population of size 2000
- Enter the values shown below in cells C4, C6, and C7
- We want to set cell C9 to 3 by changing C10



	A	B	C	D
1				
2		**Finite population sampling**		
3				
4		Population size	2,000	
5				
6		Guess for sample % defective	30	
7		Desired MOE for population % defective	3	
9		Actual MOE for population % defective	89.817	
10		Sample size (N)	1	
11				
12		95	% Confidence level	
13				
14		1.9600	z-value for the given confidence level	

Data
↓
What If Analysis
↓
Goal Seek
↓
Set up as shown on the next slide

Finite population sampling (cont'd)



Set cell: $C$9
To value: 3
By changing cell: $C$10

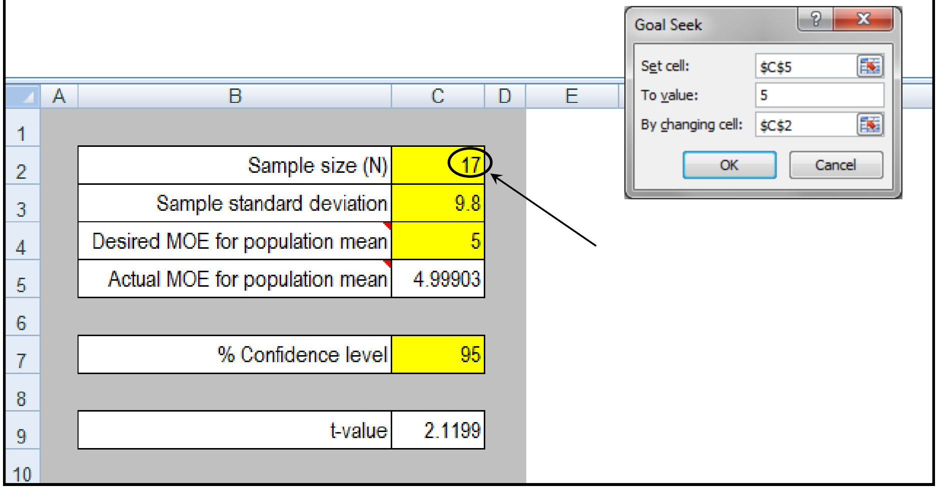
	A	B	C	D	E
1					
2		**Finite population sampling**			
3					
4		Population size	2,000		
5					
6		Guess for sample % defective	30		
7		Desired MOE for population % defective	3		
9		Actual MOE for population % defective	3.000		
10		Sample size (N)	619		
11					
12		95	% Confidence level		
13					
14		1.9600	z-value for the given confidence level		

Sample size for estimating a population mean

- This requires an estimate of the standard deviation
- Common practice:
  - ✓ Collect a small amount of data, calculate the standard deviation
  - ✓ Do a sample size calculation to see how much more you need
  - ✓ You can also get a rough estimate of the mean from this data
- Suppose our rough estimates are μ = 50.4 and σ = 9.8
- We want our MOE to be 10% of the mean → MOE = .1 * 50.4 = 5
- Go to the sheet *Pop. mean for quant. Y* → enter the value 2 in cell C2, 9.8 in C3, and 5 in C4
- Select *Data* → *What If Analysis* → *Goal Seek*

Sample size for population mean (cont'd)

- We want to set cell C5 to 5 by changing cell C2
- Set *Goal Seek* up as shown here, click OK



Set cell: $C$5

To value: 5

By changing cell: $C$2

Sample size (N)	17
Sample standard deviation	9.8
Desired MOE for population mean	5
Actual MOE for population mean	4.99903
% Confidence level	95
t-value	2.1199

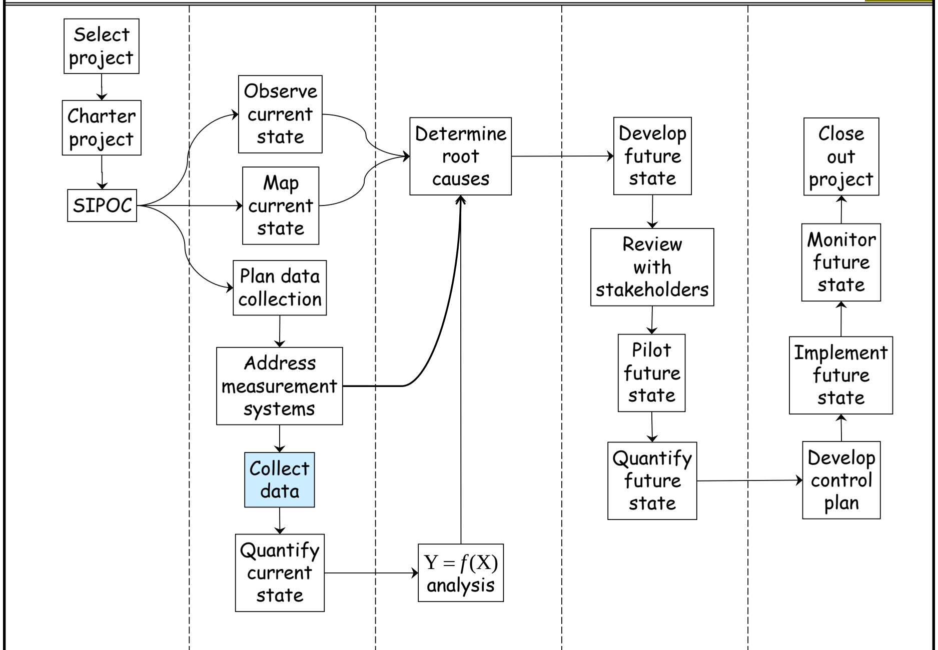
Exercise 16.4

a) For the previous example, calculate the sample size assuming we want our MOE to be 5% of the mean instead of 10%.

b) Calculate the sample size assuming we want MOE to be 1% of the mean.

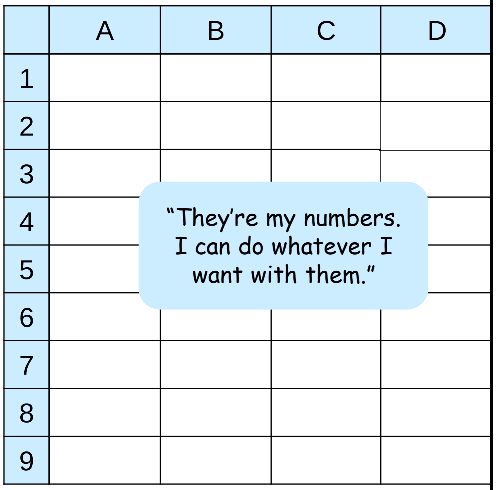
Notes

17 Data Formatting



The spreadsheet: a truly marvelous invention

- Automates arithmetic
- Dynamic cell formulas
- Addins expand functionality
- No rules for formatting data
- No rules for analyzing data



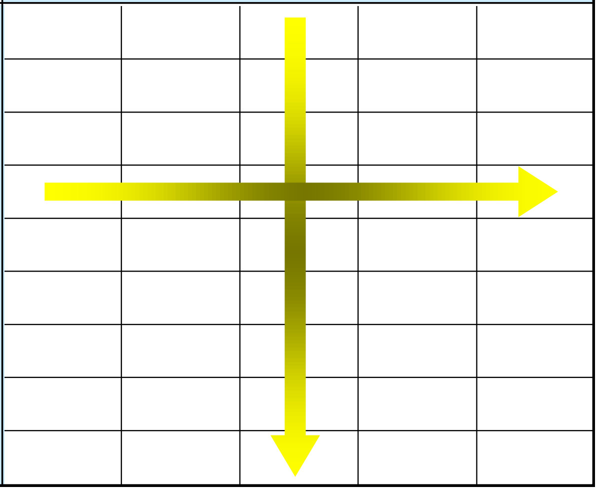
Standard data matrix format

Each column

- A unique *field* (database terminology)
- A unique *variable* (statistical terminology)

Each row

- A unique *record* (database terminology)
- An observation (Statistical terminology)
- A part, sample, lot, batch, transaction, time period, person, . . .
- The number of rows is the *sample size*



Data matrix example 1

← *Data variables* →

S/N	Length	Diameter
501	599.54	48.92
502	598.31	47.89
503	598.37	48.16
504	599.06	48.06
505	598.14	47.78
506	598.93	48.21
507	599.28	47.44
508	599.66	48.22
509	599.60	49.09
510	597.52	47.38
511	598.39	48.78
512	599.31	48.48
513	600.20	48.89
514	599.63	48.23

Each row represents one serial number of a particular part number

Data matrix example 2

← *Data variables* →

Quote Num	AcctMgr	BU	Initial RFQ	Month	Cycles	Finance reviews	TAT
3250024	8	3	12-Jun-03	2003.06	1	1	2
3250029	2	3	04-Jul-03	2003.07	1	0	2
3250031	5	3	29-Aug-03	2003.08	1	1	1
3250032	4	3	16-Jun-03	2003.06	1	0	1
3250033	3	3	06-Jun-03	2003.06	1	1	2
3250034	20	3	30-Jun-03	2003.06	1	1	4
3250035	3	3	09-Jun-03	2003.06	1	1	1
3250036	4	3	16-Jun-03	2003.06	1	0	1
3250037	4	3	16-Jun-03	2003.06	1	0	2
3250038	4	3	26-Jun-03	2003.06	1	0	1
3250039	8	3	30-Jun-03	2003.06	1	1	9
3250040	4	3	26-Jun-03	2003.06	1	0	1
3250041	4	3	26-Jun-03	2003.06	1	0	1
3250042	4	3	01-Jul-03	2003.07	1	0	1
3250043	11	3	07-Jul-03	2003.07	1	0	1
3250045	20	3	12-Aug-03	2003.08	1	1	2
3250046	3	3	14-Jul-03	2003.07	1	0	11
3250047	2	3	14-Jul-03	2003.07	1	0	3

Each row represents one quote

Data matrix example 3

← *Data variables* →

WORK ORDER	PARENT P/N	COMP P/N	AREA	CATEGORY	SCRAP QTY
35709	672-5668-00	162-4219-66	HDSI	TRAINING ISSUE	16
88198	174-B983-00	178-2758-66	WC	RECUT	40
88198	174-B983-00	178-2764-66	WC	RECUT	82
96772	180-9272-66	M83519/2-3	CH	TRAINING ISSUE	5
97130	672-6163-66	174-5274-00	HDSI	SPLICES	22
97166	180-8208-66	178-2564-66	WC	FAILED TEST	16
97166	180-8208-66	388-5021-66	NC	BAD MOLDING	1
97166	180-8208-66	388-5021-66	NC	FAILED TEST	1
97327	H542E371-01	162-4356-66	CH	FAILED TEST	1
97327	H542E371-01	162-4718-66	CH	FAILED TEST	2
97327	H542E371-01	47180GY-25	CH	FAILED TEST	1
97544	180-0829-66	178-1565-66	PR	FAILED TEST	5
97555	196-3501-66	47439-001LF	WC	MACHINE/TOOLING	200
97563	170-0135-66	178-0103-66	WC	MACHINE/TOOLING	12
97563	170-0135-66	178-0104-66	WC	MACHINE/TOOLING	7
97564	170-0148-66	131-0965-00	WC	MACHINE/TOOLING	300
97570	180-8728-66	132-6158-66	CH	TRAINING ISSUE	10
97582	010-0735-00	131-7989-00	HDSI	VENDOR MATL	32
97582	010-0735-00	174-5274-00	HDSI	TRAINING ISSUE	25
97582	010-0735-00	174-5274-00	HDSI	VENDOR MATL	17

Each row represents one work order, one component part number,
one process area, one defect category

Data matrix example 4

← Data variables →

Week	Inspected	Defective
1	400	2
2	169	1
3	208	1
4	510	3
5	132	1
6	500	3
7	393	2
8	625	3
9	167	1
10	395	3
11	200	1
12	122	1
13	178	2
14	527	4
15	132	1
16	171	2
17	610	5
18	446	5
19	428	5
20	207	3
21	708	15
22	565	13
23	149	3

Each row
represents
one week

Exercise 17.1 (a)

Average monthly WIP

	2001	2002	2003
Jan	19	20	20
Feb	27	22	15
Mar	20	19	27
Apr	16	16	25
May	18	22	17
Jun	25	19	19
Jul	22	25	28
Aug	24	22	
Sep	17	18	
Oct	25	20	
Nov	15	16	
Dec	17	17	

Is this a valid data matrix?

If not, give the column headings for the standard data matrix format.

Exercise 17.1 (b)

Patients admitted to an emergency department

Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01	Oct '01	Nov '01	Dec '01
3114	2778	3026	2869	3009	3119	3000	3069	2841	2962	2707	2815
Jan '02	**Feb '02**	**Mar '02**	**Apr '02**	**May '02**	**June '02**	**July '02**	**Aug '02**	**Sept. '02**	**Oct. '02**		
3015	2991	2769	2961	2991	3055	3328	3337	3209	2921		

Is this a valid data matrix?

If not, give the column headings for the standard data matrix format.

Exercise 17.1 (c)

Pass/fail & failure reasons

Test Date & Time	Model Number	Serial Number	Test Station	Result	Failure Reason
3/1/2006 6:02	690	6099948	3	Passed	
3/1/2006 6:03	692	6087149	1	Passed	
3/1/2006 6:05	690	6099949	3	Failed	DoBatteryAccuracyTest
3/1/2006 6:06	690	6099949	3	Passed	
3/1/2006 6:12	692	6087150	1	Passed	
3/1/2006 6:12	690	6099932	3	Passed	
3/1/2006 6:13	692	6099622	2	Passed	
3/1/2006 6:15	690	6099933	3	Failed	Operating current outside of allowed range
3/1/2006 6:17	692	6099623	2	Passed	

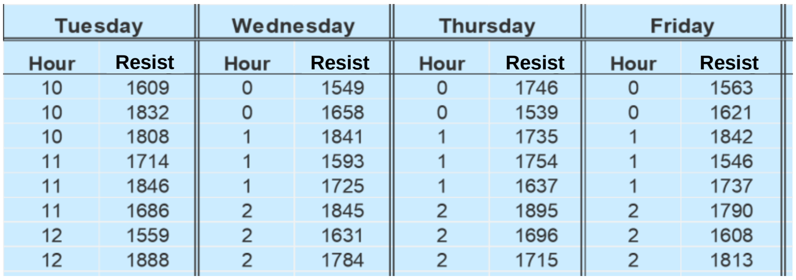
⋮

Is this a valid data matrix?

If not, give the column headings for the standard data matrix format.

Exercise 17.1 (d)

DI water sampled every 20 minutes



Tuesday		Wednesday		Thursday		Friday	
Hour	Resist	Hour	Resist	Hour	Resist	Hour	Resist
10	1609	0	1549	0	1746	0	1563
10	1832	0	1658	0	1539	0	1621
10	1808	1	1841	1	1735	1	1842
11	1714	1	1593	1	1754	1	1546
11	1846	1	1725	1	1637	1	1737
11	1686	2	1845	2	1895	2	1790
12	1559	2	1631	2	1696	2	1608
12	1888	2	1784	2	1715	2	1813

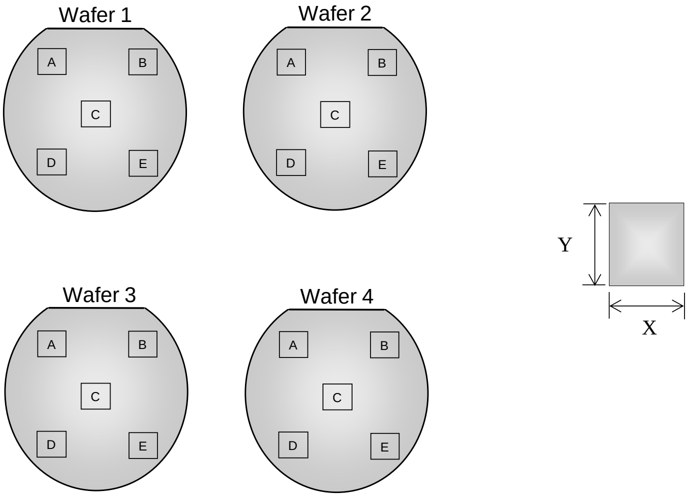
. . .

⋮

Is this a valid data matrix?

If not, give the column headings for the standard data matrix format.

Exercise 17.2



Exercise 17.2 (cont'd)

Computer chips are cut from silicon wafers. We selected chips cut from the same 5 locations on 4 wafers. We measured the X and Y dimensions of each chip. (It may help to sketch the data matrix.)

(a) Give the column headings for the standard data matrix format.

(b) How many rows are there?

(c) What does each row represent?

Example formats for manual data collection

Business Unit 1, 2, etc.	**Quote Number** XXXXXXX	**Rev** AA, AB, etc.	**First quote?** Yes/No	**FY Requested** 06, 07, etc.	**Date Requested** Format: 6/2/06	**Service Approval** Yes/No	**Finance Approval** Yes/No	**Date Sent** Format: 6/3/06	**Region** See code sheet	**Account Manager** AG, ET, GR, etc.

DATE Format: 10/28/04	**JOB NO.** 31, 32, etc.	**TASK** See code sheet	**OPER** AG, ET, GR, etc.	**T0TAL HOURS** X.XX	**VA HOURS** X.XX

Data collection forms (cont'd)

These examples are set up to match the desired data matrix format. This makes data entry easier.

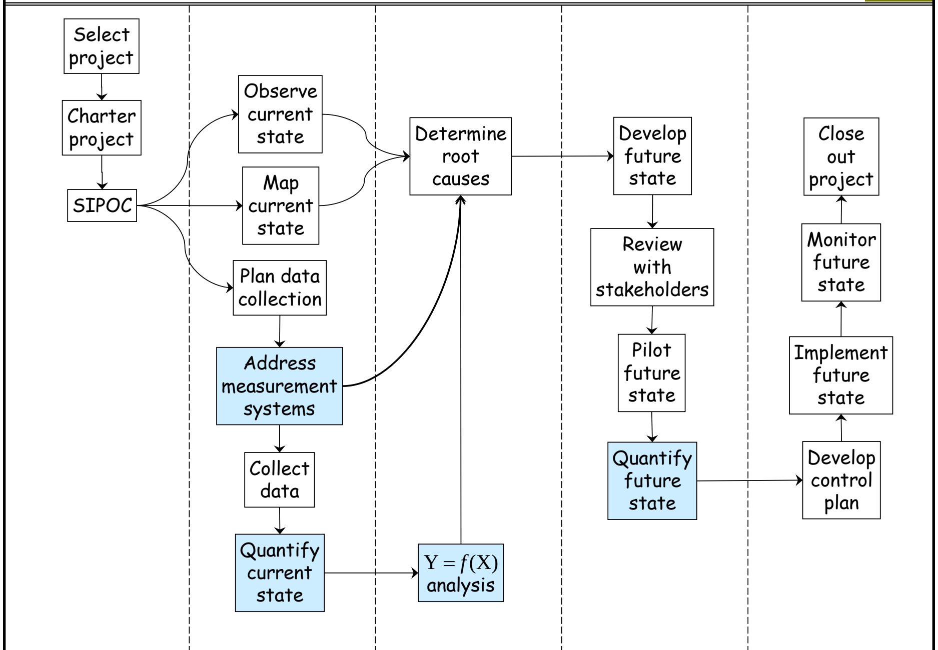
The most important thing about a data collection form is to eliminate as much variation in data entry as possible. Specify desired date and time formats. Use codes instead of free form text. Use uppercase initials instead of names. Specify desired numeric formats precisely.

Try to fit all the variables for which you want data collected on one page. Try to make the spaces big enough to write in. These things may work against each other. If there are too many columns to fit into portrait mode, use landscape mode instead. Do not include variables that can be calculated from other variables after the data are entered into a spreadsheet.

Best Practice: Have at least one person ***test the form*** or spreadsheet by collecting data for a short period of time, to make sure it works well before deploying it more broadly for data collection.

Notes

18 Types of Data



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Summary of data types

	Also known as	Examples
Quantitative measurement	✓Continuous ✓Variable ✓Parameter	Physical/chemical/electrical/optical properties, dimensions, distance, time, counts, . . .
Categorical classification	✓Qualitative ✓Discrete ✓Attribute	**Y variables** Pass/fail, type of defect, quality rating, . . . **X variables** Batch, lot, part number, supplier, customer, machine, operator, method, time period, location, condition, . . .

Quantitative Y variables

Dimensions of cylindrical castings

S/N	Length	Diameter
501	599.54	48.92
502	598.31	47.89
503	598.37	48.16
504	599.06	48.06
505	598.14	47.78
506	598.93	48.21
507	599.28	47.44
508	599.66	48.22
509	599.60	49.09
510	597.52	47.38
511	598.39	48.78
512	599.31	48.48
513	600.20	48.89
514	599.63	48.23
515	601.10	50.14
516	599.90	49.20
517	599.37	49.17

⋮

- True values may be infinitesimally close to each other
- Data resolution is determined by the measurement system
- Is **S/N** a quantitative measurement?

Quantitative Y variables

Resistivity of DI water

Tuesday		Wednesday	
Hour	Resist	Hour	Resist
10	1609	0	1549
10	1832	0	1658
10	1808	1	1841
11	1714	1	1593
11	1846	1	1725
11	1686	2	1845
12	1559	2	1631
12	1888	2	1784
13	1592	3	1704
13	1752	3	1676
13	1784	3	1860
14	1443	4	1619
14	1502	4	1398
14	1700	5	1556
15	1500	5	1687
15	1675	5	1574
15	1707	6	1733

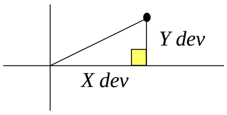
- Deionized water used in machining and cutting operations
- Electrical resistivity is the opposite of conductivity
- Higher resistivity means lower conductivity, which is good
- Data resolution is determined by the measurement system
- **Day of week** is a categorical classification
- **Hour of day**: quantitative or categorical?

Quantitative Y variables

X dev	Y dev
8	-6
-7	-2
-9	-4
-10	-5
-21	-7
-20	6
-13	-3
-16	9
-20	-1
-14	-4
-14	-6
-16	3
-14	-6
-23	-4
-11	-10
-19	7
-14	3
-10	-6

⋮

Alignment of assembled components



- Deviations from target in X and Y directions
- Reported to the nearest thousandth of an inch
- Decimal point dropped

Quantitative Y variables

ED patient visits

Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01	Oct '01	Nov '01	Dec '01
3114	2778	3026	2869	3009	3119	3000	3069	2841	2962	2707	2815
Jan '02	**Feb '02**	**Mar '02**	**Apr '02**	**May '02**	**June '02**	**July '02**	**Aug '02**	**Sept. '02**	**Oct. '02**		
3015	2991	2769	2961	2991	3055	3328	3337	3209	2921		

- ✓ **Count data** — number of occurrences of some defined event
- ✓ Whole numbers only, no negative numbers
- ✓ **Month-year** is categorical

Quantitative Y variables

Date	# Units	# Defects	DPU
9-Feb-90	8	8	1.00
10-Feb-90	8	17	2.13
11-Feb-90	9	18	2.00
12-Feb-90	8	15	1.88
15-Feb-90	8	23	2.88
16-Feb-90	7	9	1.29
17-Feb-90	7	19	2.71
18-Feb-90	8	6	0.75
19-Feb-90	8	14	1.75
22-Feb-90	8	17	2.13
23-Feb-90	7	13	1.86
24-Feb-90	8	15	1.88
25-Feb-90	9	16	1.78
26-Feb-90	9	22	2.44
1-Mar-90	8	13	1.63
2-Mar-90	8	10	1.25
3-Mar-90	4	14	3.50
4-Mar-90	8	9	1.13
5-Mar-90	12	23	1.92
8-Mar-90	12	21	1.75
9-Mar-90	16	51	3.19
10-Mar-90	8	31	3.88
11-Mar-90	4	3	0.75

Defects per unit

- Scratches on lenses, particles on silicon wafers, bubbles in a laminate, errors in documents, . . .
- **DPU** = number of defects divided by number of units inspected
- Used instead of DPMO when multiple defects per unit are possible, but there is not a finite number of identifiable defect opportunities per unit
- If the number of units is always 1, this is count data
- **Date**: quantitative or categorical?

Quantitative Y variables

Date requested	Date sent	Calendar days	Business days
05/26/04	05/26/04	1	1
05/26/04	05/26/04	1	1
06/02/04	06/02/04	1	1
06/02/04	06/02/04	1	1
06/02/04	06/02/04	1	1
06/02/04	06/02/04	1	1
06/02/04	06/03/04	2	2
06/03/04	06/04/04	2	2
06/04/04	06/04/04	1	1
06/04/04	06/07/04	4	2
06/07/04	06/07/04	1	1
06/07/04	06/07/04	1	1
06/07/04	06/08/04	2	2
06/08/04	06/08/04	1	1
06/08/04	06/08/04	1	1
06/08/04	06/08/04	1	1
06/09/04	06/09/04	1	1
06/11/04	06/11/04	1	1
06/11/04	06/11/04	1	1
06/14/04	06/14/04	1	1
06/14/04	06/14/04	1	1

Transaction turnaround time

- (Date sent) - (date requested)

or

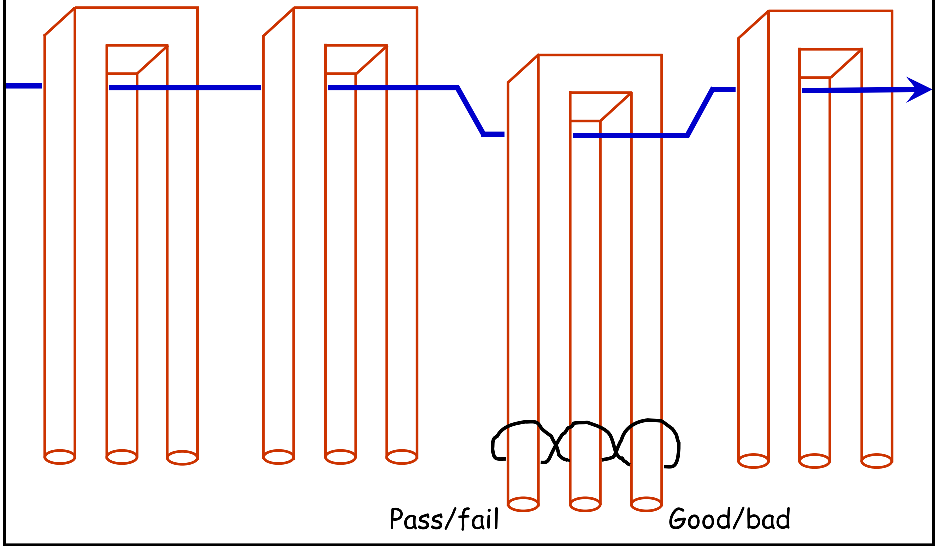
- (Date sent) – (date requested) + 1
- Calendar or business* days
- The whole number resolution is a limitation of the measurement system

---

*The Excel function NETWORKDAYS subtracts out the weekends

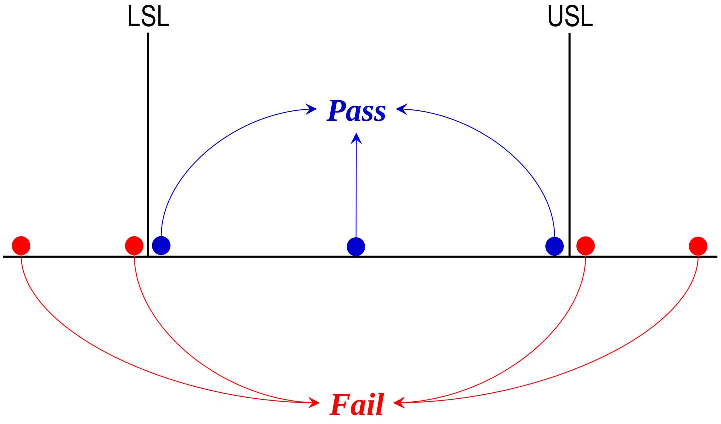
Pass/fail Y variable

Testing fit, form and function on the mounting bracket production line



Pass/fail Y variable

Can be derived from quantitative data and spec limits



- Necessary for computing % out of spec
- Do not discard or ignore the underlying quantitative data!

Pass/fail Y variable

Monthly late account closings

	2001	2002	2003
Jan	3	6	2
Feb	5	4	2
Mar	3	3	4
Apr	2	2	6
May	3	4	2
Jun	7	4	5
Jul	5	1	10
Aug	4	5	
Sep	3	2	
Oct	3	7	
Nov	3	2	
Dec	2	1	

- Data for 35 offices
- Tabulated pass/fail data
- Underlying raw data:

  On time or late for each office for each month
- What we really want is **days late** for each office for each month

Pass/fail Y variables

Result & failure reasons

Test Date & Time	Model Number	Serial Number	Test Station	Result	Failure Reason
3/1/2006 6:02	690	6099948	3	Passed	
3/1/2006 6:03	692	6087149	1	Passed	
3/1/2006 6:05	690	6099949	3	Failed	DoBatteryAccuracyTest
3/1/2006 6:06	690	6099949	3	Passed	
3/1/2006 6:12	692	6087150	1	Passed	
3/1/2006 6:12	690	6099932	3	Passed	
3/1/2006 6:13	692	6099622	2	Passed	
3/1/2006 6:15	690	6099933	3	Failed	Operating current outside of allowed range
3/1/2006 6:17	692	6099623	2	Passed	
3/1/2006 6:18	690	6099933	3	Failed	DoBatteryAccuracyTest
3/1/2006 6:18	690	6099933	3	Failed	Operating current outside of allowed range
3/1/2006 6:19	692	6087151	1	Passed	
3/1/2006 6:20	690	6099782	3	Passed	
3/1/2006 6:21	692	6099624	2	Passed	
3/1/2006 6:22	692	6087152	1	Passed	
3/1/2006 6:22	690	6099934	3	Passed	
3/1/2006 6:24	690	6099935	3	Failed	DoSwitchTest
3/1/2006 6:24	692	6087153	1	Failed	Sleep current outside of allowed range
3/1/2006 6:25	692	6099625	2	Passed	
3/1/2006 6:27	690	6099935	3	Failed	DoSwitchTest

Tabulated defect data

Date	Shift	Defect	Freq
3/1/1991	A	Contamination	15
3/1/1991	A	Corrosion	2
3/1/1991	A	Doping	1
3/1/1991	A	Metallization	2
3/1/1991	A	Miscellaneous	3
3/1/1991	A	Oxide Defect	8
3/1/1991	A	Silicon Defect	1
3/1/1991	B	Contamination	8
3/1/1991	B	Corrosion	2
3/1/1991	B	Doping	1
3/1/1991	B	Metallization	4
3/1/1991	B	Miscellaneous	2
3/1/1991	B	Oxide Defect	10
3/1/1991	B	Silicon Defect	3
3/2/1991	A	Contamination	16
3/2/1991	A	Corrosion	3
3/2/1991	A	Doping	1
3/2/1991	A	Metallization	3
3/2/1991	A	Miscellaneous	1
3/2/1991	A	Oxide Defect	9
3/2/1991	A	Silicon Defect	2

Defects by type

- **Defect** is a categorical classification
- **Freq** is quantitative — it counts the number of defects of each type for each day and shift
- Good for Pareto analysis
- Can we get actual occurrence rates? What is missing?
- **Shift** is a categorical classification
- **Date**: quantitative or categorical?

Categorical Y variable

Application	Appraiser	Rating
1	Simpson	5
1	Montgomery	5
1	Holmes	5
1	Duncan	4
1	Hayes	5
2	Simpson	2
2	Montgomery	2
2	Holmes	2
2	Duncan	1
2	Hayes	2
3	Simpson	4
3	Montgomery	3
3	Holmes	3
3	Duncan	3
3	Hayes	3
4	Simpson	1
4	Montgomery	1
4	Holmes	1
4	Duncan	1
4	Hayes	1
5	Simpson	0
5	Montgomery	0

Quality rating

- Five-point scale: 1, 2, 3, 4, 5
- In this case, higher is better
- Treated as quantitative when we want to average the ratings (for example, GPA)
- **Appraiser** is a categorical classification
- **Application**: quantitative or categorical?

Exercise 18.1

Pretend the data shown below contains actual data on actual cars. Check the appropriate data type for each variable.

In some cases, the data type may go either way, depending on how the variable is used.

	Quantitative	Categorical
Model year		
Origin		
Make		
Model		
Cylinders		
Displacement		
Horsepower		
Weight		
Accel		
MPG		

Exercise 18.1 (cont'd)

Model year	Origin	Make	Model	Cylinders	Displace	Horsepower	Weight	Accel	MPG
79	Europe	Mercedes	300D	5	183	77	3530	20.1	25.4
80	Europe	Mercedes	240D	4	146	67	3250	21.8	30.4
79	America	Cadillac	Eldorado	8	350	125	3900	17.4	23.0
81	Japan	Toyota	Cressida	6	168	116	2900	12.6	25.4
81	Europe	Volvo	Diesel	6	145	76	3160	19.6	30.7
81	Europe	Peugeot	505S DI	4	141	80	3230	20.4	28.1
82	America	Chevrolet	Camaro	4	151	90	2950	17.3	27.0
81	Japan	Datsun	810 Maxima	6	146	120	2930	13.8	24.2
81	Europe	Saab	900S	4	121	110	2800	15.4	
80	Japan	Datsun	280-ZX	6	168	132	2910	11.4	32.7
80	Europe	Audi	5000S DI	5	121	67	2950	19.9	36.4
82	Japan	Toyota	Celica GT	4	144	96	2665	13.9	32.0
82	America	Oldsmobile	Cutlass DI	6	262	85	3015	17.0	38.0
82	America	Buick	CenturyLmt	6	181	110	2945	16.4	25.0
80	Japan	Mazda	RX-7 GS	3	70	100	2420	12.5	23.7
80	Europe	Volkswagen	Rabbit	4	98	76	2144	14.7	41.5
80	Europe	Volkswagen	Rabbit	4	89	62	1845	15.3	29.8
81	America	Oldsmobile	Cutlass LS	8	350	105	3725	19.0	26.6
81	America	Buick	Century	6	231	110	3415	15.8	22.4
82	Japan	Honda	Accord	4	107	75	2205	14.5	36.0
82	Japan	Nissan	Stanza XE	4	120	88	2160	14.5	36.0

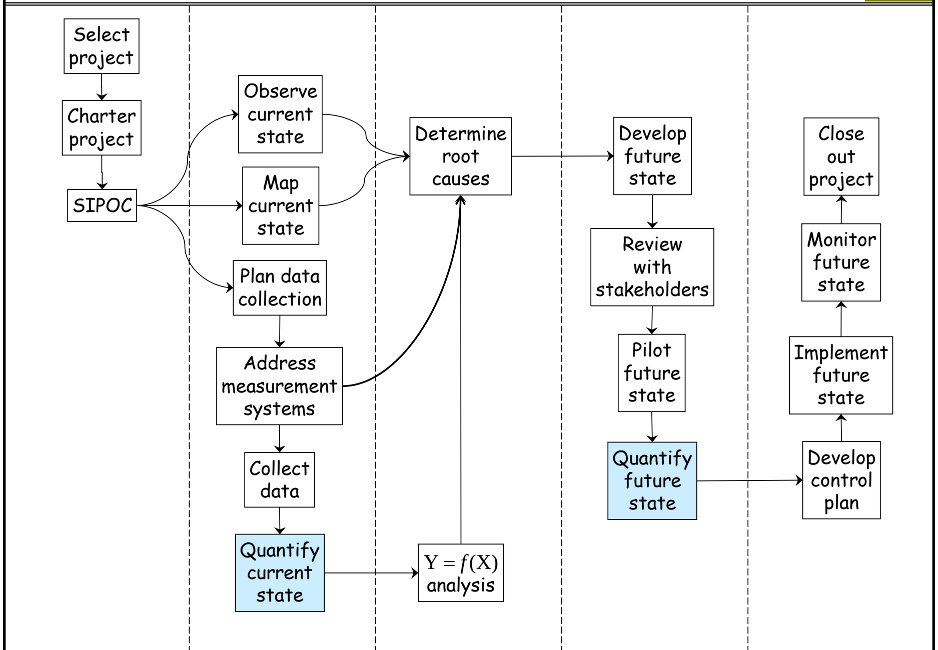
Exercise 18.2

(a) Which useful statistical project metrics can be calculated from a quantitative Y variable?

(b) Which useful statistical project metrics can be calculated from a pass/fail Y variable?

Notes

19 Basic Statistics and Normal Distribution



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Basic statistic summary for continuous (quantitative) data

$$\text{Average} = \left(\text{Sum of N numbers}\right)\big/\text{N}$$

$$\text{Sample mean} = \text{Average of a sample from a population}$$

A set of numbers: 76, 80, 80, 81, 82, 82, 88, 92

$$\text{N} = 8$$

$$\begin{aligned}\text{Average} &= (76 + 80 + 80 + 81 + 82 + 82 + 88 + 92)\big/8\\ &= 661/8\\ &= 82.6\end{aligned}$$

Minimum = 76

Maximum = 92

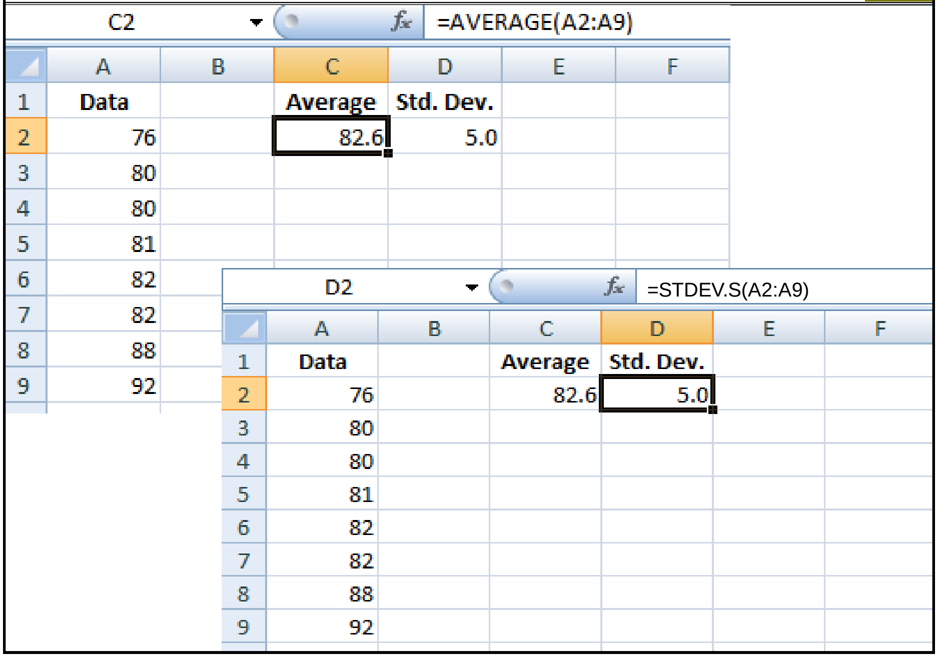
Basic statistics (cont'd)

Sample standard deviation $=$

$$\sqrt{\frac{(76-82.6)^2+(80-82.6)^2+(80-82.6)^2+(81-82.6)^2 +(82-82.6)^2+(82-82.6)^2+(88-82.6)^2+(92-82.6)^2}{7}}$$

$$= 5.04$$

Average and standard deviation in Excel



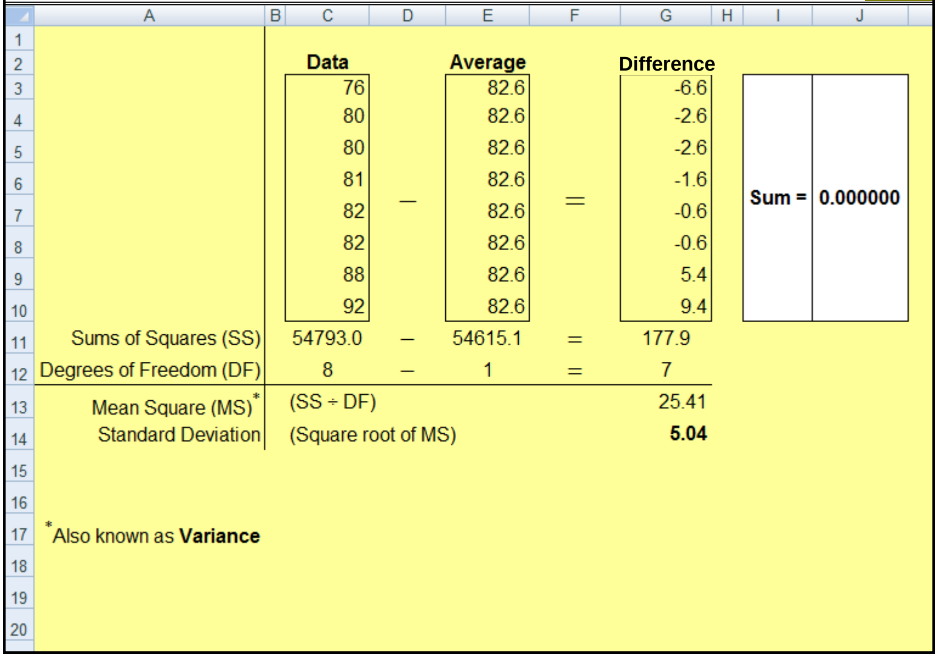
C2 =AVERAGE(A2:A9)

	A	B	C	D	E	F
1	Data		Average	Std. Dev.		
2	76		82.6	5.0		
3	80					
4	80					
5	81					
6	82					
7	82					
8	88					
9	92					

D2 =STDEV.S(A2:A9)

	A	B	C	D	E	F
1	Data		Average	Std. Dev.		
2	76		82.6	5.0		
3	80					
4	80					
5	81					
6	82					
7	82					
8	88					
9	92					

Open *Student Files* → *anatomy of STDEV*



	A	B	C	D	E	F	G	H	I	J
1										
2			**Data**		**Average**		**Difference**			
3			76		82.6		-6.6			
4			80		82.6		-2.6			
5			80		82.6		-2.6			
6			81		82.6		-1.6			
7			82	−	82.6	=	-0.6		**Sum =**	**0.000000**
8			82		82.6		-0.6			
9			88		82.6		5.4			
10			92		82.6		9.4			
11	Sums of Squares (SS)		54793.0	−	54615.1	=	177.9			
12	Degrees of Freedom (DF)		8	−	1	=	7			
13	Mean Square (MS)*		(SS ÷ DF)				25.41			
14	Standard Deviation		(Square root of MS)				**5.04**			
15										
16										
17	*Also known as **Variance**									
18										
19										
20										

Anatomy of STDEV (cont'd)

This sheet lays out the calculation of the sample standard deviation (the STDEV.S function in Excel).

The *Data* column contains 8 independent measurements (no constraints among them). We describe this by saying this column has 8 *degrees of freedom* (DFs).

The *Average* column contains a single value, repeated 8 times. We describe this by saying this column has 1 DF.

The *Difference* column is mathematically constrained to sum to 0, so it contains only 7 mathematically independent values. From any 7 values in this column, we can calculate the remaining value. (What is the formula?) We describe this by saying this column has 7 DFs.

This is why the sum of the squared differences is divided by 7 rather than 8. Dividing by 8 would bias it downwards.

Exercise 19.1

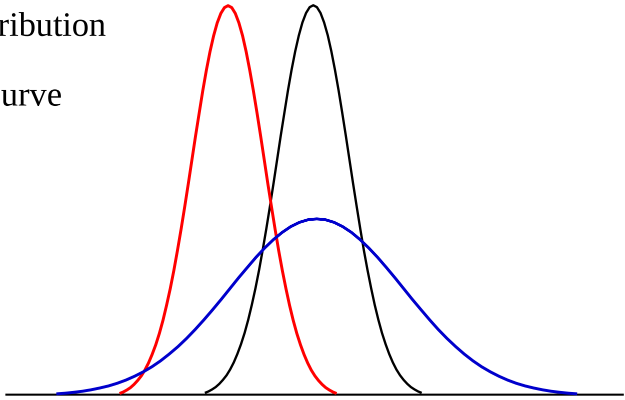
a) Open *Data Sets* → *solution properties*. Calculate the average and standard deviation for *Spec grav*. Save your work.

b) Open *Data Sets* → *ED patient visits*. Calculate the average and standard deviation of *Visits*. Save your work.

The Normal Distribution

Also known as

- Gaussian distribution
- Bell-shaped curve



Everyone believes in the Normal curve: experimenters think it is a mathematical theorem, mathematicians think it is an experimental fact. —G. Lippman

Normal distribution (cont'd)

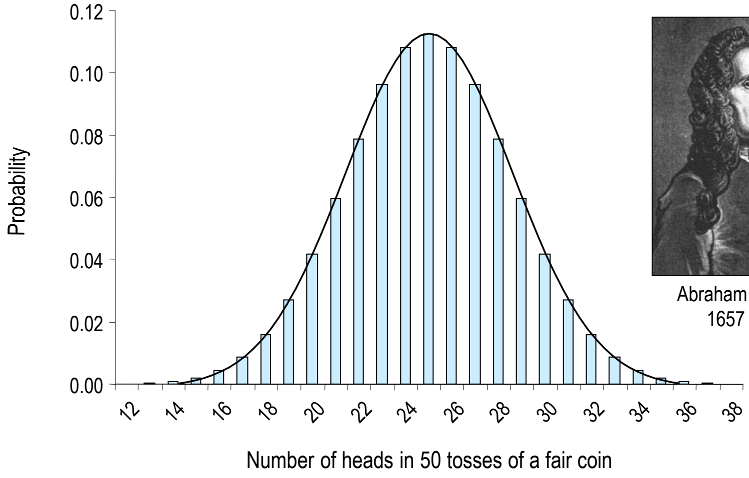
The Normal distribution is an abstraction, an idealization, a mathematical construct. At the same time, it has been a device of great practical value in Statistics.

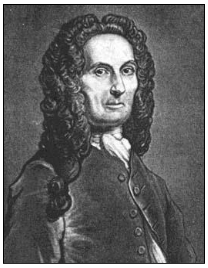
It's called the Gaussian distribution because the German mathematician Carl Friedrich Gauss made important early applications to astronomy in the 1820s. As we will see, it was actually discovered a century earlier by the French mathematician Abraham de Moivre.

I guess life really isn't fair.

Origin of the Normal distribution

As the number of tosses of a fair coin increases, the probability distribution of the number of heads approaches a bell shaped curve.





Abraham de Moivre
1657 - 1754

Origin of Normal distribution (cont'd)

The statistical model for the number of heads in N tosses of a coin is called the Binomial distribution. In 1730, the French mathematician Abraham de Moivre discovered the bell-shaped curve as the limiting form approached by the Binomial distribution as the sample size N increases without bound. He never made any money on his discovery of the Normal distribution, and in fact died a pauper. To add insult to injury, it was eventually named after someone else (Gauss).

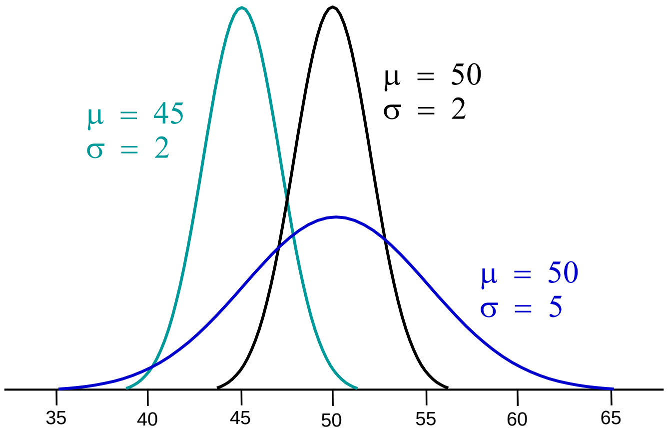
Over the next 200 years, de Moivre's discovery was extended far beyond coin tossing. Today, we know that many quantitative measurements are sums of large numbers of small, independent, possibly unobservable contributing factors. Measurements of this type in a stable population will follow the Normal distribution, at least as a good approximation. Statisticians call this phenomenon the Central Limit Theorem.

The Normal distribution is the default population model for quantitative measurements.

The bell shaped curve

μ = Greek letter *mu* → Population mean

σ = Greek letter *sigma* → Population standard deviation



Bell-shaped curve (cont’d)

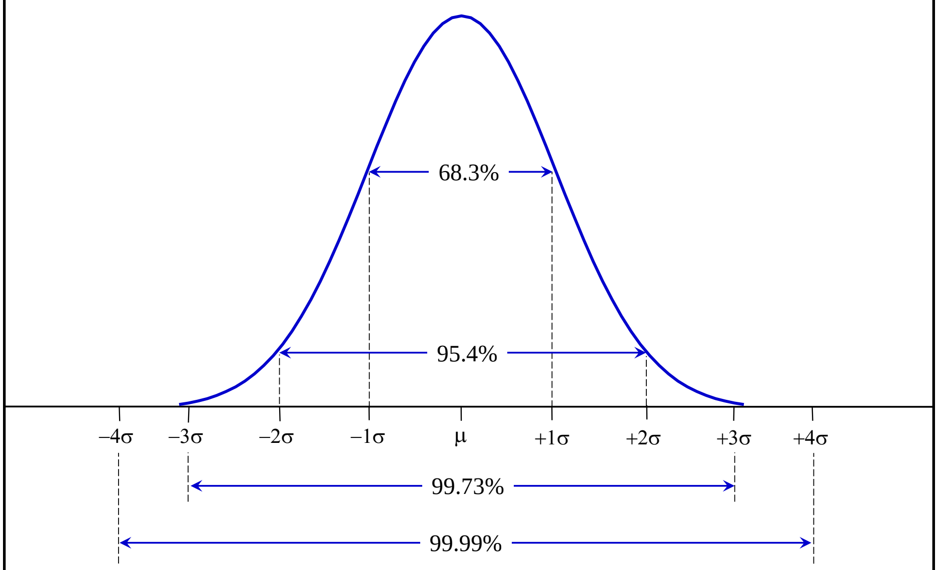
A population model is an equation that can be used to make predictions about a population. When we represent the mean and standard deviation by Greek letters, as above, we are thinking of the mean and standard deviation of the entire population, not just the numbers in our data set. It means we are thinking of the Normal distribution as a population model.

The formula for the bell shaped curve is given below. In this equation, $f(y)$ is the height of the curve above the value y on the horizontal axis.

$$f(y)=\frac{1}{\sqrt{2\pi}}\frac{1}{\sigma}e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^{2}}$$

You may have been graded “on the curve” at some point in your academic career. Well, this is the curve.

Area under curve = % of population



Area under curve (cont'd)

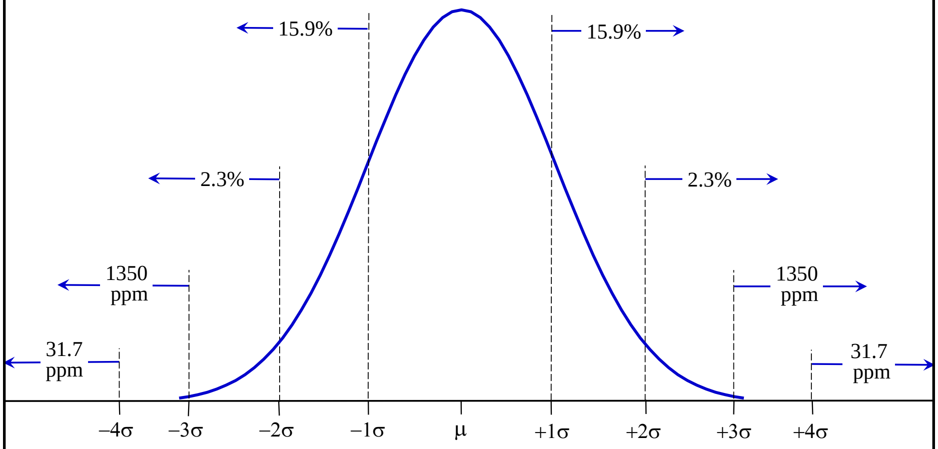
For a Normal population:

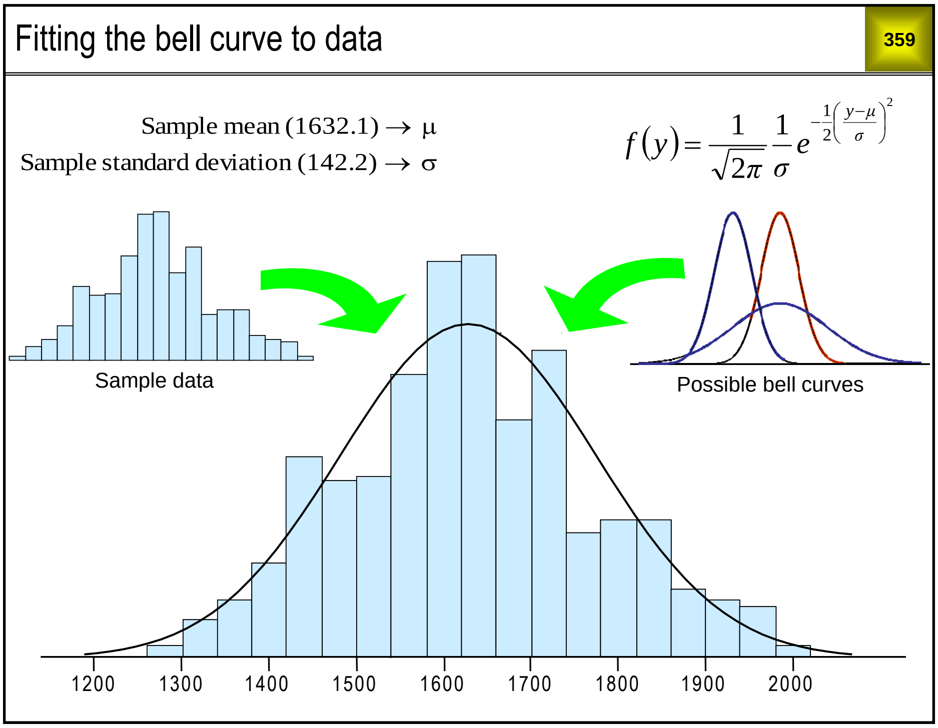
- The 1.960σ limits contain 95% of the population.
- The 2σ limits contain 95.45% of the population.

- The 2.576σ limits contain 99% of a Normal population
- The 3σ limits contain 99.73% of the population.

Area under curve = % of population

Usually we care mostly about % *beyond* certain points



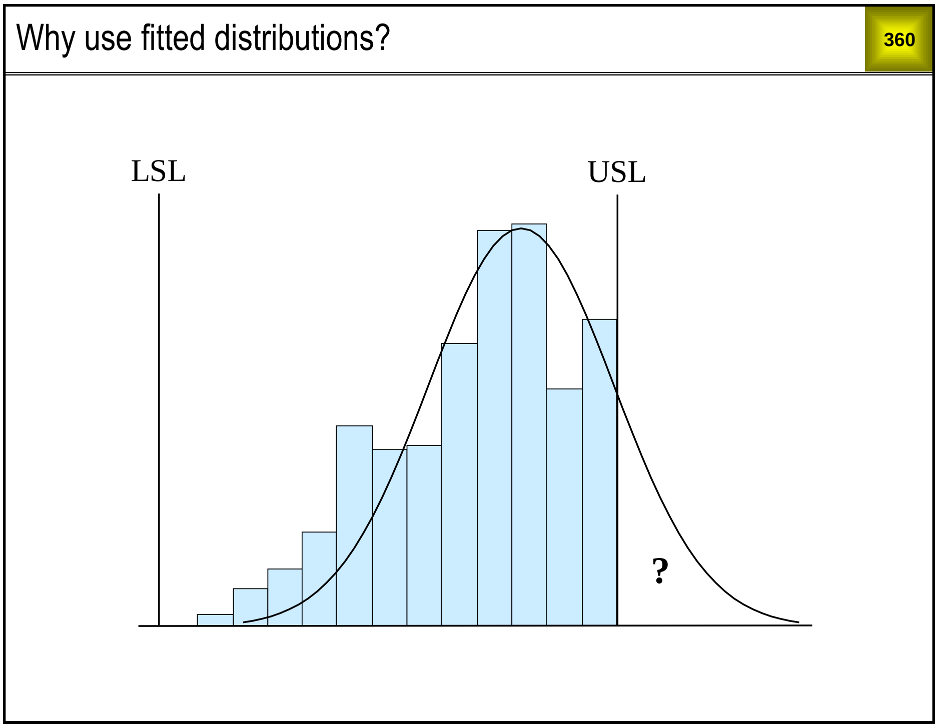


Fitting the bell curve to data

Sample mean (1632.1) → μ

Sample standard deviation (142.2) → σ

$$f(y)=\frac{1}{\sqrt{2\pi}}\frac{1}{\sigma}e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2}$$



Why use fitted distributions?

Why distributions? (cont'd)

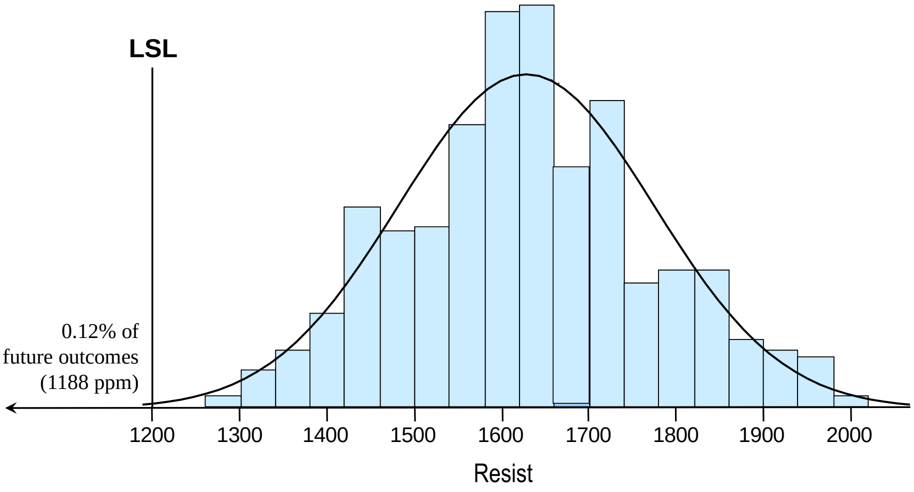
The practice of calculating % defective or DPPM by means of fitted distributions instead of raw data came about historically as a crude but effective way for customers in the aerospace and automotive supply chains to expose the "hidden factories" of their suppliers.

Suppliers would present final inspection data to customers to document their process capability. In the example shown above, the supplier claims 100% yield. When plotted as a histogram, the data mysteriously disappears right at the upper spec limit. This is because parts exceeding the upper limit are either scrapped or reworked to the limit. Often the rework is done by the inspector and not recorded as rework. In many cases, the first pass data is not recorded.

A distribution curve pays no attention to spec limits and will always produce a positive value for % defective or DPPM. This gives an estimate of the supplier's first pass yield. In the example shown above, it is obvious that the first pass yield is far below 100%.

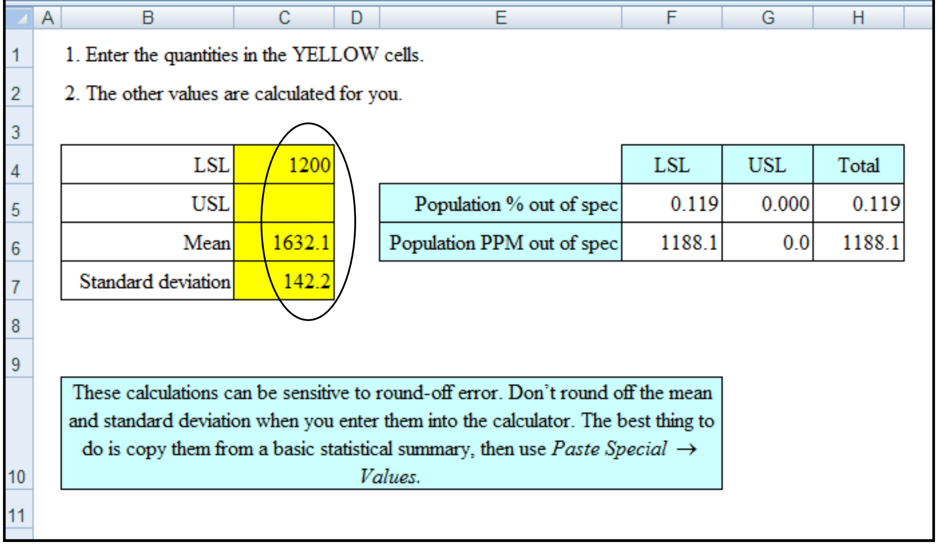
Using the Normal curve to predict % defective or DPPM

Allows extrapolation (😊 ☹)



% below 1200

Student Files → calculator - Normal distribution



1. Enter the quantities in the YELLOW cells.

2. The other values are calculated for you.

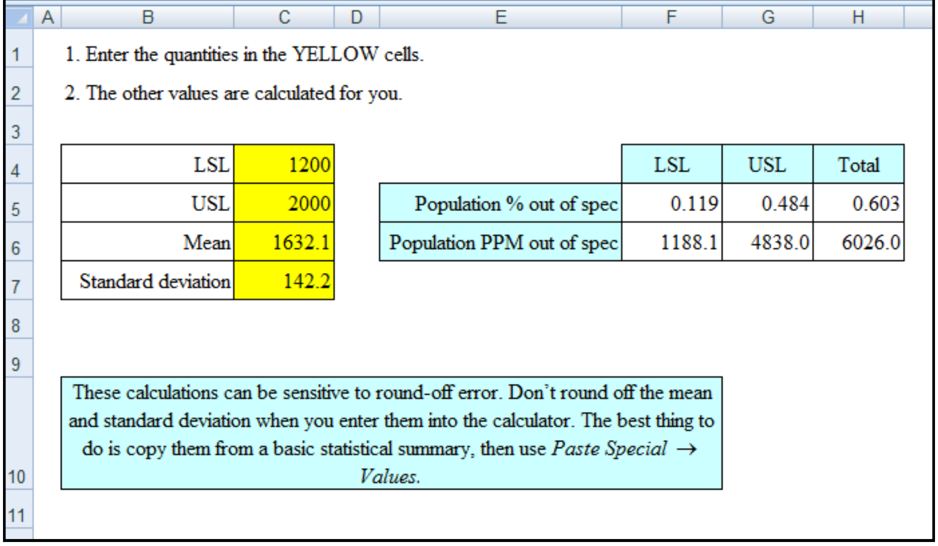
LSL	1200
USL	
Mean	1632.1
Standard deviation	142.2

	LSL	USL	Total
Population % out of spec	0.119	0.000	0.119
Population PPM out of spec	1188.1	0.0	1188.1

These calculations can be sensitive to round-off error. Don't round off the mean and standard deviation when you enter them into the calculator. The best thing to do is copy them from a basic statistical summary, then use *Paste Special → Values.*

% below 1200 **or** above 2000

Student Files → calculator - Normal distribution



1. Enter the quantities in the YELLOW cells.

2. The other values are calculated for you.

LSL	1200
USL	2000
Mean	1632.1
Standard deviation	142.2

	LSL	USL	Total
Population % out of spec	0.119	0.484	0.603
Population PPM out of spec	1188.1	4838.0	6026.0

These calculations can be sensitive to round-off error. Don't round off the mean and standard deviation when you enter them into the calculator. The best thing to do is copy them from a basic statistical summary, then use *Paste Special → Values.*

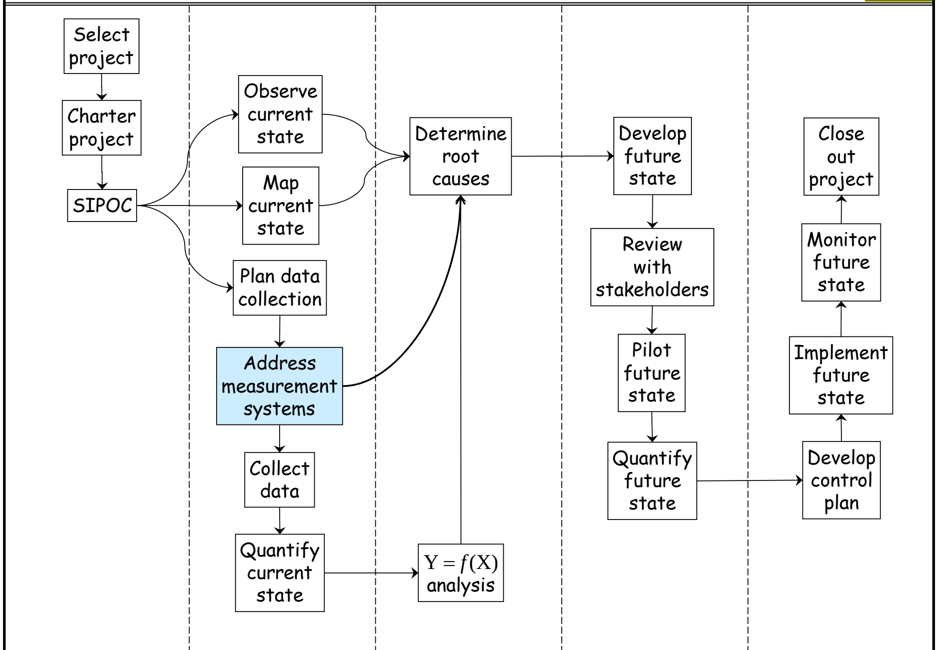
Exercise 19.2

a) Open *Data Sets* → *solution properties*. Use the mean and standard deviation you calculated in Exercise 19.1 to find the % or PPM for which *Spec grav* is greater than 0.925.

b) Open *Data Sets* → *ED patient visits*. Use the mean and standard deviation you calculated in Exercise 19.1 to find the % or PPM for which *Visits* is either less than 2700 or greater than 3300.

Notes

20 Measurement Variation



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

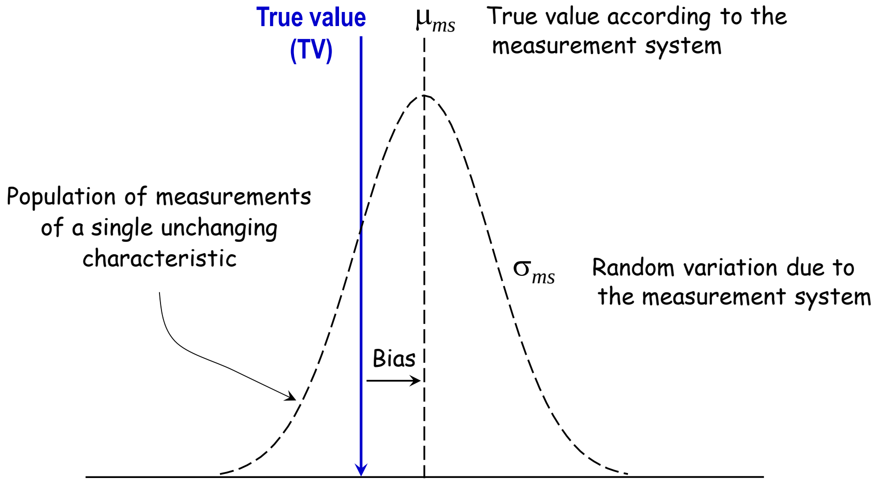
Develop control plan

Topics

- Population model for measurement variation
- How components of variation add up
- Calculating measurement variation*
- Degrees of freedom

*In the situation where there is only one appraiser.

Population model for measurement variation



Measurement error = Systematic error (bias) + Random error

Population model (cont'd)

- The purpose of calibration is to eliminate gage bias
- Calibration requires standards (measurable items whose true values are known) or a calibrated second gage of higher accuracy
- The primary objective of quantitative measurement system analysis (MSA) is to determine the variation contributed by the measurement system, σ_{ms}, which is *more than gage bias*

To be clear, calibration is not enough!

- Quantitative MSA does not require standards
- If gage bias is constant during the MSA, the resulting σ_{ms} will be accurate
- If gage bias changes during the MSA, the resulting σ_{ms} will be biased upwards

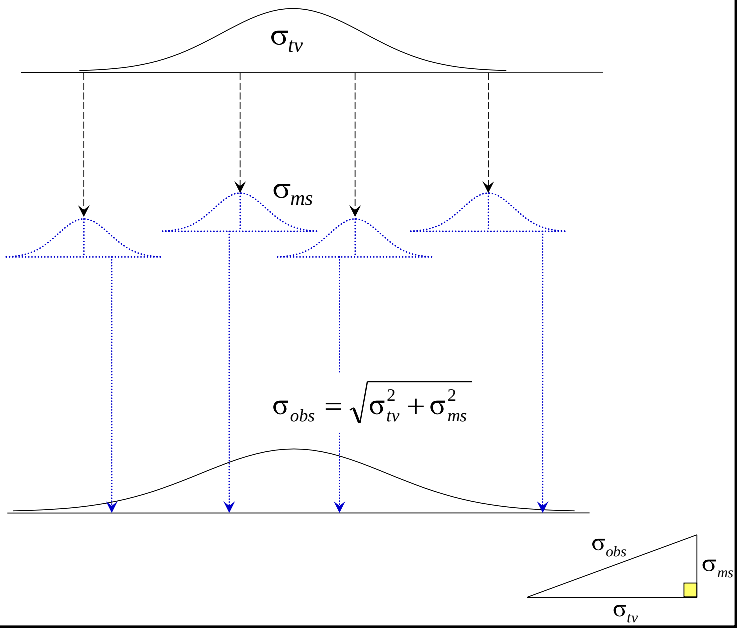
How components of *variation* add up

Variation in true values

+

Measurement variation

Observed variation



$$\sigma_{obs} = \sqrt{\sigma_{tv}^2 + \sigma_{ms}^2}$$

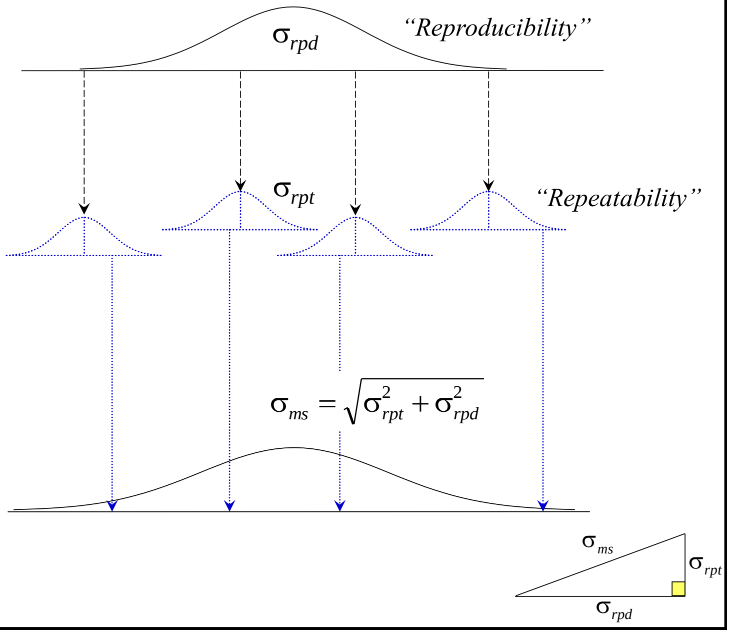
Components of *measurement system variation*

Appraisers not agreeing with each other

+

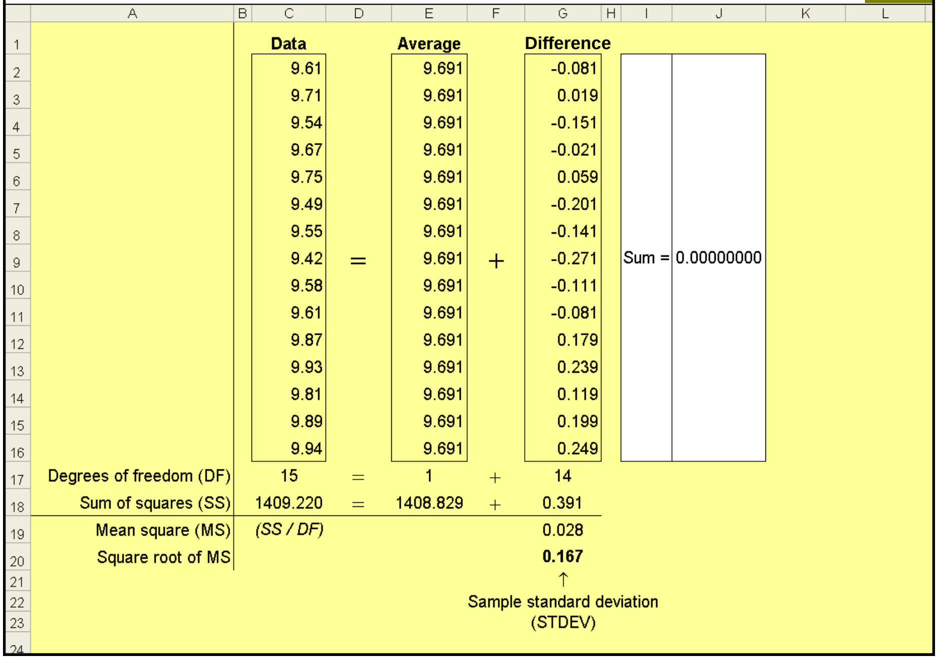
Appraisers not agreeing with themselves

Measurement system variation



$$\sigma_{ms} = \sqrt{\sigma_{rpt}^2 + \sigma_{rpd}^2}$$

STDEV revisited



	A	C	D	E	F	G	I	J
1		**Data**		**Average**		**Difference**		
2		9.61		9.691		-0.081		
3		9.71		9.691		0.019		
4		9.54		9.691		-0.151		
5		9.67		9.691		-0.021		
6		9.75		9.691		0.059		
7		9.49		9.691		-0.201		
8		9.55		9.691		-0.141		
9		9.42	=	9.691	+	-0.271	Sum =	0.00000000
10		9.58		9.691		-0.111		
11		9.61		9.691		-0.081		
12		9.87		9.691		0.179		
13		9.93		9.691		0.239		
14		9.81		9.691		0.119		
15		9.89		9.691		0.199		
16		9.94		9.691		0.249		
17	Degrees of freedom (DF)	15	=	1	+	14		
18	Sum of squares (SS)	1409.220	=	1408.829	+	0.391		
19	Mean square (MS)	*(SS / DF)*				0.028		
20	Square root of MS					**0.167**		
21						↑		
22						Sample standard deviation		
23						(STDEV)		
24								

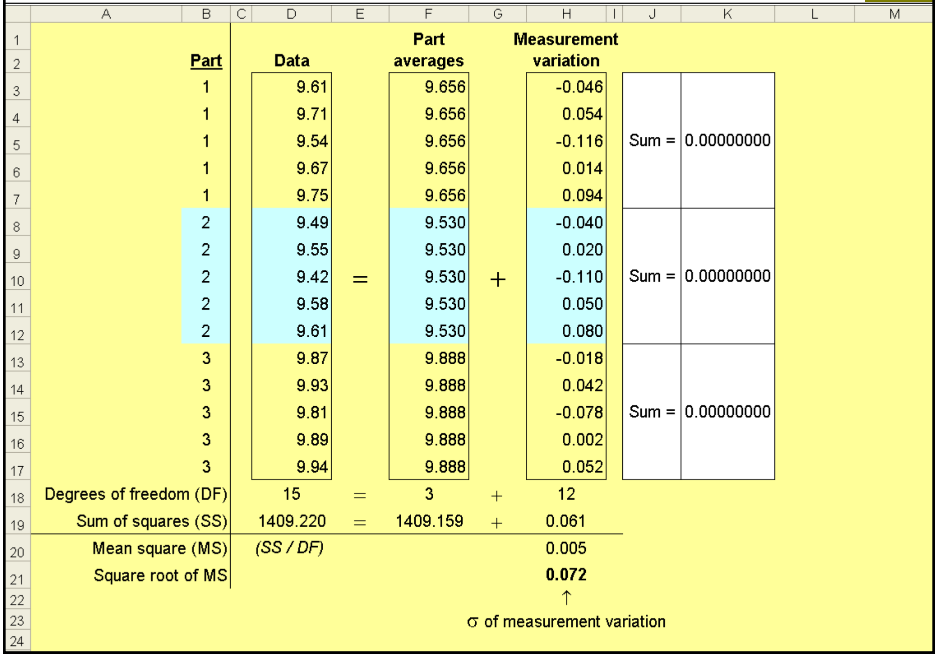
STDEV (cont'd)

The slide above is a screen shot of the worksheet *Observed variation* in *Student Files* → *MSA - one appraiser*. This sheet reviews the calculation of the sample standard deviation. In MSA, this is called the "observed variation." In other types of data analysis, it is called the "total variation."

<u>Recap of *degrees of freedom* (DFs)</u>

- The *Data* column has 15 DFs because it consists of 15 independent measurements.
- The *Average* column has 1 DF because it consists of a single value repeated 15 times.
- The *Difference* column is constrained to sum to 0, so it contains only 14 independent values, so it has 14 DFs.
- DFs have to add up. For example, 15 = 1 + 14.

MSA with one appraiser (cont’d)



	A	B	D	E	F	G	H	J	K
1					Part		Measurement		
2		**Part**	**Data**		**averages**		**variation**		
3		1	9.61		9.656		-0.046	Sum =	0.00000000
4		1	9.71		9.656		0.054		
5		1	9.54		9.656		-0.116		
6		1	9.67		9.656		0.014		
7		1	9.75		9.656		0.094		
8		2	9.49		9.530		-0.040	Sum =	0.00000000
9		2	9.55		9.530		0.020		
10		2	9.42	=	9.530	+	-0.110		
11		2	9.58		9.530		0.050		
12		2	9.61		9.530		0.080		
13		3	9.87		9.888		-0.018	Sum =	0.00000000
14		3	9.93		9.888		0.042		
15		3	9.81		9.888		-0.078		
16		3	9.89		9.888		0.002		
17		3	9.94		9.888		0.052		
18	Degrees of freedom (DF)		15	=	3	+	12		
19	Sum of squares (SS)		1409.220	=	1409.159	+	0.061		
20	Mean square (MS)		*(SS / DF)*				0.005		
21	Square root of MS						**0.072**		
22							↑		
23							σ of measurement variation		
24									

MSA with one appraiser (cont’d)

The slide above is a screen shot of the sheet *Measurement variation*. It lays out the calculation of σ_{ms} when each of 3 parts is measured 5 times by one appraiser.

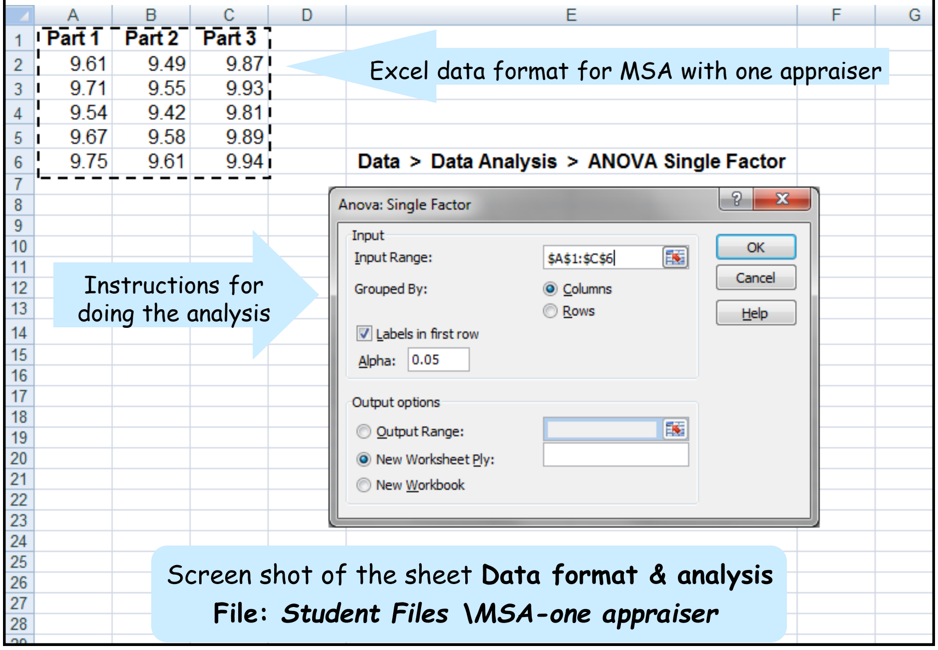
The *Part averages* column has 3 DFs because it consists of 3 independent values (the part averages).

In the *Measurement variation* column, the values for each part are constrained to sum to 0, so any 4 of them determine the remaining value. There are 3 parts, so there are only 3 × 4 = 12 independent values in this column, so it has 12 DFs.

Because the calculation of σ_{ms} involves only 12 independent values, we sometimes refer to σ_{ms} itself as having 12 DFs. The greater the DFs for σ_{ms}, the more accurate it is.

As before, DFs have to add up: 15 = 3 + 12.

MSA with one appraiser (cont'd)



Part 1	Part 2	Part 3
9.61	9.49	9.87
9.71	9.55	9.93
9.54	9.42	9.81
9.67	9.58	9.89
9.75	9.61	9.94

Excel data format for MSA with one appraiser

Data > Data Analysis > ANOVA Single Factor

Instructions for doing the analysis

Anova: Single Factor

Input

Input Range: $A$1:$C$6

Grouped By: ● Columns ○ Rows

☑ Labels in first row

Alpha: 0.05

Output options

○ Output Range:

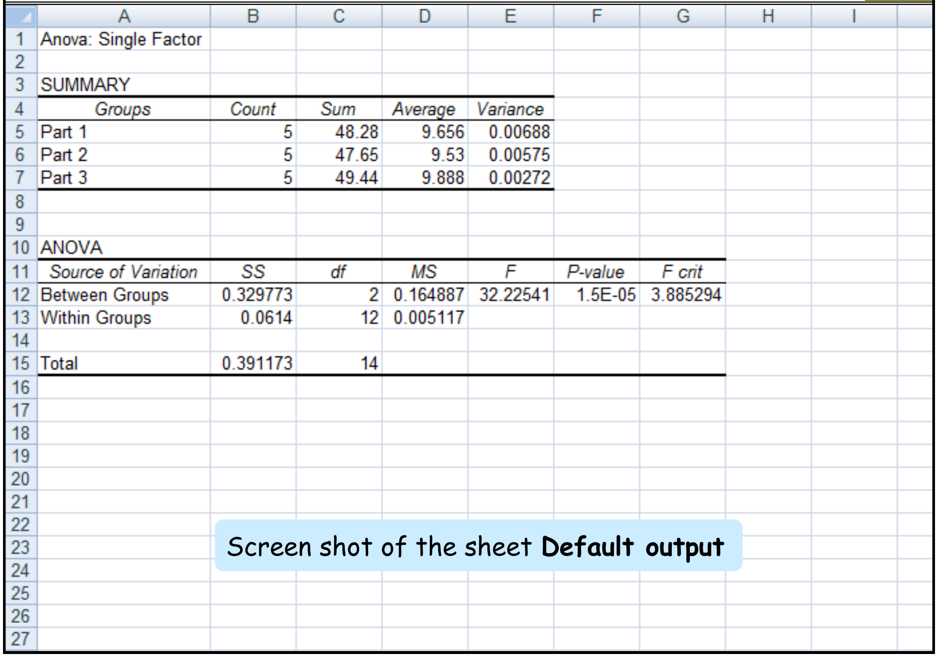
● New Worksheet Ply:

○ New Workbook

Screen shot of the sheet **Data format & analysis**

File: *Student Files \MSA-one appraiser*

MSA with one appraiser (cont'd)



Anova: Single Factor

SUMMARY

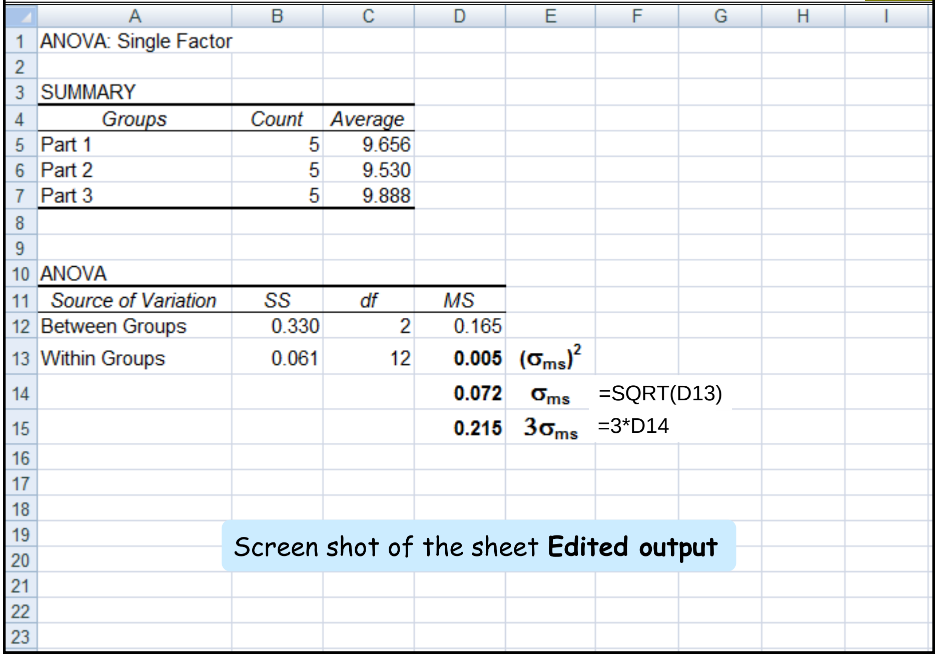
Groups	Count	Sum	Average	Variance
Part 1	5	48.28	9.656	0.00688
Part 2	5	47.65	9.53	0.00575
Part 3	5	49.44	9.888	0.00272

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.329773	2	0.164887	32.22541	1.5E-05	3.885294
Within Groups	0.0614	12	0.005117			
Total	0.391173	14				

Screen shot of the sheet **Default output**

MSA with one appraiser (cont'd)



ANOVA: Single Factor					
SUMMARY					
Groups	*Count*	*Average*			
Part 1	5	9.656			
Part 2	5	9.530			
Part 3	5	9.888			
ANOVA					
Source of Variation	*SS*	*df*	*MS*		
Between Groups	0.330	2	0.165		
Within Groups	0.061	12	**0.005**	$(\sigma_{ms})^2$	
			0.072	σ_{ms}	=SQRT(D13)
			0.215	$3\sigma_{ms}$	=3*D14

Screen shot of the sheet **Edited output**

Exercise 20.1

Open file *Student Files \ MSA-one appraiser*

Perform the analysis shown in the last three slides.

The value $3\sigma_{ms}$ is the *measurement error* — the amount by which a single measurement could vary (+ or -) from the true value.

Degrees of freedom for MSA with one appraiser

- Let: N = sample size of an MSA (total number of measurements)

  I = number of items in the MSA (parts, transactions, samples, . . .)

- DF for σ_{ms} = N – I

NOTE:
I, not 1 (one) !

- In the previous example: N = 15, I = 3
- DF for σ_{ms} = N – I = 15 – 3 = 12

Exercise 20.2

For each scenario below, give the total number of measurements and the degrees of freedom for σ_{ms}.

	N	DF
(a) 1 item is measured 15 times		
(b) Each of 15 items is measured 1 time		
(c) Each of 3 items is measured 5 times		
(d) Each of 3 items is measured 10 times		
(e) Each of 15 items is measured 2 times		
(f) Each of 4 items is measured 10 times		
(g) Each of 20 items is measured 2 times		
(h) Each of 8 items is measured 8 times		
(i) Each of 36 items is measured 2 times		

Degrees of freedom for MSA with multiple appraisers

- Let: N = sample size of an MSA (total number of measurements)

  I = number of items in the MSA (parts, transactions, whatever)

  A = number of appraisers

  S = number of *sessions* (measurements per item per appraiser)

- In general: DF for σ_{ms} . . . . N – I

  DF for σ_{rpt} (repeatability) . . . . . IA(S – 1)

  DF for σ_{rpd} (reproducibility) . . . . I(A – 1)

- Note that the DFs for σ_{rpt} and σ_{rpd} add up to the DF for σ_{ms} (because N = IAS)

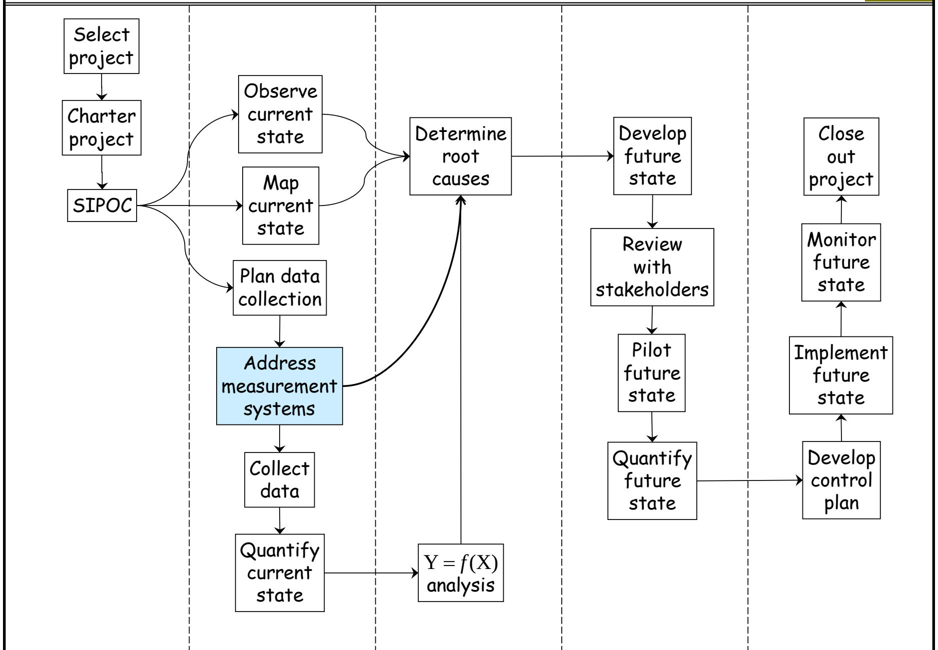
Example

- 5 items, 7 appraisers, 2 sessions
- N = (5)(7)(2) = 70
- DF for σ_{ms} = N – I = 70 – 5 = 65
- DF for σ_{rpt} (repeatability) = IA(S – 1) = 5(7)(1) = 35
- DF for σ_{rpd} (reproducibility) = I(A – 1) = 5(6) = 30

Exercise 20.3

Repeat these calculations for 10 items, 3 appraisers, and 3 sessions.

21 Measurement System Analysis



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Topics

- Gages
- Measurement systems
- Statistical model for measurement variation
- Impact of measurement variation
- Measurement system analysis (MSA)
- Basic assumption for MSA
- MSA for quantitative measurements

Gages

- A *gage* is a measurement device
- Gages can produce quantitative measurements or categorical classifications
- The people who use the gages are usually called *appraisers*, *inspectors*, or *operators*
- For visual inspections, the appraisers are themselves the gages, but they are not called that
- For automated measurement systems, the appraisers may not play a significant role in producing the results

Measurement system

- A set of gages used to measure defined characteristics of a defined class of objects or events
- The gages produce the same type of data
- For quantitative measurements, the gages provide the same data resolution (x.x, x.xx, x.xxx, xx.x, . . .)
- The appraisers are part of the system
- The methods and documentation are part of the system
- If there are standards, they are part of the system

Impact of measurement variation

Action taken

		Pass	Fail
True outcome	**Good**	☺	*"False alarm"*
	Bad	*"Escape"*	☺

Which type of error is more costly? For which is the cost easier to quantify?

Impact of measurement variation (cont'd)

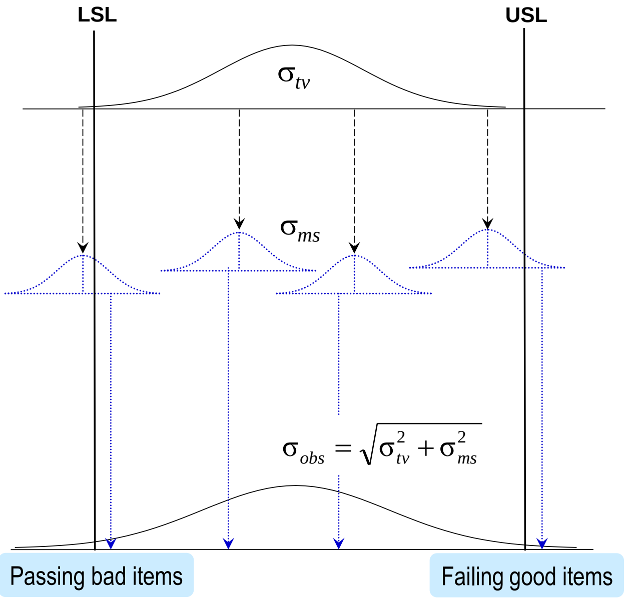
Variation in true values

\+

Measurement variation

↓

Variation in observed values



$$\sigma_{obs} = \sqrt{\sigma_{tv}^2 + \sigma_{ms}^2}$$

Passing bad items

Failing good items

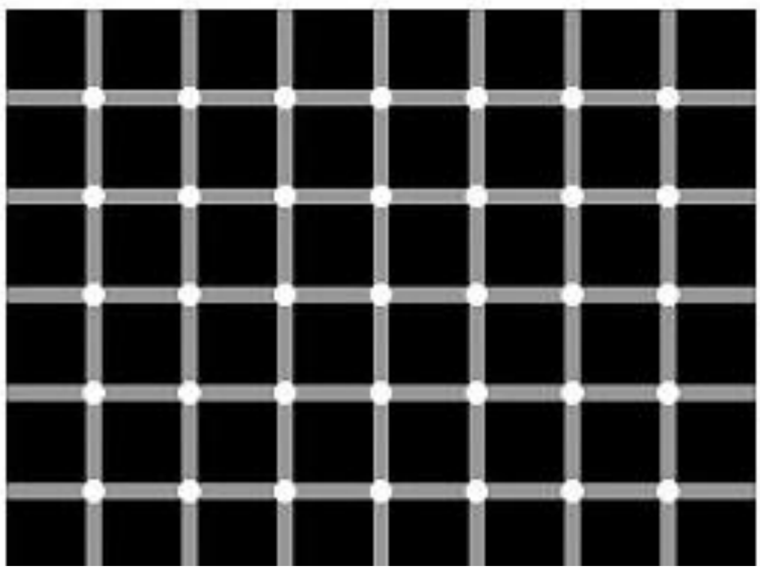
Measurement system analysis (MSA)

- Companies should make decisions based on data
- Bad data → bad decisions
- One large company estimated the annual cost impact of excessive measurement variation as $33M
- MSA quantifies and classifies measurement variation
- MSA → corrective action → reduced measurement variation → reduced cost

Common corrective actions

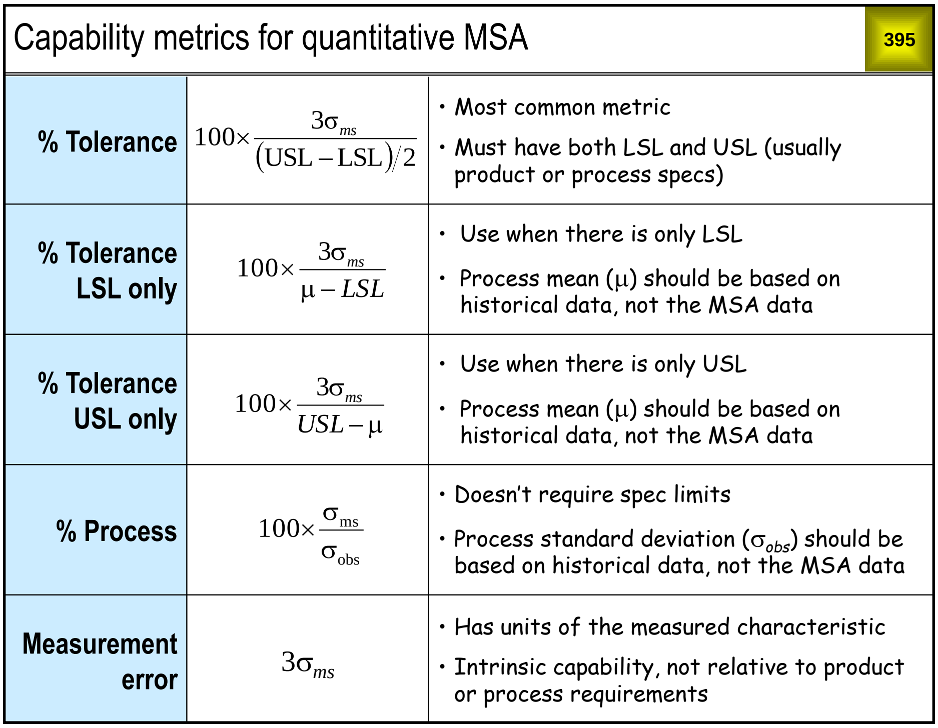
- Improving procedures and fixtures
- Improving gages
- Training appraisers
- Acquiring better gages

Exercise: count the black dots



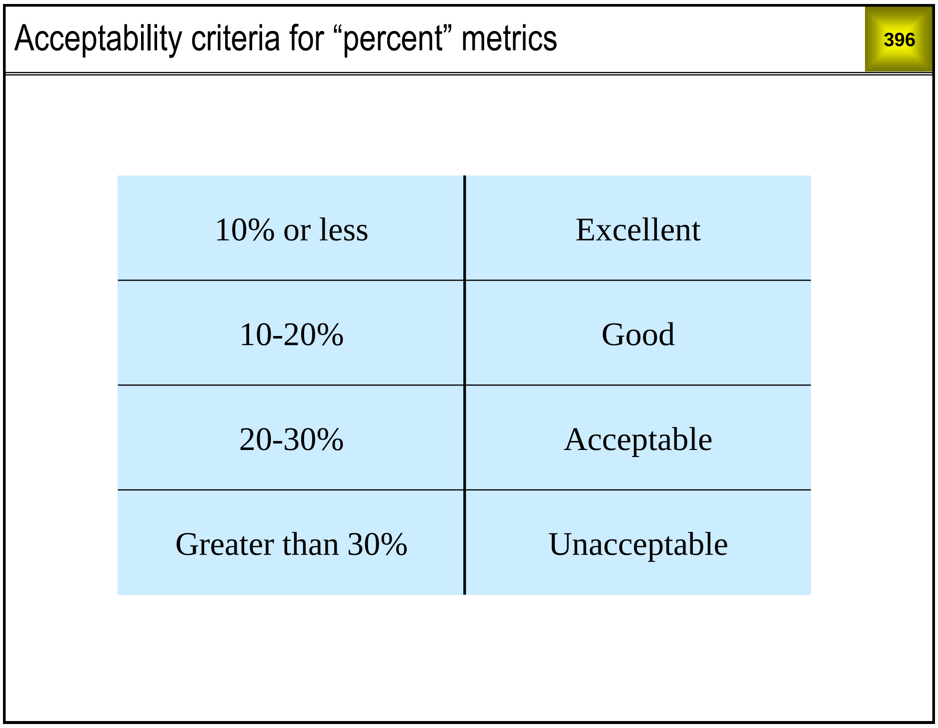
Basic assumption for MSA

- MSA requires multiple measurements of “unchanging objects”
- This is not always possible
    - ✓ *Measurement process may destroy measured items*
    - ✓ *Measurement process may change measured characteristics*
    - ✓ *Measured characteristics may change over time*
- In such cases, ad hoc workarounds are used
    - ✓ *Treat contiguous material samples as the same sample*
    - ✓ *Treat items categorized as “very similar” as the same item*
- Workarounds bias σ_{ms} upwards
    - ✓ *Measurement system looks worse than it really is*



Capability metrics for quantitative MSA

% Tolerance	$100\times\frac{3\sigma_{ms}}{(\mathrm{USL}-\mathrm{LSL})/2}$	• Most common metric • Must have both LSL and USL (usually product or process specs)
% Tolerance LSL only	$100\times\frac{3\sigma_{ms}}{\mu-LSL}$	• Use when there is only LSL • Process mean (μ) should be based on historical data, not the MSA data
% Tolerance USL only	$100\times\frac{3\sigma_{ms}}{USL-\mu}$	• Use when there is only USL • Process mean (μ) should be based on historical data, not the MSA data
% Process	$100\times\frac{\sigma_{\mathrm{ms}}}{\sigma_{\mathrm{obs}}}$	• Doesn't require spec limits • Process standard deviation (σ_{obs}) should be based on historical data, not the MSA data
Measurement error	$3\sigma_{ms}$	• Has units of the measured characteristic • Intrinsic capability, not relative to product or process requirements



Acceptability criteria for "percent" metrics

10% or less	Excellent
10-20%	Good
20-30%	Acceptable
Greater than 30%	Unacceptable

Designing a quantitative MSA

1. Choose at least 5 items (parts, samples, documents…) spanning the range of application of the measurement system. (Spanning the range is more important than the actual number of items.)

2. If the measurement system has only a few appraisers, include them all in the study. If there are many appraisers, include as large a representative sample as possible.

3. Let I = the number of items, A = the number of appraisers, and S = the number of *sessions* (measurements per item per appraiser).
   - The quantity IA(S – 1) is the number of independent opportunities for appraisers to agree *with themselves* (repeatability). It should be at least 30.
   - The quantity I(A – 1) is the number of independent opportunities for appraisers to agree *with each other* (reproducibility). It also should be at least 30.

   It is best to satisfy these requirements by increasing A, with I = 5 and S = 2. If this is not possible, increase I.

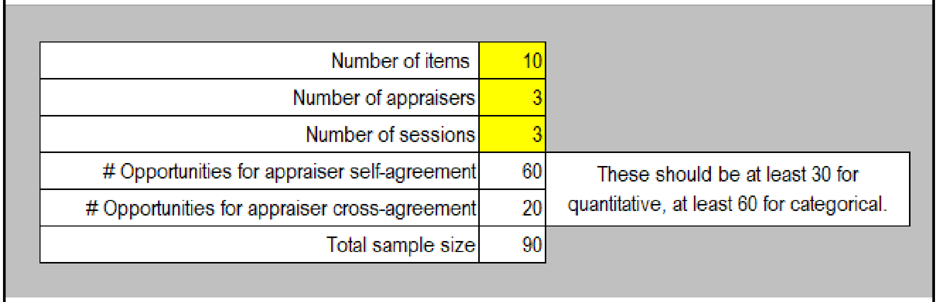
Designing a quantitative MSA (cont'd)

4. If the measurements are taken by devices, and operators have no influence on the results, the devices are the appraisers.

5. If devices are used to aid human inspection, combinations of devices and human inspectors should be treated as the appraisers. The ideal is to use all possible combinations of human inspectors and devices. If this is not possible, a DOE matrix with an acceptable number of combinations should be created.

Examples of step 3

Open *Student Files* → *calculator - sample size* → *MSA* sheet



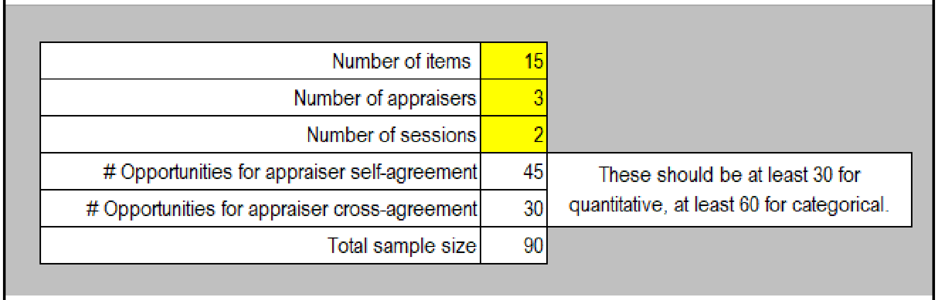
Number of items	10	
Number of appraisers	3	
Number of sessions	3	
# Opportunities for appraiser self-agreement	60	These should be at least 30 for quantitative, at least 60 for categorical.
# Opportunities for appraiser cross-agreement	20	
Total sample size	90	

- The standard automotive gage study (“10 3 3”)
- Not enough opportunities for appraiser cross agreement
- Unnecessarily many opportunities for appraiser self agreement

---

Examples of step 3

A better plan

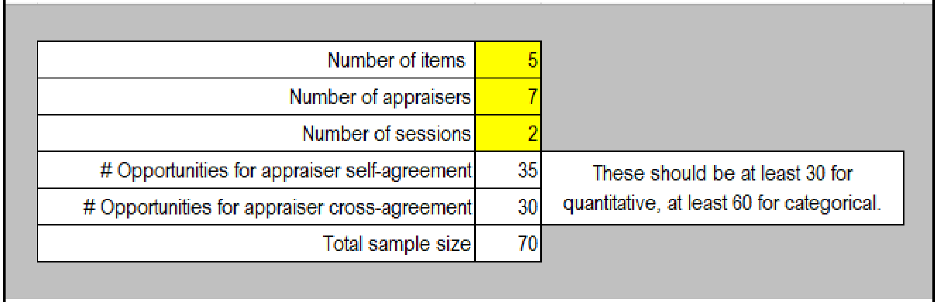


Number of items	15	
Number of appraisers	3	
Number of sessions	2	
# Opportunities for appraiser self-agreement	45	These should be at least 30 for quantitative, at least 60 for categorical.
# Opportunities for appraiser cross-agreement	30	
Total sample size	90	

- Better balance of opportunities for self and cross agreement
- Same total sample size

Examples of step 3

Best plan, assuming there are actually 7 appraisers



Number of items	5
Number of appraisers	7
Number of sessions	2
# Opportunities for appraiser self-agreement	35
# Opportunities for appraiser cross-agreement	30
Total sample size	70

These should be at least 30 for quantitative, at least 60 for categorical.

- Adequate opportunities for self and cross agreement
- Smaller total sample size

Conducting a quantitative MSA

1. Perform this sequence for each session:

First appraiser measures all items once

Second appraiser measures all items once

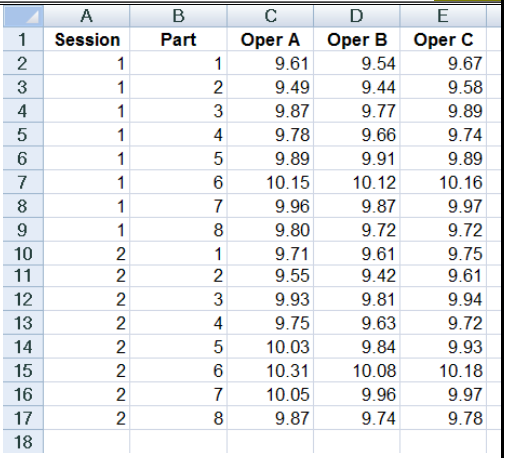
.
.
.

Last appraiser measures all items once.

2. The order in which the items are measured should be reversed each time the appraiser changes. Or, better yet, randomize the order each time.

Analyzing a quantitative MSA

- Open *Data Sets* → *msa velocity gage*
- Measurements are of Drop Velocity
- This is the data format required for continuous MSA in Excel
- The standard analysis requires that every appraiser measures every part the same number of times
- I = 8, A = 3, S = 2
- Was this a well designed MSA?



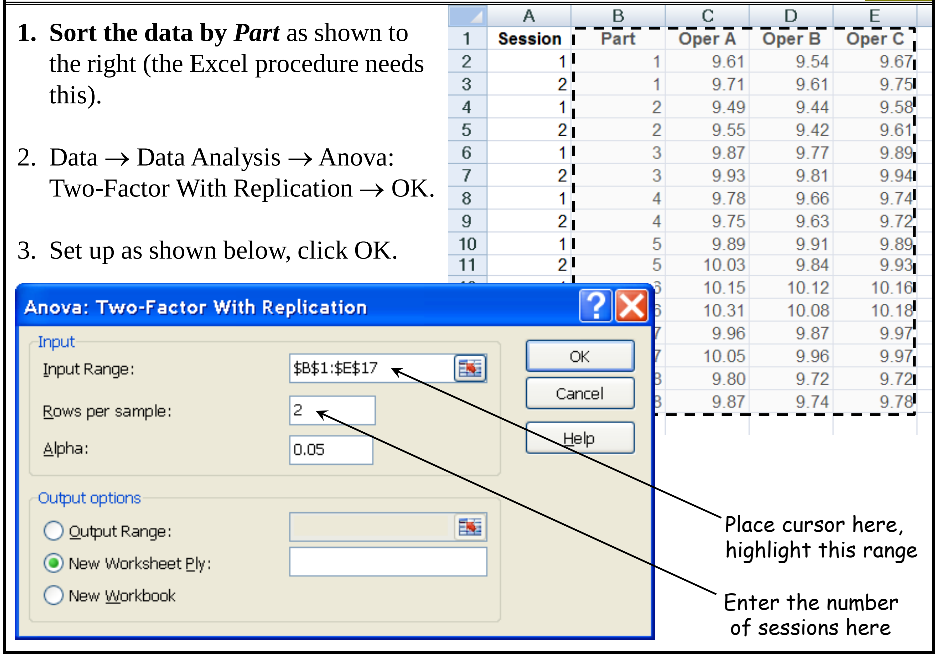
	A	B	C	D	E
1	Session	Part	Oper A	Oper B	Oper C
2	1	1	9.61	9.54	9.67
3	1	2	9.49	9.44	9.58
4	1	3	9.87	9.77	9.89
5	1	4	9.78	9.66	9.74
6	1	5	9.89	9.91	9.89
7	1	6	10.15	10.12	10.16
8	1	7	9.96	9.87	9.97
9	1	8	9.80	9.72	9.72
10	2	1	9.71	9.61	9.75
11	2	2	9.55	9.42	9.61
12	2	3	9.93	9.81	9.94
13	2	4	9.75	9.63	9.72
14	2	5	10.03	9.84	9.93
15	2	6	10.31	10.08	10.18
16	2	7	10.05	9.96	9.97
17	2	8	9.87	9.74	9.78
18					

What do the numbers in cell range C2:C9 represent:
part variation, measurement variation, or observed variation?

What do the numbers in cell range C2:E2 represent:
part variation, measurement variation, or observed variation?

Worked example

1. **Sort the data by *Part*** as shown to the right (the Excel procedure needs this).
2. Data → Data Analysis → Anova: Two-Factor With Replication → OK.
3. Set up as shown below, click OK.



	A	B	C	D	E
1	Session	Part	Oper A	Oper B	Oper C
2	1	1	9.61	9.54	9.67
3	2	1	9.71	9.61	9.75
4	1	2	9.49	9.44	9.58
5	2	2	9.55	9.42	9.61
6	1	3	9.87	9.77	9.89
7	2	3	9.93	9.81	9.94
8	1	4	9.78	9.66	9.74
9	2	4	9.75	9.63	9.72
10	1	5	9.89	9.91	9.89
11	2	5	10.03	9.84	9.93
		6	10.15	10.12	10.16
		6	10.31	10.08	10.18
		7	9.96	9.87	9.97
		7	10.05	9.96	9.97
		8	9.80	9.72	9.72
		8	9.87	9.74	9.78

Anova: Two-Factor With Replication

Input

Input Range: $B$1:$E$17

Rows per sample: 2

Alpha: 0.05

Output options

○ Output Range:

● New Worksheet Ply:

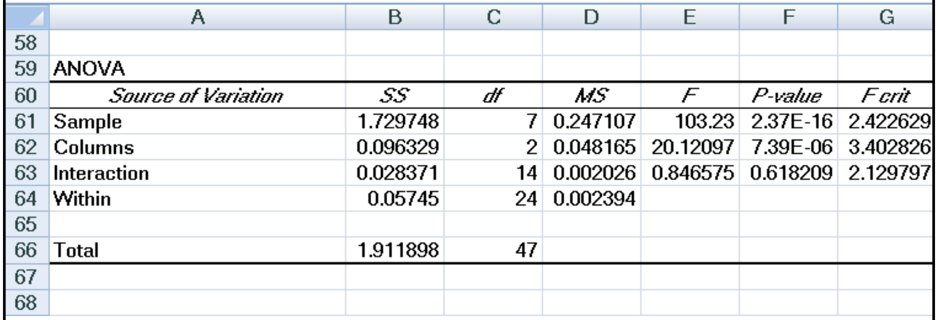
○ New Workbook

Place cursor here, highlight this range

Enter the number of sessions here

Example (cont'd)

4. Scroll down to the ANOVA table as shown here.

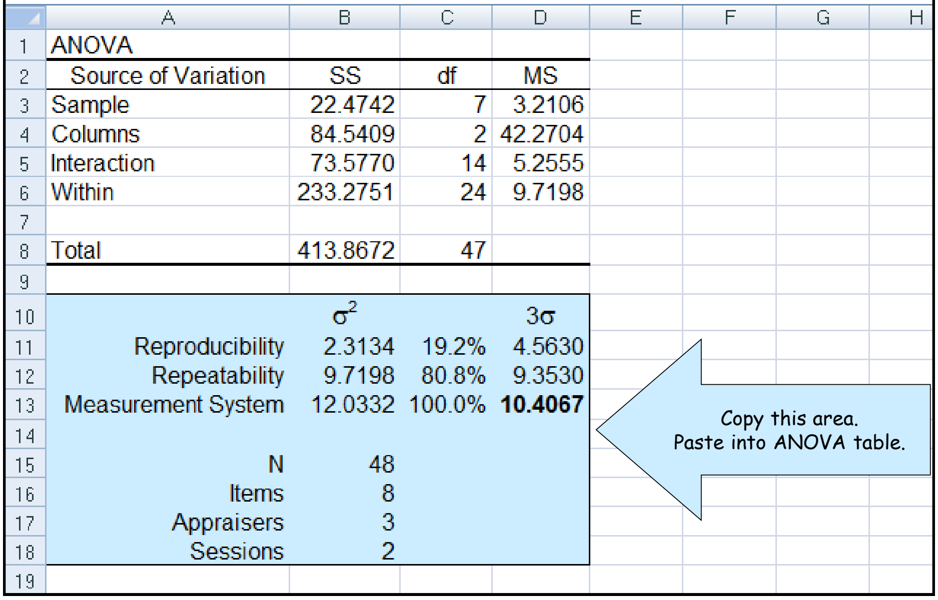


	A	B	C	D	E	F	G
58							
59	ANOVA						
60	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
61	Sample	1.729748	7	0.247107	103.23	2.37E-16	2.422629
62	Columns	0.096329	2	0.048165	20.12097	7.39E-06	3.402826
63	Interaction	0.028371	14	0.002026	0.846575	0.618209	2.129797
64	Within	0.05745	24	0.002394			
65							
66	Total	1.911898	47				
67							
68							

5. Open *Student Files → calculator – Gage R&R.*

Example (cont'd)

6. Copy the shaded area.



	A	B	C	D	E	F	G	H
1	ANOVA							
2	Source of Variation	SS	df	MS				
3	Sample	22.4742	7	3.2106				
4	Columns	84.5409	2	42.2704				
5	Interaction	73.5770	14	5.2555				
6	Within	233.2751	24	9.7198				
7								
8	Total	413.8672	47					
9								
10		σ^2		3σ				
11	Reproducibility	2.3134	19.2%	4.5630				
12	Repeatability	9.7198	80.8%	9.3530				
13	Measurement System	12.0332	100.0%	**10.4067**				
14								
15	N	48						
16	Items	8						
17	Appraisers	3						
18	Sessions	2						
19								

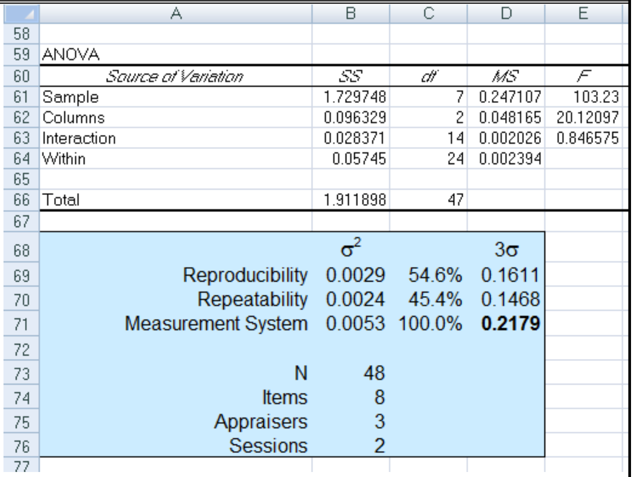
Copy this area.
Paste into ANOVA table.

Example (cont’d)

7. Paste the shaded area below your ANOVA table as shown.

$3\sigma_{ms} = 0.2179$

Reproducibility is the dominant component, but not by much.



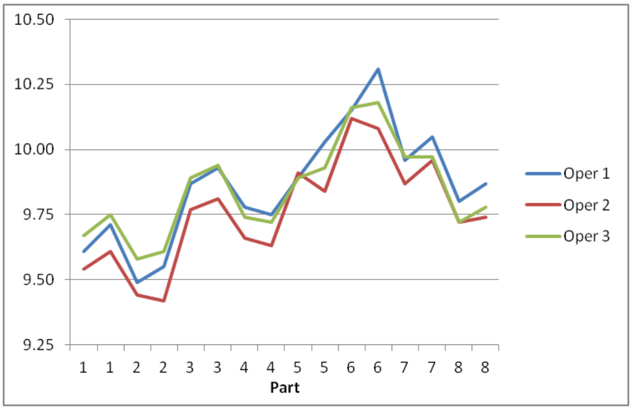
	A	B	C	D	E
58					
59	ANOVA				
60	*Source of Variation*	*SS*	*df*	*MS*	*F*
61	Sample	1.729748	7	0.247107	103.23
62	Columns	0.096329	2	0.048165	20.12097
63	Interaction	0.028371	14	0.002026	0.846575
64	Within	0.05745	24	0.002394	
65					
66	Total	1.911898	47		
67					
68		σ^2		3σ	
69	Reproducibility	0.0029	54.6%	0.1611	
70	Repeatability	0.0024	45.4%	0.1468	
71	Measurement System	0.0053	100.0%	**0.2179**	
72					
73	N	48			
74	Items	8			
75	Appraisers	3			
76	Sessions	2			
77					

8. For this measurement “Drop Velocity,” (USL–LSL)/2 = 1.65.
Use Excel to calculate the *% Tolerance* metric.

$$\%\text{Tol} = 100 \times \frac{3\sigma_{\text{ms}}}{1.65} = 13.2\%$$

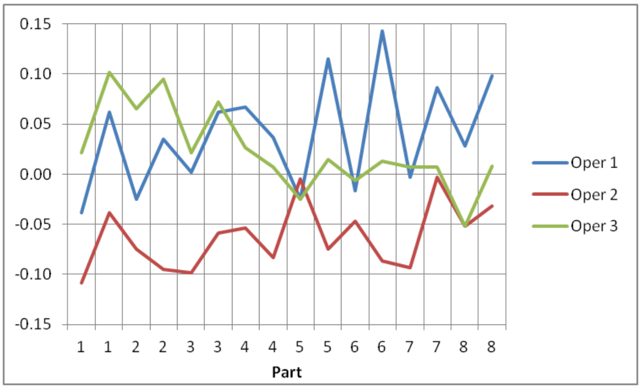
Example (cont’d)

9. Create a line chart of the operator columns by part (Highlight columns > Insert Line Chart)
10. This is what a good one looks like. The operator curves are close together and roughly parallel, showing they are getting similar measurements for each part.



Example (cont'd)

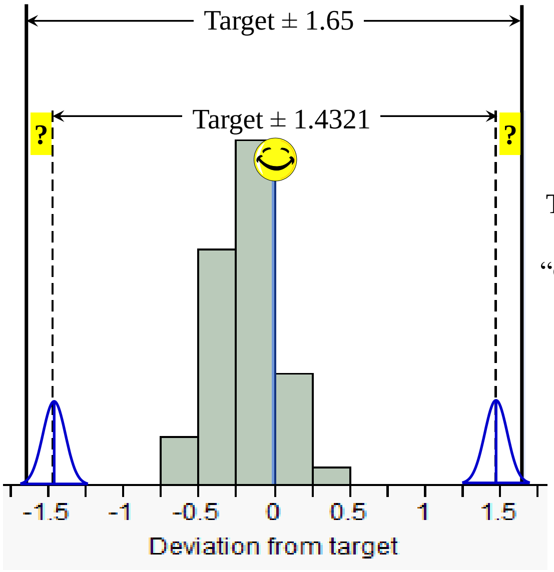
- If part variation is large enough relative to measurement variation, the lines on the previous chart will appear to be superimposed on each other
- The file *Data Sets* → *msa velocity gage with charts* gives the calculations for the chart below, which shows the data with the part averages subtracted out.
- This helps you see what's going on with the measurements by each operator, when part variation in the study is large compared to measurement variation.



Interpreting $3\sigma_{ms}$

- In this example, $3\sigma_{ms} = 0.2179$
- For a given measurement *m*, the true value lies in the interval
  $$m \pm 0.2179$$
  with 99.7% confidence
- The tolerance for drop velocity is ± 1.65 (Given on previous slide)
- 1.65 – 0.2179 = 1.4321
- To be confident that a drop velocity is in spec, it must be within 1.4321 of the target value (see next slide)

Interpreting $3\sigma_{ms}$ (cont'd)

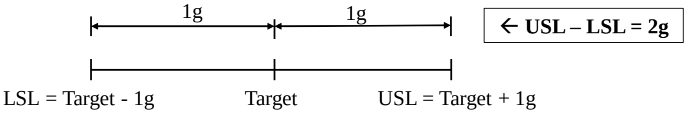


These are also known as "Guard Bands"

Exercise 21.1

Open *Data Sets* → *msa weight*. Three operators weighed 10 samples 3 times each, all using the same scale.

(a) The tolerance for the weight is *target* ± 1g. Find $3\sigma_{ms}$ and calculate the *% Tolerance* metric. Classify the measurement system as excellent, good, acceptable, or unacceptable. (*Target* is another word for *center of the spec*.)



← USL – LSL = 2g

(b) Create a line chart of the operator columns. If this is not informative, open tab *with avg* to mimic the calculations in *msa velocity gage with charts*. Create a plot of the weights with the part averages subtracted out. What seems to be the problem here? (It might help to use *Session* as the X-axis variable.)

Exercise 21.2

Open *Data Sets* → *msa calipers*. These are dimensional inspections of PVC extrusions made with a hand held digital caliper.

(a) The tolerance for this dimension is Target ± 0.020″. Find $3\sigma_{ms}$ and calculate the *% Tolerance* metric. Classify the measurement system as excellent, good, acceptable, or unacceptable.

(b) Create a line chart of the operator columns. Who seems to be the greatest opportunity for improvement?

Exercise 21.3

Open *Data Sets* → *msa gloss*. These are measurements of % gloss on 7 sheets of photographic paper (the “parts”) by 9 technicians. MSAs were conducted at 3 different temperatures to determine the effect of temperature on measurement error.

a) Find the measurement error ($3\sigma_{ms}$) at 20 deg. Identify the dominant component of σ_{ms}.

b) Find the measurement error ($3\sigma_{ms}$) at 60 deg. Identify the dominant component of σ_{ms}.

c) Find the measurement error ($3\sigma_{ms}$) at 85 deg. Identify the dominant component of σ_{ms}.

d) What is the effect of temperature on measurement error?

Exercise 21.4

Each team is to conduct an MSA involving coins of different diameters. Every team member will be an appraiser in the study. Each appraiser will measure the diameter of each coin twice (S = 2). Each team is to do the following:

a) Develop a procedure for measuring the diameter.

b) Determine the number of coins needed for the study.

c) Create an appropriately formatted Excel worksheet for data collection.

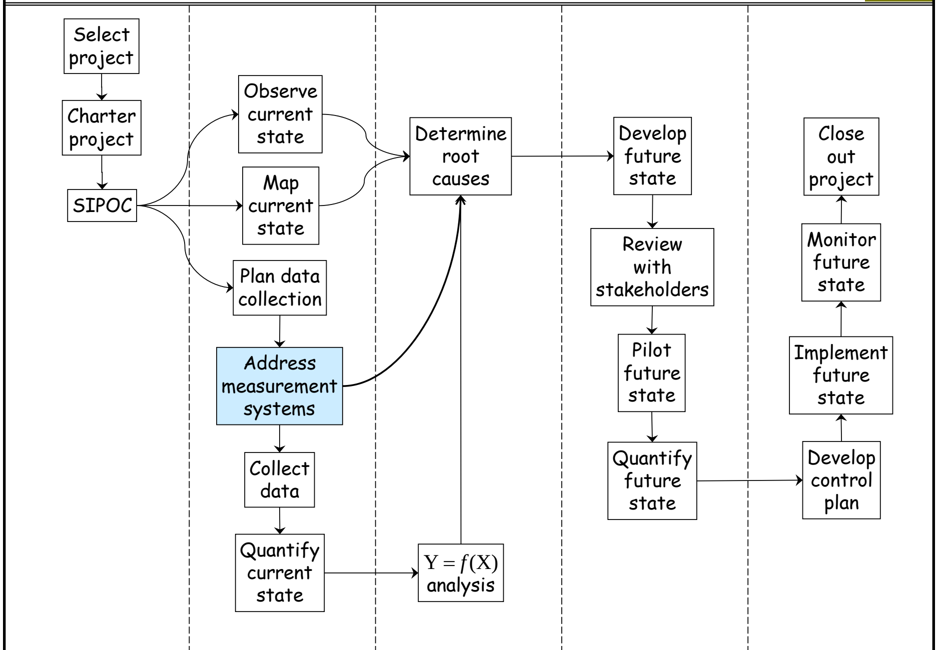
d) Follow the guidelines for conducting a quantitative MSA.

e) Collect and enter the data. Give the $3\sigma_{ms}$ value and calculate the *% Tolerance* metric. (The tolerance for all diameters is *target* ± 0.050".) $\pm$ 1.27 mm

f) Is the measurement system excellent, good, acceptable or unacceptable?

Notes

22 Categorical MSA



Select project
Charter project
SIPOC
Observe current state
Map current state
Plan data collection
Address measurement systems
Collect data
Quantify current state
Determine root causes
Y = f(X) analysis
Develop future state
Review with stakeholders
Pilot future state
Quantify future state
Develop control plan
Implement future state
Monitor future state
Close out project

Categorical MSA

- Also known as *Attribute Gage Study*
- Applied most often to pass/fail inspections
- The terms *repeatability* and *reproducibility* are not used in this context
- In this section we assume that the study is based on *standards* (items for which we know the true value)
- Primary objective in this case:

Determine the % agreement with standard
(Also known as % correct)

Designing a categorical MSA

1. Choose at least 10 items (parts, samples, documents…) to be inspected. There should be roughly equal numbers of items that are clearly passing, borderline passing, borderline failing and clearly failing. Choose an expert appraiser to function as the reference standard.

2. If the measurement system has only a few appraisers, include them all in the study. If there are many appraisers, include as large a representative sample as possible.

3. Let I = the number of items, A = the number of appraisers, and S = the number of measurements per item per appraiser.
    - The quantity IA(S – 1) is the number of independent opportunities for appraisers to agree *with themselves*. It should be at least 60.
    - The quantity I(A – 1) is the number of independent opportunities for appraisers to agree *with each other*. It should be at least 60.

   It is best to satisfy these requirements by increasing A with I = 10 and S = 2. If this is not possible, increase I.

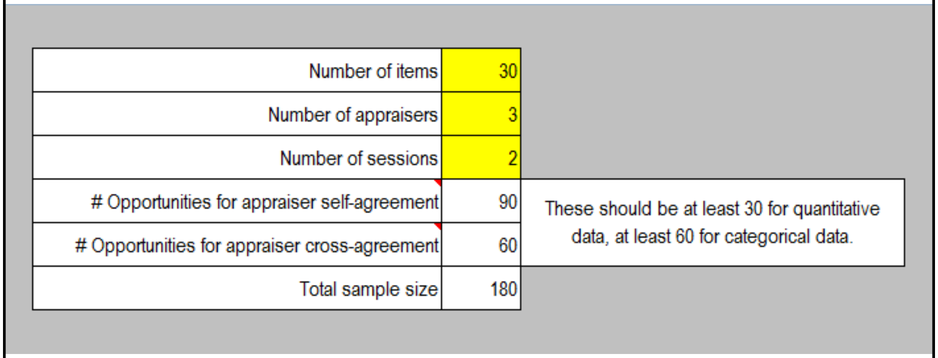
Designing a categorical MSA (cont'd)

4. If the measurements are taken by devices, and operators have no influence on the results, the devices are the appraisers.

5. If devices are used to aid human inspection, combinations of devices and human inspectors should be treated as the appraisers. The ideal is to use all possible combinations of human inspectors and devices. If this is not possible, a DOE matrix with an acceptable number of combinations should be created.

Examples of step 3

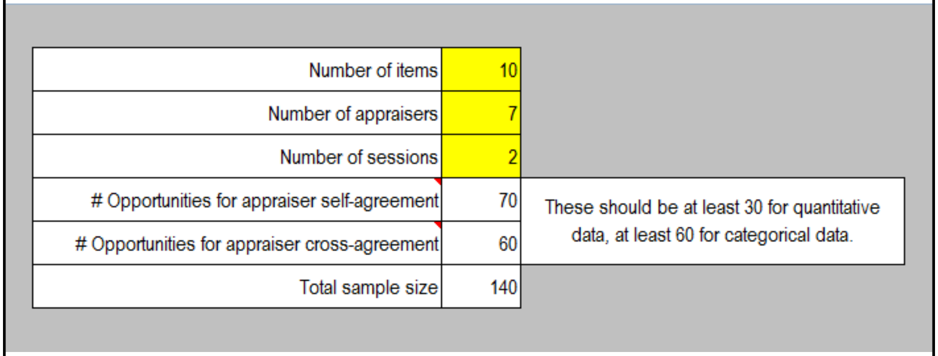
Open *Student Files* → *calculator - sample size* → *MSA* sheet



Number of items	30	
Number of appraisers	3	
Number of sessions	2	
# Opportunities for appraiser self-agreement	90	These should be at least 30 for quantitative data, at least 60 for categorical data.
# Opportunities for appraiser cross-agreement	60	
Total sample size	180	

Best plan if there are only 3 appraisers

Examples of step 3



Number of items	10	
Number of appraisers	7	
Number of sessions	2	
# Opportunities for appraiser self-agreement	70	These should be at least 30 for quantitative data, at least 60 for categorical data.
# Opportunities for appraiser cross-agreement	60	
Total sample size	140	

Best plan if there are 7 appraisers

Conducting a categorical MSA[*]

1. Perform this sequence for each session:

First appraiser measures all items once

Second appraiser measures all items once

.

.

.

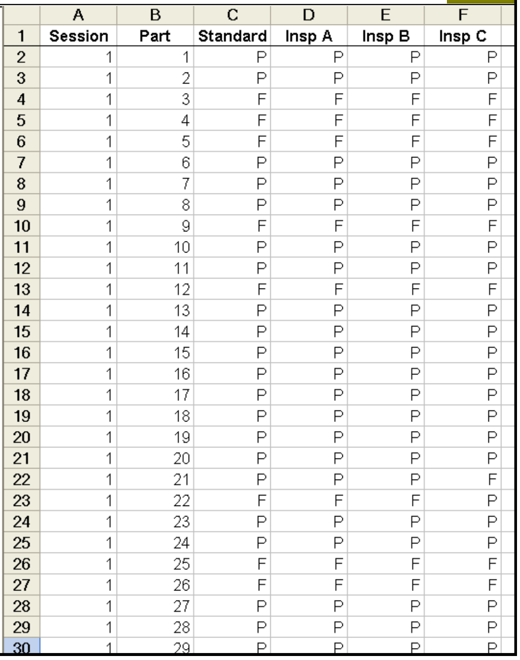
Last appraiser measures all items once.

2. The order in which the items are measured should be reversed each time the appraiser changes.

[*] Same as for quantitative MSA

Analyzing a categorical MSA

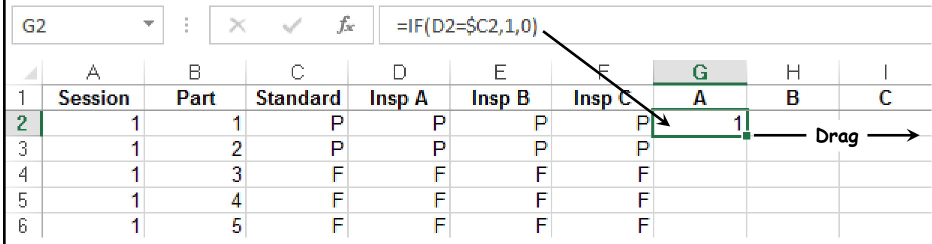
- Open *Data Sets \ msa passfail*
- I = 50, A = 3, S = 3
- Did they follow the best plan for 3 appraisers?
- P = pass, F = fail
- *Standard* gives the correct answer for each part inspected
- The analysis is based on % agreement with the standard



	A	B	C	D	E	F
1	Session	Part	Standard	Insp A	Insp B	Insp C
2	1	1	P	P	P	P
3	1	2	P	P	P	P
4	1	3	F	F	F	F
5	1	4	F	F	F	F
6	1	5	F	F	F	F
7	1	6	P	P	P	P
8	1	7	P	P	P	P
9	1	8	P	P	P	P
10	1	9	F	F	F	F
11	1	10	P	P	P	P
12	1	11	P	P	P	P
13	1	12	F	F	F	F
14	1	13	P	P	P	P
15	1	14	P	P	P	P
16	1	15	P	P	P	P
17	1	16	P	P	P	P
18	1	17	P	P	P	P
19	1	18	P	P	P	P
20	1	19	P	P	P	P
21	1	20	P	P	P	P
22	1	21	P	P	P	F
23	1	22	F	F	F	P
24	1	23	P	P	P	P
25	1	24	P	P	P	P
26	1	25	F	F	F	F
27	1	26	F	F	F	F
28	1	27	P	P	P	P
29	1	28	P	P	P	P
30	1	29	P	P	P	P

Worked example

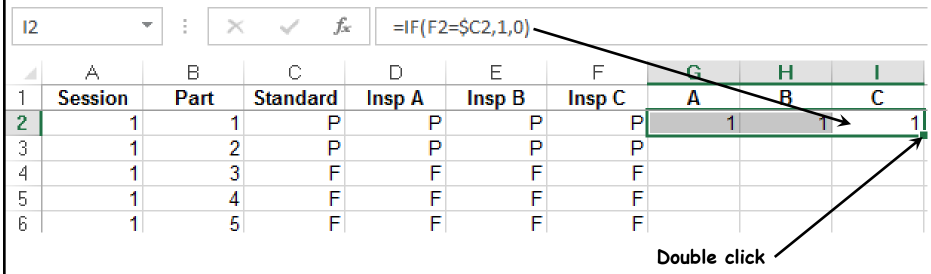
The first step is to define new columns indicating whether A, B, and C agree or disagree with *Standard* in each case (1 = agree, 0 = disagree)



G2 =IF(D2=$C2,1,0)

	A	B	C	D	E	F	G	H	I
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C
2	1	1	P	P	P	P	1		
3	1	2	P	P	P	P			
4	1	3	F	F	F	F			
5	1	4	F	F	F	F			
6	1	5	F	F	F	F			

Drag



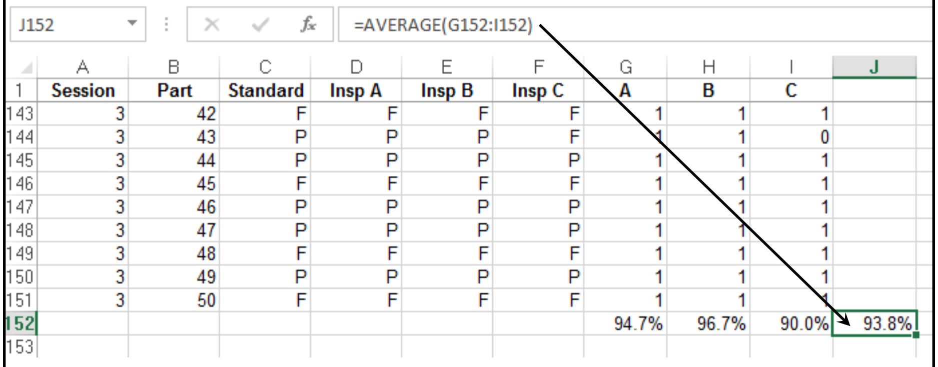
I2 =IF(F2=$C2,1,0)

	A	B	C	D	E	F	G	H	I
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C
2	1	1	P	P	P	P	1	1	1
3	1	2	P	P	P	P			
4	1	3	F	F	F	F			
5	1	4	F	F	F	F			
6	1	5	F	F	F	F			

Double click

Example (cont'd)

- Use the *Average* function on the *AutoSum* button to get the % agreement with standard for each inspector (cells G152 through I152)
- Use it again to get the overall % agreement with standard (cell J152)
- If improvement is needed, Inspector C is the greatest opportunity

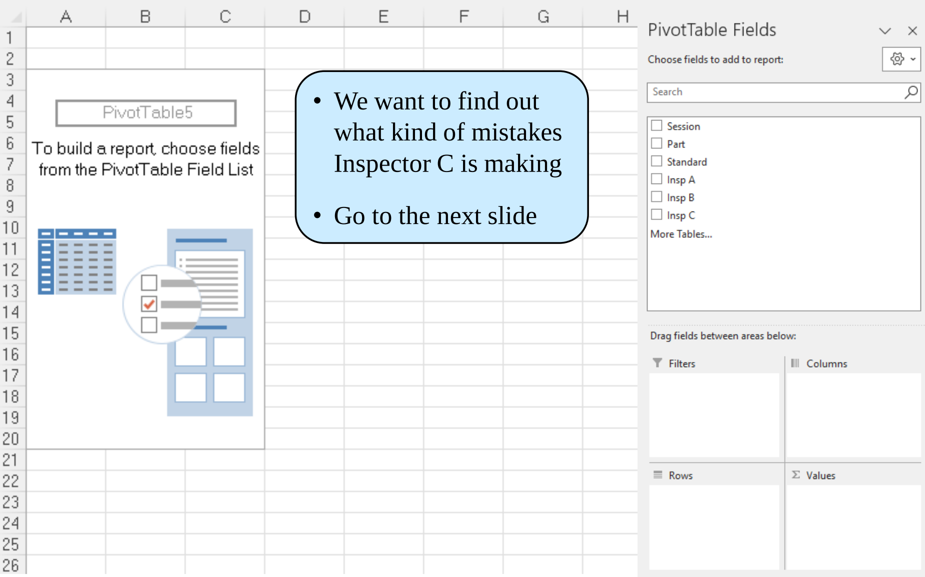


J152 =AVERAGE(G152:I152)

	A	B	C	D	E	F	G	H	I	J
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C	
143	3	42	F	F	F	F	1	1	1	
144	3	43	P	P	P	F	1	1	0	
145	3	44	P	P	P	P	1	1	1	
146	3	45	F	F	F	F	1	1	1	
147	3	46	P	P	P	P	1	1	1	
148	3	47	P	P	P	P	1	1	1	
149	3	48	F	F	F	F	1	1	1	
150	3	49	P	P	P	P	1	1	1	
151	3	50	F	F	F	F	1	1	1	
152							94.7%	96.7%	90.0%	93.8%
153										

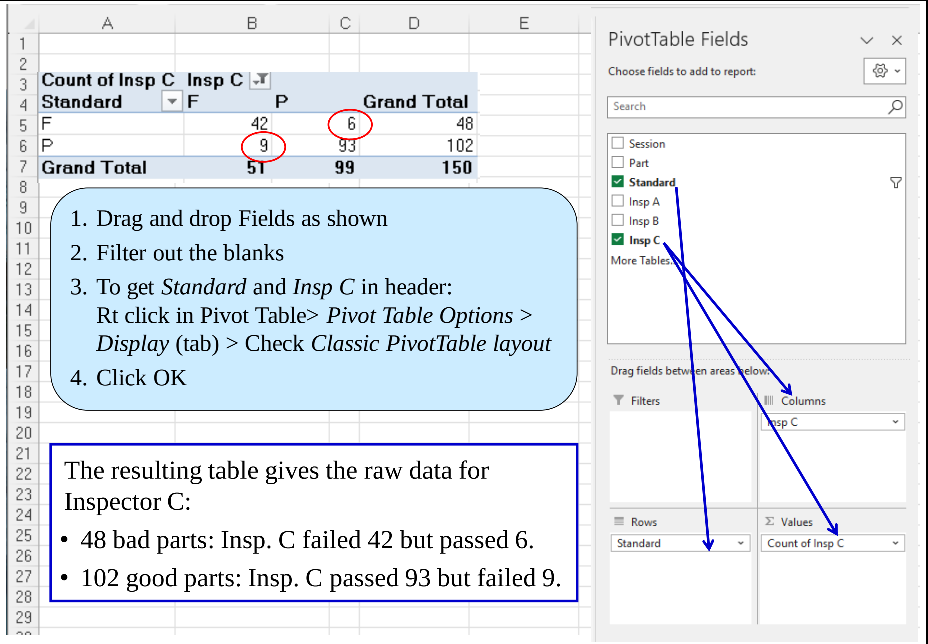
Example (cont'd)

Highlight columns A-F → select the *Insert* ribbon → select *PivotTable* → OK



- We want to find out what kind of mistakes Inspector C is making
- Go to the next slide

Example (cont'd)



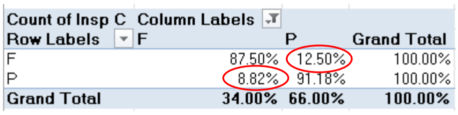
Count of Insp C	Insp C		
Standard	F	P	Grand Total
F	42	6	48
P	9	93	102
Grand Total	51	99	150

1. Drag and drop Fields as shown
2. Filter out the blanks
3. To get *Standard* and *Insp C* in header: Rt click in Pivot Table> *Pivot Table Options* > *Display* (tab) > Check *Classic PivotTable layout*
4. Click OK

The resulting table gives the raw data for Inspector C:

- 48 bad parts: Insp. C failed 42 but passed 6.
- 102 good parts: Insp. C passed 93 but failed 9.

Example (cont'd)



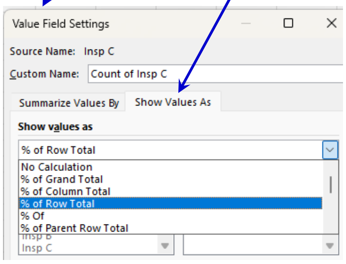
Count of Insp C	Column Labels		
Row Labels	F	P	Grand Total
F	87.50%	12.50%	100.00%
P	8.82%	91.18%	100.00%
Grand Total	34.00%	66.00%	100.00%

- Inspector C passed 12.5% of the bad parts
- and failed 8.8% of the good parts
- Inspector C needs further training to reduce both types of errors

Click dropdown on *Count of Insp C >*

Value Field Settings >

Show Values As >
% of row total



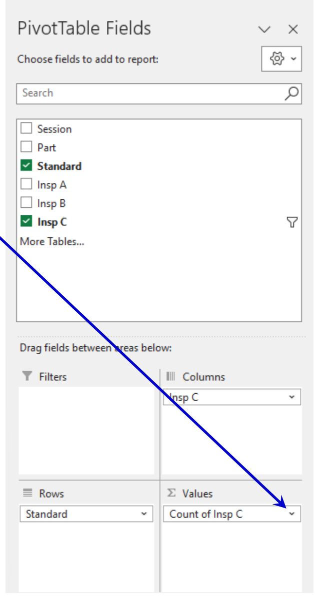
Value Field Settings

Source Name: Insp C

Custom Name: Count of Insp C

Show values as

% of Row Total



Exercise 22.1

Open *Data Sets → msa print samples 1*. These are visual inspections of print samples by 3 inspectors. The standards were determined by a committee of experienced print quality evaluators.

(a) Calculate the % agreement with standard by inspector and overall.

(b) Which inspector offers the greatest opportunity for improvement? Make a pivot table to determine whether the main problem is passing bad samples, failing good ones, or both.

(c) Save your work.

Exercise 22.2

Open *Data Sets* → *msa print samples 2*. These are visual inspections of new print samples by the same 3 inspectors after additional training.

(a) Calculate the % agreement with standard by inspector and overall. Have we improved?

(b) There is something interesting about the data for sample 18 (not row 18). What are the possible explanations? (Sorting by sample number will help.)

(c) It turns out the standard for sample 18 was wrong. Reclassify the standard for sample 18 as passing. What is the % agreement now?

(d) Save your work.

Exercise 22.3

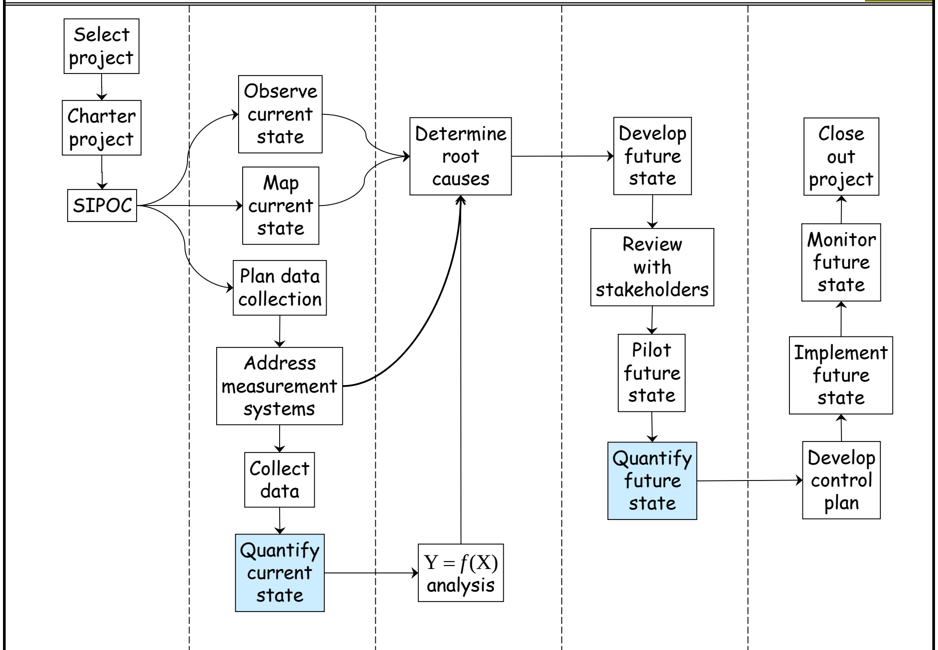
Open *Data Sets* → *msa ratings.* Each of 15 employment applications was rated twice on a five point scale (1 = worst, 5 = best) by each of five appraisers.

a) Calculate the % agreement by appraiser and overall.

b) Which inspector offers the greatest opportunity for improvement? Make a pivot table to determine the particular error this inspector often makes.

c) Save your work.

23 Establishing Baselines — Pass/fail Y



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

Y = *f*(X) analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

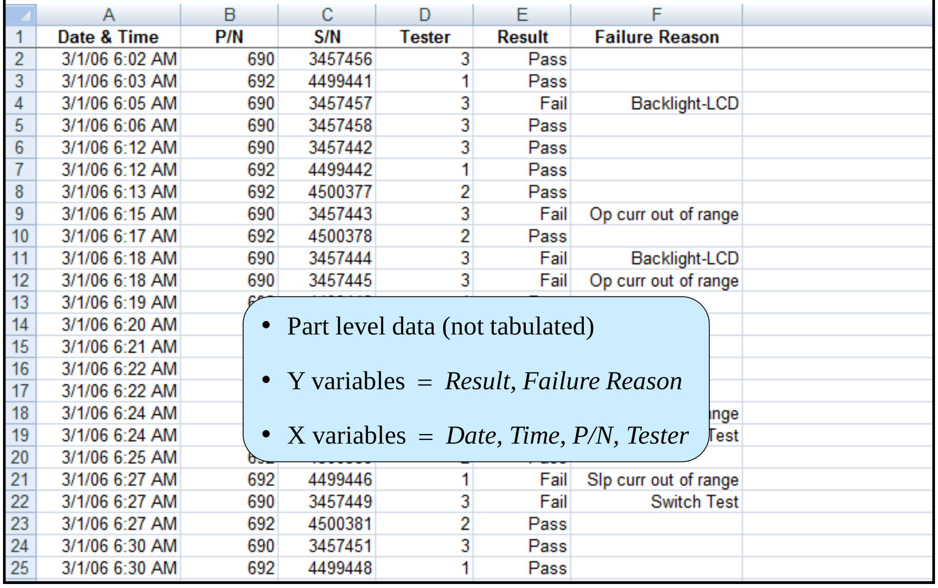
Develop control plan

Topics

- Calculating % defective from “raw” pass/fail data
- Pareto analysis of failure reasons from “raw” failure/defect data
- Calculating % defective from tabulated pass/fail data
- Pareto analysis from tabulated failure/defect data

% Defective from “raw” pass/fail data

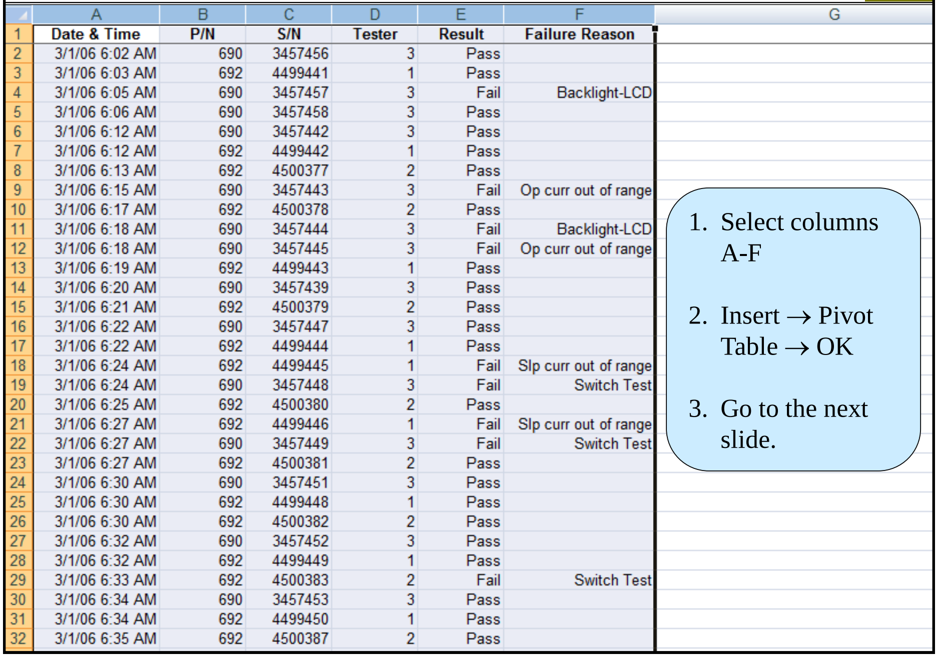
Open *Data Sets* → *ATE Mar & Apr*



	A	B	C	D	E	F
1	Date & Time	P/N	S/N	Tester	Result	Failure Reason
2	3/1/06 6:02 AM	690	3457456	3	Pass	
3	3/1/06 6:03 AM	692	4499441	1	Pass	
4	3/1/06 6:05 AM	690	3457457	3	Fail	Backlight-LCD
5	3/1/06 6:06 AM	690	3457458	3	Pass	
6	3/1/06 6:12 AM	690	3457442	3	Pass	
7	3/1/06 6:12 AM	692	4499442	1	Pass	
8	3/1/06 6:13 AM	692	4500377	2	Pass	
9	3/1/06 6:15 AM	690	3457443	3	Fail	Op curr out of range
10	3/1/06 6:17 AM	692	4500378	2	Pass	
11	3/1/06 6:18 AM	690	3457444	3	Fail	Backlight-LCD
12	3/1/06 6:18 AM	690	3457445	3	Fail	Op curr out of range
13	3/1/06 6:19 AM					
14	3/1/06 6:20 AM					
15	3/1/06 6:21 AM					
16	3/1/06 6:22 AM					
17	3/1/06 6:22 AM					
18	3/1/06 6:24 AM					nge
19	3/1/06 6:24 AM					Test
20	3/1/06 6:25 AM					
21	3/1/06 6:27 AM	692	4499446	1	Fail	Slp curr out of range
22	3/1/06 6:27 AM	690	3457449	3	Fail	Switch Test
23	3/1/06 6:27 AM	692	4500381	2	Pass	
24	3/1/06 6:30 AM	690	3457451	3	Pass	
25	3/1/06 6:30 AM	692	4499448	1	Pass	

- Part level data (not tabulated)
- Y variables = *Result, Failure Reason*
- X variables = *Date, Time, P/N, Tester*

% Defective (cont’d)



	A	B	C	D	E	F
1	Date & Time	P/N	S/N	Tester	Result	Failure Reason
2	3/1/06 6:02 AM	690	3457456	3	Pass	
3	3/1/06 6:03 AM	692	4499441	1	Pass	
4	3/1/06 6:05 AM	690	3457457	3	Fail	Backlight-LCD
5	3/1/06 6:06 AM	690	3457458	3	Pass	
6	3/1/06 6:12 AM	690	3457442	3	Pass	
7	3/1/06 6:12 AM	692	4499442	1	Pass	
8	3/1/06 6:13 AM	692	4500377	2	Pass	
9	3/1/06 6:15 AM	690	3457443	3	Fail	Op curr out of range
10	3/1/06 6:17 AM	692	4500378	2	Pass	
11	3/1/06 6:18 AM	690	3457444	3	Fail	Backlight-LCD
12	3/1/06 6:18 AM	690	3457445	3	Fail	Op curr out of range
13	3/1/06 6:19 AM	692	4499443	1	Pass	
14	3/1/06 6:20 AM	690	3457439	3	Pass	
15	3/1/06 6:21 AM	692	4500379	2	Pass	
16	3/1/06 6:22 AM	690	3457447	3	Pass	
17	3/1/06 6:22 AM	692	4499444	1	Pass	
18	3/1/06 6:24 AM	692	4499445	1	Fail	Slp curr out of range
19	3/1/06 6:24 AM	690	3457448	3	Fail	Switch Test
20	3/1/06 6:25 AM	692	4500380	2	Pass	
21	3/1/06 6:27 AM	692	4499446	1	Fail	Slp curr out of range
22	3/1/06 6:27 AM	690	3457449	3	Fail	Switch Test
23	3/1/06 6:27 AM	692	4500381	2	Pass	
24	3/1/06 6:30 AM	690	3457451	3	Pass	
25	3/1/06 6:30 AM	692	4499448	1	Pass	
26	3/1/06 6:30 AM	692	4500382	2	Pass	
27	3/1/06 6:32 AM	690	3457452	3	Pass	
28	3/1/06 6:32 AM	692	4499449	1	Pass	
29	3/1/06 6:33 AM	692	4500383	2	Fail	Switch Test
30	3/1/06 6:34 AM	690	3457453	3	Pass	
31	3/1/06 6:34 AM	692	4499450	1	Pass	
32	3/1/06 6:35 AM	692	4500387	2	Pass	

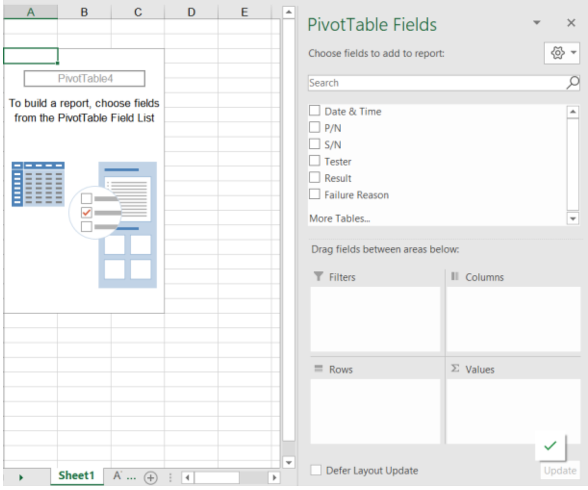
1. Select columns A-F
2. Insert → Pivot Table → OK
3. Go to the next slide.

% Defective (cont’d)

4. Drag/drop *Result* into the *Columns* box

5. Drag/drop *Result* into the *Values* box

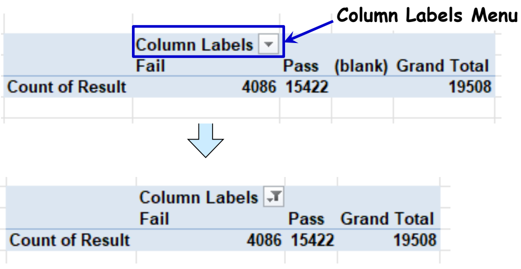
6. Go to the next slide.



To build a report, choose fields from the PivotTable Field List

---

% Defective (cont’d)



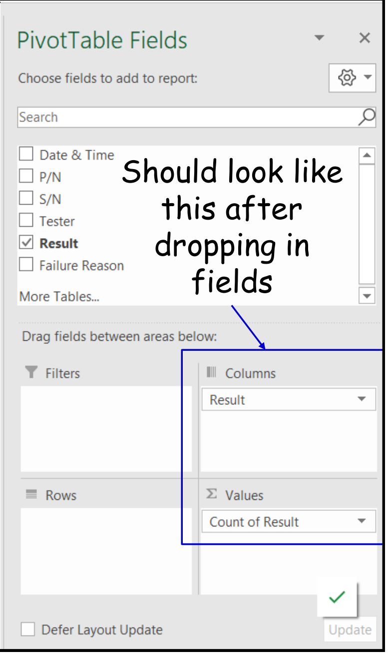
	Column Labels			
	Fail	Pass	(blank)	Grand Total
Count of Result	4086	15422		19508

	Column Labels		
	Fail	Pass	Grand Total
Count of Result	4086	15422	19508

7. Pull down the *Column Labels* menu (shown above)

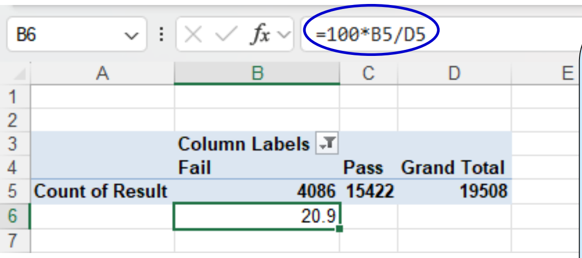
8. Uncheck *(blank)* on that menu, select OK

9. Go to the next slide.



Should look like this after dropping in fields

% Defective (cont'd)



B6 =100*B5/D5

	A	B	C	D
3		Column Labels		
4		Fail	Pass	Grand Total
5	Count of Result	4086	15422	19508
6		20.9		

10. Select cell B6

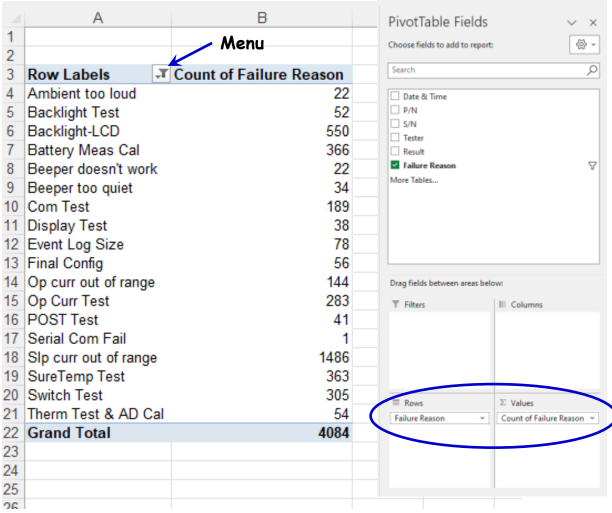
11. Enter the formula shown above (Note: You can type in formula or click on cells. Clicking will display *GETPIVOTDATA* function in formula bar. Result is the same.

12. Use the *Decrease Decimal* button on the *Home* ribbon to format

13. Alternative: leave out the 100, format as a percentage

Project metric	% Defective
Baseline value	20.9%

Pareto analysis of failure reasons



Menu

	A	B
3	**Row Labels**	**Count of Failure Reason**
4	Ambient too loud	22
5	Backlight Test	52
6	Backlight-LCD	550
7	Battery Meas Cal	366
8	Beeper doesn't work	22
9	Beeper too quiet	34
10	Com Test	189
11	Display Test	38
12	Event Log Size	78
13	Final Config	56
14	Op curr out of range	144
15	Op Curr Test	283
16	POST Test	41
17	Serial Com Fail	1
18	Slp curr out of range	1486
19	SureTemp Test	363
20	Switch Test	305
21	Therm Test & AD Cal	54
22	**Grand Total**	**4084**

PivotTable Fields

Choose fields to add to report:

☐ Date & Time
☐ P/N
☐ S/N
☐ Tester
☐ Result
☑ **Failure Reason**

Rows: Failure Reason

Values: Count of Failure Reason

1. Go back to the data sheet, launch a new *PivotTable*

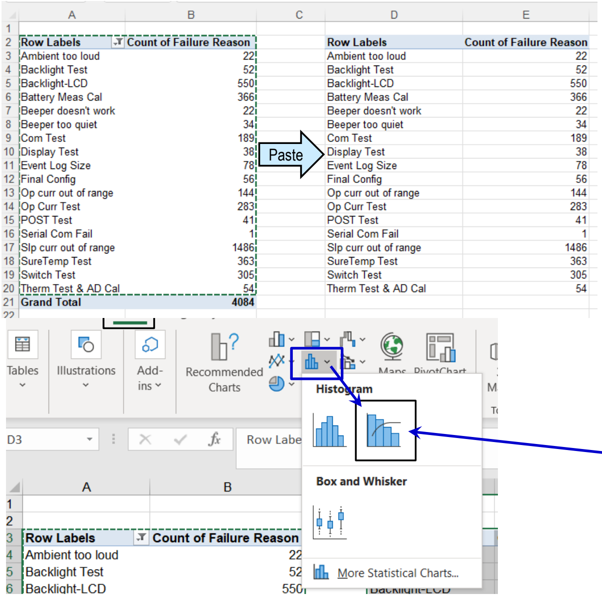
2. Drag/drop *Failure Reason* to *Rows* and to *Values*

3. Uncheck *(blank)* on the *Row Labels* menu as needed

4. Click on one of the values in column B

5. Go to the next slide

Pareto analysis of failure reasons (cont'd)



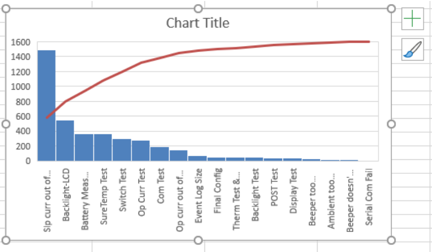
Row Labels	Count of Failure Reason
Ambient too loud	22
Backlight Test	52
Backlight-LCD	550
Battery Meas Cal	366
Beeper doesn't work	22
Beeper too quiet	34
Com Test	189
Display Test	38
Event Log Size	78
Final Config	56
Op curr out of range	144
Op Curr Test	283
POST Test	41
Serial Com Fail	1
Slp curr out of range	1486
SureTemp Test	363
Switch Test	305
Therm Test & AD Cal	54
Grand Total	4084

Row Labels	Count of Failure Reason
Ambient too loud	22
Backlight Test	52
Backlight-LCD	550
Battery Meas Cal	366
Beeper doesn't work	22
Beeper too quiet	34
Com Test	189
Display Test	38
Event Log Size	78
Final Config	56
Op curr out of range	144
Op Curr Test	283
POST Test	41
Serial Com Fail	1
Slp curr out of range	1486
SureTemp Test	363
Switch Test	305
Therm Test & AD Cal	54

Row Labels	Count of Failure Reason
Ambient too loud	22
Backlight Test	52
Backlight-LCD	550

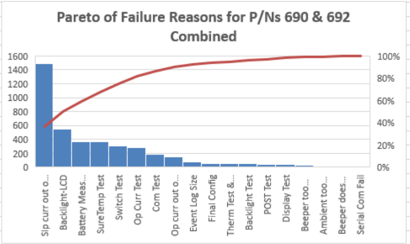
6. Copy Pivot table except for the Grand Total
7. Paste one column to the right
8. Highlight entire table you just pasted
9. Select *Insert* > Charts Section > *Insert Statistic Chart* dropdown > *Pareto*
10. Go to the next slide

Pareto analysis of failure reasons (cont'd)



Click the "+" button to edit chart elements

Select and edit desired elements including Chart Title, Axes Titles, and Secondary Axis



Exercise 23.1

All files are in the *Data Sets* folder.

a) Open *lot sampling*. Find the % failing. Save your work.

b) Open *old cars*. Assume that each row represents one automotive product recall, and the *make* column lists the brand of car involved in the recall. Create a Pareto chart of *make* by frequency of occurrence. Save your work.

Exercise 23.1 (cont'd)

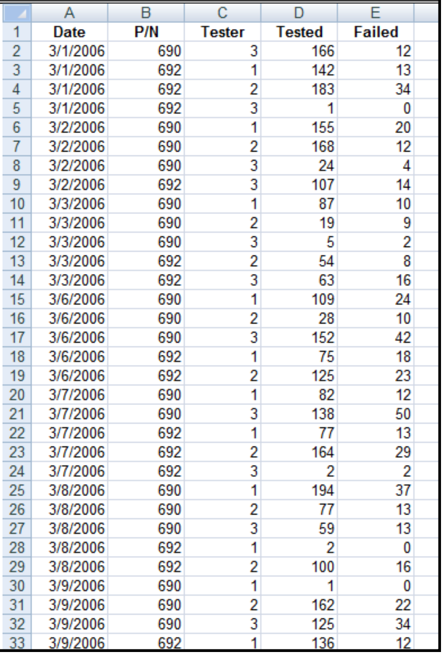
c) Open *supplier comparison*. Find the % failing. Save your work.

d) Open *unplanned downtime log*. Each row represents a downtime event in a manufacturing process. Create a Pareto chart of *Problem area* by frequency of occurrence. Save your work.

% Defective from tabulated pass/fail data

- Open *Data Sets → ATE failure occurrence tabulated*

- Daily summaries, not part level data



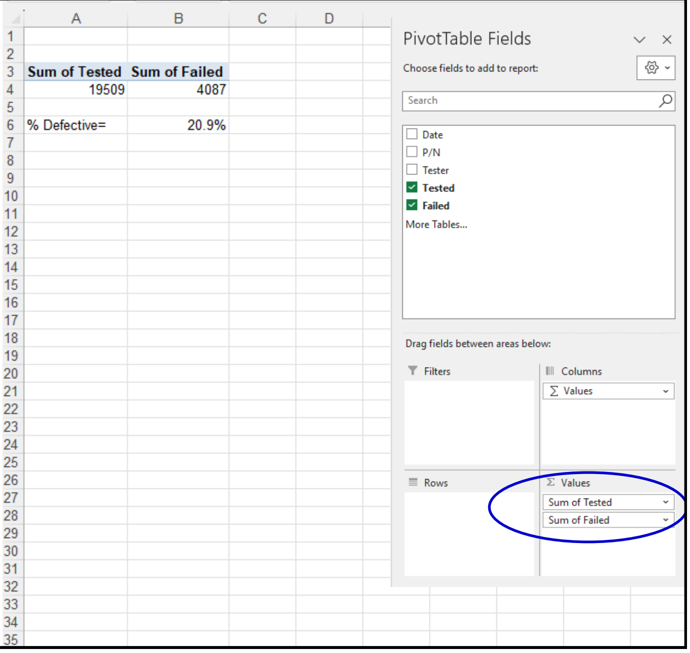
	A	B	C	D	E
1	Date	P/N	Tester	Tested	Failed
2	3/1/2006	690	3	166	12
3	3/1/2006	692	1	142	13
4	3/1/2006	692	2	183	34
5	3/1/2006	692	3	1	0
6	3/2/2006	690	1	155	20
7	3/2/2006	690	2	168	12
8	3/2/2006	690	3	24	4
9	3/2/2006	692	3	107	14
10	3/3/2006	690	1	87	10
11	3/3/2006	690	2	19	9
12	3/3/2006	690	3	5	2
13	3/3/2006	692	2	54	8
14	3/3/2006	692	3	63	16
15	3/6/2006	690	1	109	24
16	3/6/2006	690	2	28	10
17	3/6/2006	690	3	152	42
18	3/6/2006	692	1	75	18
19	3/6/2006	692	2	125	23
20	3/7/2006	690	1	82	12
21	3/7/2006	690	3	138	50
22	3/7/2006	692	1	77	13
23	3/7/2006	692	2	164	29
24	3/7/2006	692	3	2	2
25	3/8/2006	690	1	194	37
26	3/8/2006	690	2	77	13
27	3/8/2006	690	3	59	13
28	3/8/2006	692	1	2	0
29	3/8/2006	692	2	100	16
30	3/9/2006	690	1	1	0
31	3/9/2006	690	2	162	22
32	3/9/2006	690	3	125	34
33	3/9/2006	692	1	136	12

% Defective from tabulated data (cont'd)

- Insert a pivot table

- Set up as shown here

- Calculate the % defective



	A	B
3	Sum of Tested	Sum of Failed
4	19509	4087
6	% Defective=	20.9%

PivotTable Fields

Choose fields to add to report:

☐ Date
☐ P/N
☐ Tester
☑ **Tested**
☑ **Failed**

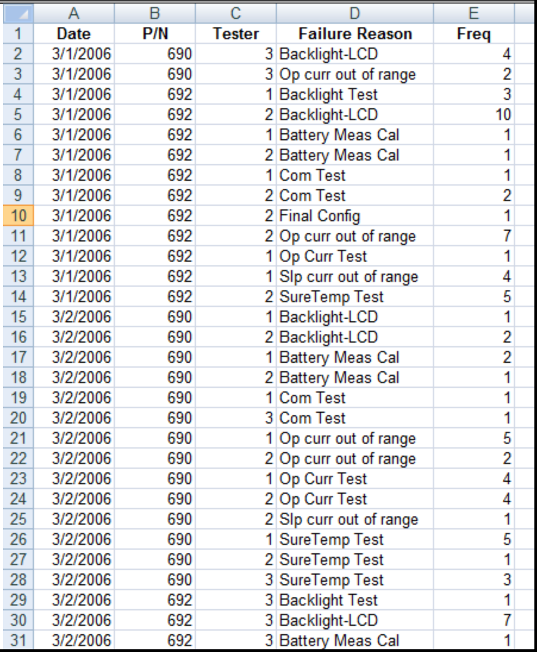
Drag fields between areas below:

Columns: Σ Values

Values: Sum of Tested, Sum of Failed

Pareto analysis from tabulated data

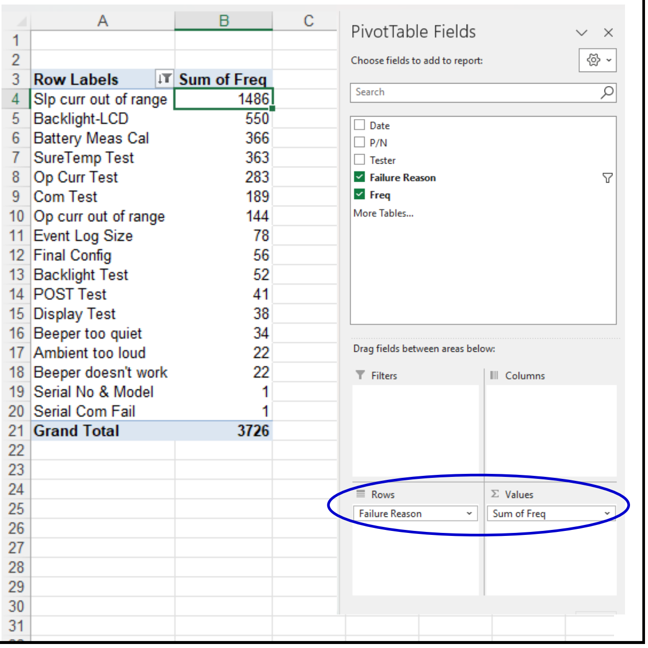
- Open *Data Sets → ATE failure reasons tabulated*
- Daily summaries, not part level data
- *Freq* = number of failures for each day, P/N, tester, and failure reason
- The total number of tests for each day, P/N, and tester is not given
- This is very common in tabulated failure/defect data



	A	B	C	D	E
1	Date	P/N	Tester	Failure Reason	Freq
2	3/1/2006	690	3	Backlight-LCD	4
3	3/1/2006	690	3	Op curr out of range	2
4	3/1/2006	692	1	Backlight Test	3
5	3/1/2006	692	2	Backlight-LCD	10
6	3/1/2006	692	1	Battery Meas Cal	1
7	3/1/2006	692	2	Battery Meas Cal	1
8	3/1/2006	692	1	Com Test	1
9	3/1/2006	692	2	Com Test	2
10	3/1/2006	692	2	Final Config	1
11	3/1/2006	692	2	Op curr out of range	7
12	3/1/2006	692	1	Op Curr Test	1
13	3/1/2006	692	1	Slp curr out of range	4
14	3/1/2006	692	2	SureTemp Test	5
15	3/2/2006	690	1	Backlight-LCD	1
16	3/2/2006	690	2	Backlight-LCD	2
17	3/2/2006	690	1	Battery Meas Cal	2
18	3/2/2006	690	2	Battery Meas Cal	1
19	3/2/2006	690	1	Com Test	1
20	3/2/2006	690	3	Com Test	1
21	3/2/2006	690	1	Op curr out of range	5
22	3/2/2006	690	2	Op curr out of range	2
23	3/2/2006	690	1	Op Curr Test	4
24	3/2/2006	690	2	Op Curr Test	4
25	3/2/2006	690	2	Slp curr out of range	1
26	3/2/2006	690	1	SureTemp Test	5
27	3/2/2006	690	2	SureTemp Test	1
28	3/2/2006	690	3	SureTemp Test	3
29	3/2/2006	692	3	Backlight Test	1
30	3/2/2006	692	3	Backlight-LCD	7
31	3/2/2006	692	3	Battery Meas Cal	1

Pareto from tabulated data (cont'd)

- Insert a pivot table
- Set it up as shown here
- Sort the failure reasons in descending order by number of occurrences
- The Pareto chart can be created the same as before



	A	B
3	Row Labels	Sum of Freq
4	Slp curr out of range	1486
5	Backlight-LCD	550
6	Battery Meas Cal	366
7	SureTemp Test	363
8	Op Curr Test	283
9	Com Test	189
10	Op curr out of range	144
11	Event Log Size	78
12	Final Config	56
13	Backlight Test	52
14	POST Test	41
15	Display Test	38
16	Beeper too quiet	34
17	Ambient too loud	22
18	Beeper doesn't work	22
19	Serial No & Model	1
20	Serial Com Fail	1
21	Grand Total	3726

PivotTable Fields

Choose fields to add to report:

☐ Date
☐ P/N
☐ Tester
☑ **Failure Reason**
☑ **Freq**

Drag fields between areas below:

Rows: Failure Reason

Values: Sum of Freq

Exercise 23.2

All files are in the *Data Sets* folder.

a) Open *parts inspected & defective*. Find the % defective. Save your work.

b) Open *defects & types*. Create a Pareto chart of defect types by frequency of occurrence. Is it possible to obtain % defective from this data set? Explain your answer. Save your work.

c) Open *out of box failures*. Find the % failing. Save your work.

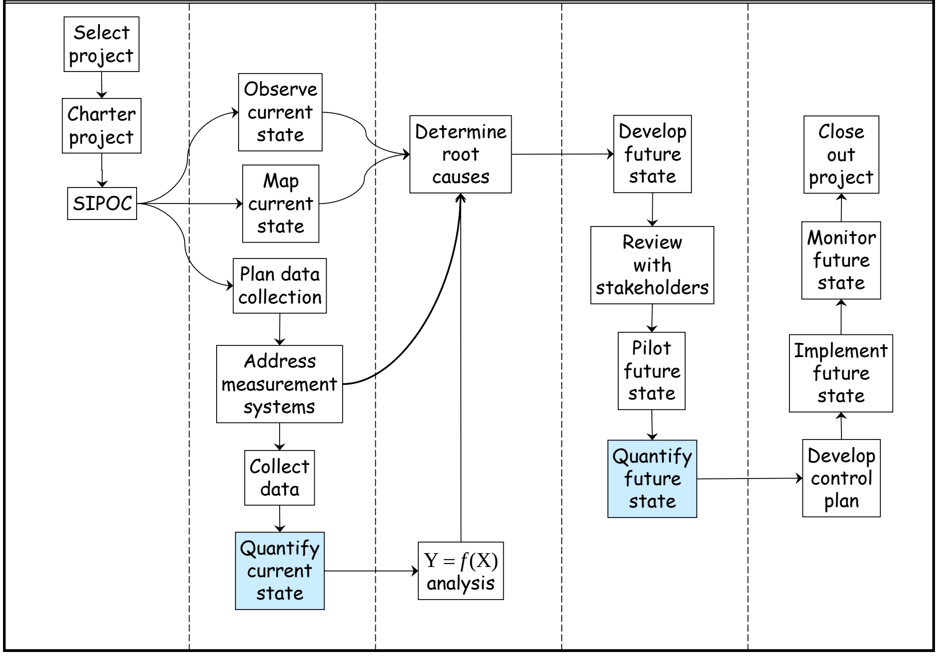
Exercise 23.2 (cont'd)

d) Open *unplanned downtime log*. Create a Pareto chart of *Problem area* by total downtime. Save your work.

e) Open *scrap quantity and cost*. Create a Pareto chart of scrap category by *quantity* scrapped. Is it possible to obtain scrap as a % of total production from this data set? Explain your answer.

f) Create a Pareto chart of scrap category by total *cost* of scrap. (You will have to create a new data column defined by a formula.) Compare this to the chart in (e). Save your work.

24 Establishing Baselines – Quantitative Y

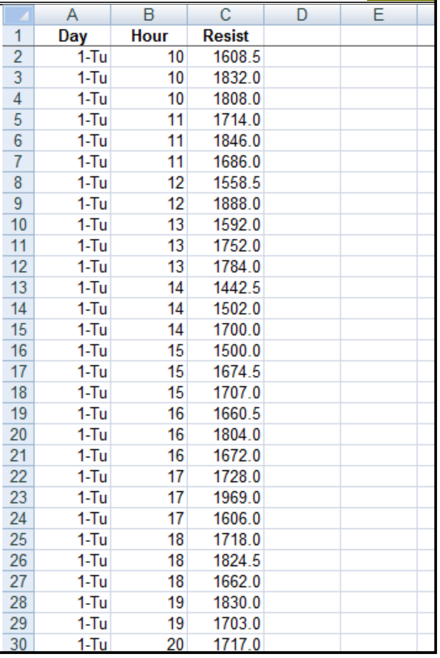


Topics

- Basic statistical summary
- Frequency histogram
- Calculating % defective from quantitative data

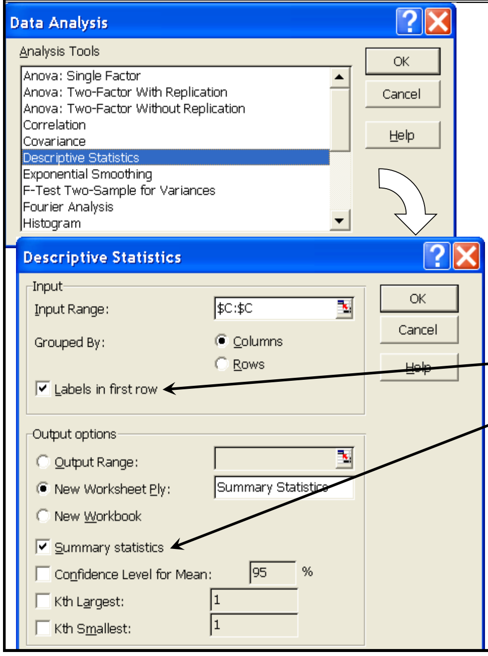
Basic statistical summary

- Open *Data Sets* → *DI water*
- Measurements taken 3 times an hour for 8 days
- Y variable = *Resist* (higher is better)
- X variables = *Day*, *Hour*



	A	B	C	D	E
1	Day	Hour	Resist		
2	1-Tu	10	1608.5		
3	1-Tu	10	1832.0		
4	1-Tu	10	1808.0		
5	1-Tu	11	1714.0		
6	1-Tu	11	1846.0		
7	1-Tu	11	1686.0		
8	1-Tu	12	1558.5		
9	1-Tu	12	1888.0		
10	1-Tu	13	1592.0		
11	1-Tu	13	1752.0		
12	1-Tu	13	1784.0		
13	1-Tu	14	1442.5		
14	1-Tu	14	1502.0		
15	1-Tu	14	1700.0		
16	1-Tu	15	1500.0		
17	1-Tu	15	1674.5		
18	1-Tu	15	1707.0		
19	1-Tu	16	1660.5		
20	1-Tu	16	1804.0		
21	1-Tu	16	1672.0		
22	1-Tu	17	1728.0		
23	1-Tu	17	1969.0		
24	1-Tu	17	1606.0		
25	1-Tu	18	1718.0		
26	1-Tu	18	1824.5		
27	1-Tu	18	1662.0		
28	1-Tu	19	1830.0		
29	1-Tu	19	1703.0		
30	1-Tu	20	1717.0		

Basic statistical summary (cont'd)



Input Range: $C:$C

Grouped By: ● Columns ○ Rows

☑ Labels in first row

○ Output Range:

● New Worksheet Ply: Summary Statistics

○ New Workbook

☑ Summary statistics

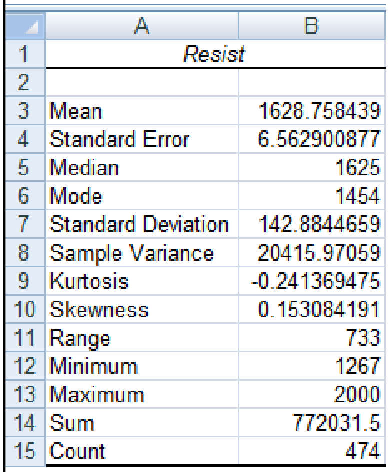
☐ Confidence Level for Mean: 95 %

☐ Kth Largest: 1

☐ Kth Smallest: 1

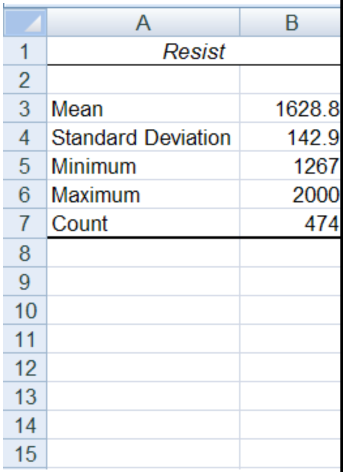
1. Select the *Data* ribbon
2. Select *Data Analysis*
3. Select *Descriptive Statistics*
4. Click OK
5. For *Input Range* select all of column C (click on the column header)
6. Select *Labels in first row*
7. Select *Summary statistics*
8. Click OK

Basic statistical summary (cont'd)



	A	B
1	*Resist*	
2		
3	Mean	1628.758439
4	Standard Error	6.562900877
5	Median	1625
6	Mode	1454
7	Standard Deviation	142.8844659
8	Sample Variance	20415.97059
9	Kurtosis	-0.241369475
10	Skewness	0.153084191
11	Range	733
12	Minimum	1267
13	Maximum	2000
14	Sum	772031.5
15	Count	474

- Edit down to the "vital few"
- Correct the default numerical formats

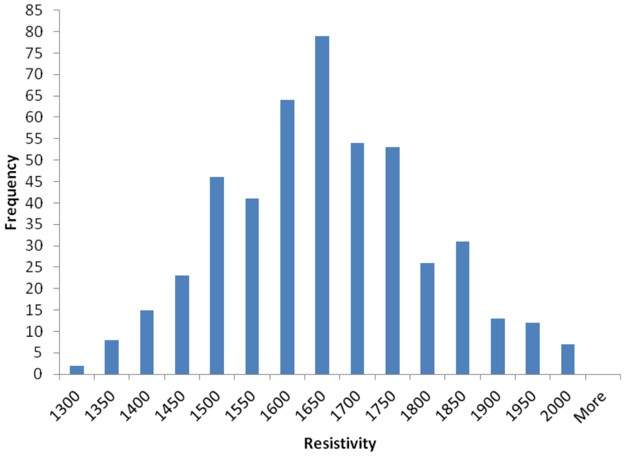


	A	B
1	*Resist*	
2		
3	Mean	1628.8
4	Standard Deviation	142.9
5	Minimum	1267
6	Maximum	2000
7	Count	474
8		
9		
10		
11		
12		
13		
14		
15		

Project metric	Average Resistivity
Baseline value	1628.8

Frequency histogram

A statistical graphic for displaying variation in quantitative data



Histogram (cont'd)

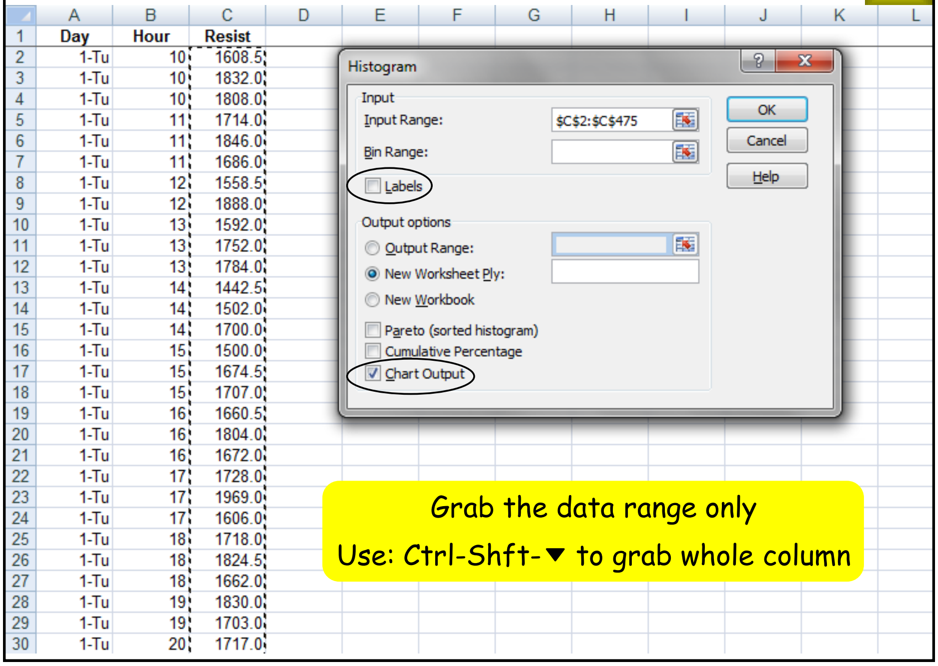
- Shows variation without plotting the data over time
  - Heights of bars show the number of data points in each bin
  - Bin widths are equal, and are a range of numbers
- Histograms and time plots are complementary — they can reveal different aspects of the data
- We will discuss time plots later

Histogram (cont'd)

Excel path to create Histogram:

Data → *Data Analysis* → *Histogram*

Histogram Setup: *Data → Data Analysis → Histogram*



	A	B	C
1	Day	Hour	Resist
2	1-Tu	10	1608.5
3	1-Tu	10	1832.0
4	1-Tu	10	1808.0
5	1-Tu	11	1714.0
6	1-Tu	11	1846.0
7	1-Tu	11	1686.0
8	1-Tu	12	1558.5
9	1-Tu	12	1888.0
10	1-Tu	13	1592.0
11	1-Tu	13	1752.0
12	1-Tu	13	1784.0
13	1-Tu	14	1442.5
14	1-Tu	14	1502.0
15	1-Tu	14	1700.0
16	1-Tu	15	1500.0
17	1-Tu	15	1674.5
18	1-Tu	15	1707.0
19	1-Tu	16	1660.5
20	1-Tu	16	1804.0
21	1-Tu	16	1672.0
22	1-Tu	17	1728.0
23	1-Tu	17	1969.0
24	1-Tu	17	1606.0
25	1-Tu	18	1718.0
26	1-Tu	18	1824.5
27	1-Tu	18	1662.0
28	1-Tu	19	1830.0
29	1-Tu	19	1703.0
30	1-Tu	20	1717.0

Histogram

Input

Input Range: $C$2:$C$475

Bin Range:

☐ Labels

Output options

○ Output Range:

● New Worksheet Ply:

○ New Workbook

☐ Pareto (sorted histogram)

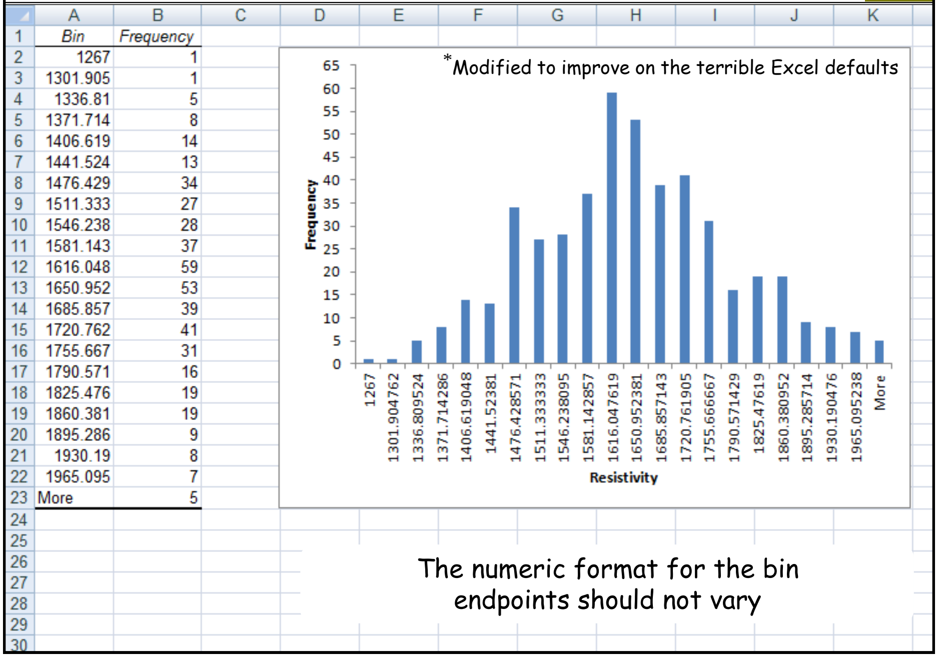
☐ Cumulative Percentage

☑ Chart Output

Grab the data range only

Use: Ctrl-Shft-▼ to grab whole column

Histogram output*

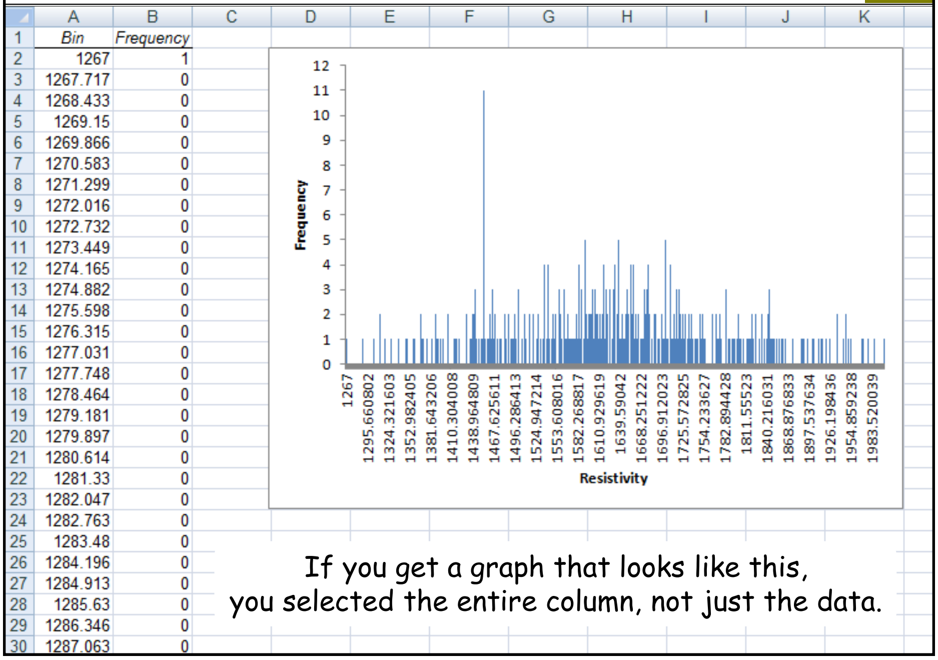


	A	B
1	*Bin*	*Frequency*
2	1267	1
3	1301.905	1
4	1336.81	5
5	1371.714	8
6	1406.619	14
7	1441.524	13
8	1476.429	34
9	1511.333	27
10	1546.238	28
11	1581.143	37
12	1616.048	59
13	1650.952	53
14	1685.857	39
15	1720.762	41
16	1755.667	31
17	1790.571	16
18	1825.476	19
19	1860.381	19
20	1895.286	9
21	1930.19	8
22	1965.095	7
23	More	5

*Modified to improve on the terrible Excel defaults

The numeric format for the bin endpoints should not vary

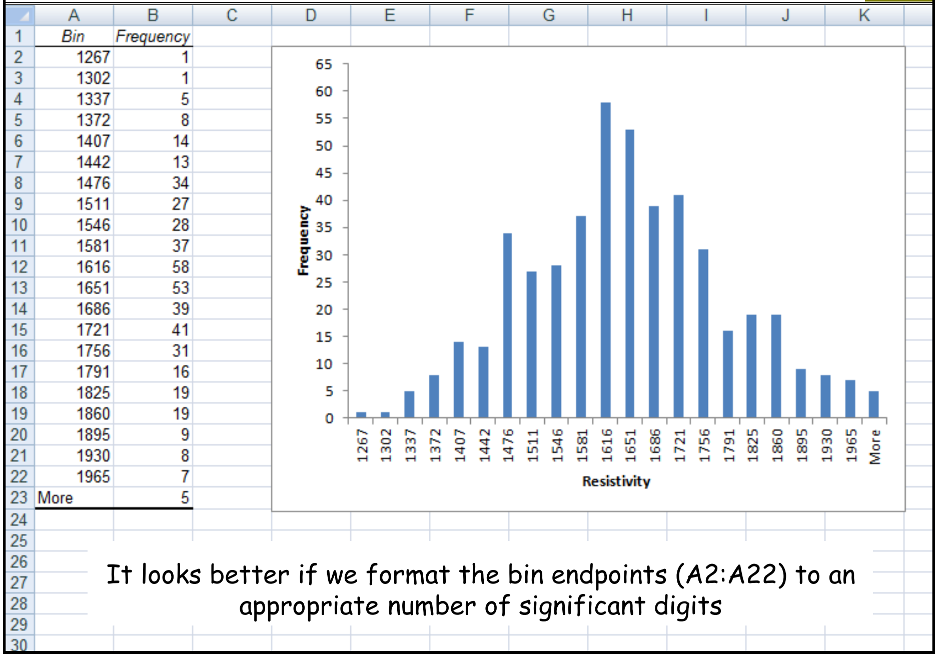
Histogram output that you don't want



Bin	Frequency
1267	1
1267.717	0
1268.433	0
1269.15	0
1269.866	0
1270.583	0
1271.299	0
1272.016	0
1272.732	0
1273.449	0
1274.165	0
1274.882	0
1275.598	0
1276.315	0
1277.031	0
1277.748	0
1278.464	0
1279.181	0
1279.897	0
1280.614	0
1281.33	0
1282.047	0
1282.763	0
1283.48	0
1284.196	0
1284.913	0
1285.63	0
1286.346	0
1287.063	0

If you get a graph that looks like this,
you selected the entire column, not just the data.

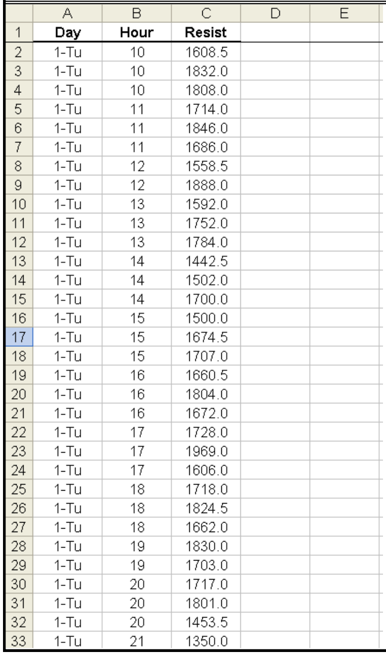
Histogram (cont'd)



Bin	Frequency
1267	1
1302	1
1337	5
1372	8
1407	14
1442	13
1476	34
1511	27
1546	28
1581	37
1616	58
1651	53
1686	39
1721	41
1756	31
1791	16
1825	19
1860	19
1895	9
1930	8
1965	7
More	5

It looks better if we format the bin endpoints (A2:A22) to an appropriate number of significant digits

% Defective from quantitative data

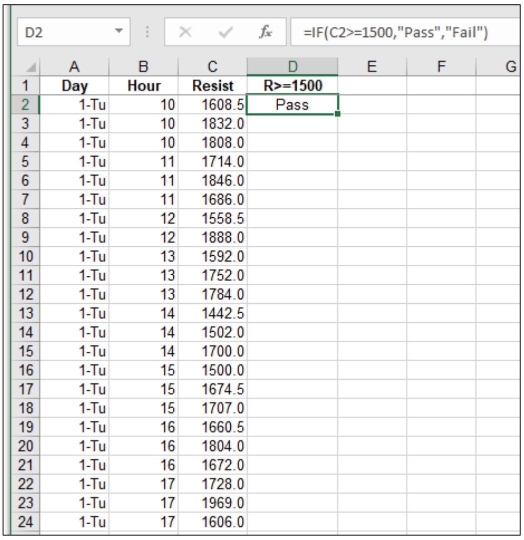


	A	B	C	D	E
1	Day	Hour	Resist		
2	1-Tu	10	1608.5		
3	1-Tu	10	1832.0		
4	1-Tu	10	1808.0		
5	1-Tu	11	1714.0		
6	1-Tu	11	1846.0		
7	1-Tu	11	1686.0		
8	1-Tu	12	1558.5		
9	1-Tu	12	1888.0		
10	1-Tu	13	1592.0		
11	1-Tu	13	1752.0		
12	1-Tu	13	1784.0		
13	1-Tu	14	1442.5		
14	1-Tu	14	1502.0		
15	1-Tu	14	1700.0		
16	1-Tu	15	1500.0		
17	1-Tu	15	1674.5		
18	1-Tu	15	1707.0		
19	1-Tu	16	1660.5		
20	1-Tu	16	1804.0		
21	1-Tu	16	1672.0		
22	1-Tu	17	1728.0		
23	1-Tu	17	1969.0		
24	1-Tu	17	1606.0		
25	1-Tu	18	1718.0		
26	1-Tu	18	1824.5		
27	1-Tu	18	1662.0		
28	1-Tu	19	1830.0		
29	1-Tu	19	1703.0		
30	1-Tu	20	1717.0		
31	1-Tu	20	1801.0		
32	1-Tu	20	1453.5		
33	1-Tu	21	1350.0		

- Averages are common project metrics for quantitative Y variables
- Averages are useful for statistical comparisons
- However, customers feel the *variation*, not the average
- The best metric for customer dissatisfaction is the % of parts or transactions that do not meet a requirement or expectation

---

Percent less than 1500



D2

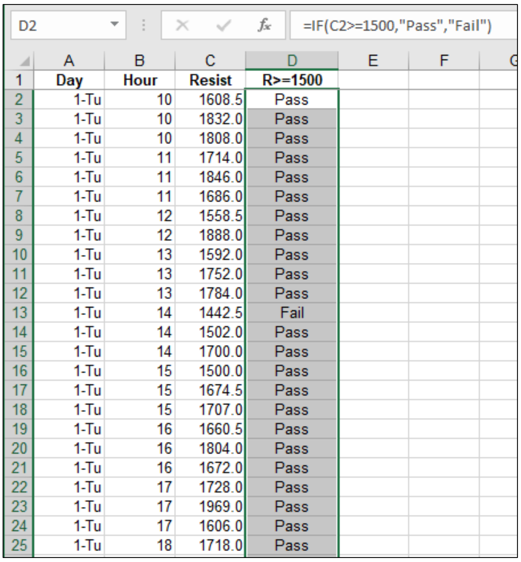
=IF(C2>=1500,"Pass","Fail")

	A	B	C	D	E	F	G
1	Day	Hour	Resist	R>=1500			
2	1-Tu	10	1608.5	Pass			
3	1-Tu	10	1832.0				
4	1-Tu	10	1808.0				
5	1-Tu	11	1714.0				
6	1-Tu	11	1846.0				
7	1-Tu	11	1686.0				
8	1-Tu	12	1558.5				
9	1-Tu	12	1888.0				
10	1-Tu	13	1592.0				
11	1-Tu	13	1752.0				
12	1-Tu	13	1784.0				
13	1-Tu	14	1442.5				
14	1-Tu	14	1502.0				
15	1-Tu	14	1700.0				
16	1-Tu	15	1500.0				
17	1-Tu	15	1674.5				
18	1-Tu	15	1707.0				
19	1-Tu	16	1660.5				
20	1-Tu	16	1804.0				
21	1-Tu	16	1672.0				
22	1-Tu	17	1728.0				
23	1-Tu	17	1969.0				
24	1-Tu	17	1606.0				

- Let's say the lower spec limit (LSL) for *Resist* is 1500.
- Use the requirement to be met as the name for a new column (cell D1)
- We want the new column to say "Pass" when *Resist* ≥ 1500 and "Fail" when *Resist* < 1500
- Enter the corresponding IF statement into cell D2

=IF(C2 >= 1500,"Pass","Fail")

Percent less than 1500 (cont'd)



D2 =IF(C2>=1500,"Pass","Fail")

	A	B	C	D
1	Day	Hour	Resist	R>=1500
2	1-Tu	10	1608.5	Pass
3	1-Tu	10	1832.0	Pass
4	1-Tu	10	1808.0	Pass
5	1-Tu	11	1714.0	Pass
6	1-Tu	11	1846.0	Pass
7	1-Tu	11	1686.0	Pass
8	1-Tu	12	1558.5	Pass
9	1-Tu	12	1888.0	Pass
10	1-Tu	13	1592.0	Pass
11	1-Tu	13	1752.0	Pass
12	1-Tu	13	1784.0	Pass
13	1-Tu	14	1442.5	Fail
14	1-Tu	14	1502.0	Pass
15	1-Tu	14	1700.0	Pass
16	1-Tu	15	1500.0	Pass
17	1-Tu	15	1674.5	Pass
18	1-Tu	15	1707.0	Pass
19	1-Tu	16	1660.5	Pass
20	1-Tu	16	1804.0	Pass
21	1-Tu	16	1672.0	Pass
22	1-Tu	17	1728.0	Pass
23	1-Tu	17	1969.0	Pass
24	1-Tu	17	1606.0	Pass
25	1-Tu	18	1718.0	Pass

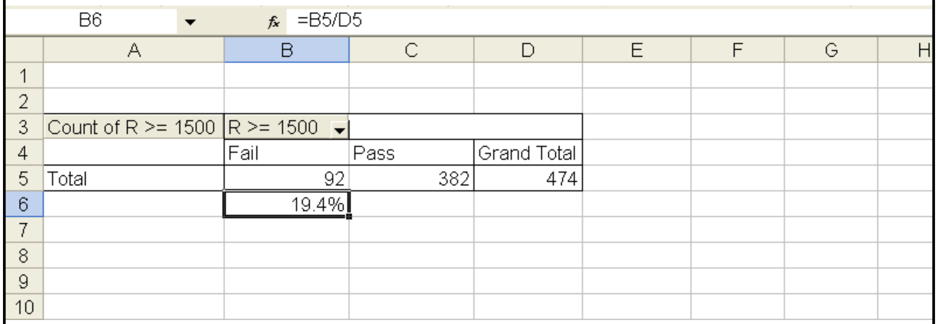
Now we need to copy the formula down to end of the column:

- Click on D2
- Double-click on the lower right-hand corner of D2
- If there are blank cells, repeat this process until you get down to the last row of data

---

Percent less than 1500 (cont'd)

- Run a pivot table on the new column
- Calculate the % less than 1500

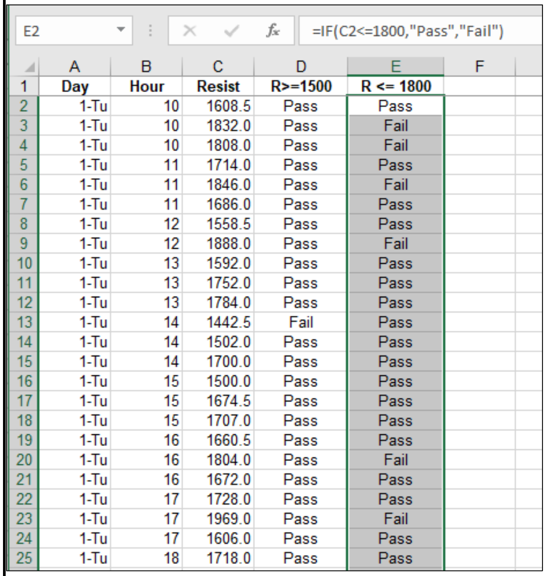


B6 =B5/D5

	A	B	C	D
3	Count of R >= 1500	R >= 1500		
4		Fail	Pass	Grand Total
5	Total	92	382	474
6		19.4%		

Project metric	% < 1500
Baseline value	19.4%

Percent greater than 1800



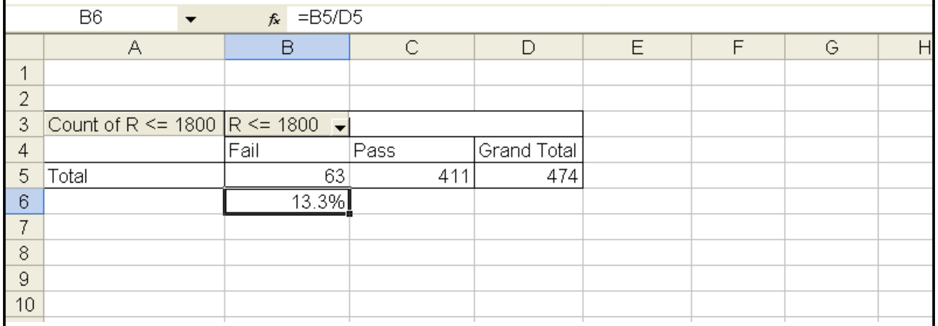
E2 =IF(C2<=1800,"Pass","Fail")

	A	B	C	D	E	F
1	Day	Hour	Resist	R>=1500	R <= 1800	
2	1-Tu	10	1608.5	Pass	Pass	
3	1-Tu	10	1832.0	Pass	Fail	
4	1-Tu	10	1808.0	Pass	Fail	
5	1-Tu	11	1714.0	Pass	Pass	
6	1-Tu	11	1846.0	Pass	Fail	
7	1-Tu	11	1686.0	Pass	Pass	
8	1-Tu	12	1558.5	Pass	Pass	
9	1-Tu	12	1888.0	Pass	Fail	
10	1-Tu	13	1592.0	Pass	Pass	
11	1-Tu	13	1752.0	Pass	Pass	
12	1-Tu	13	1784.0	Pass	Pass	
13	1-Tu	14	1442.5	Fail	Pass	
14	1-Tu	14	1502.0	Pass	Pass	
15	1-Tu	14	1700.0	Pass	Pass	
16	1-Tu	15	1500.0	Pass	Pass	
17	1-Tu	15	1674.5	Pass	Pass	
18	1-Tu	15	1707.0	Pass	Pass	
19	1-Tu	16	1660.5	Pass	Pass	
20	1-Tu	16	1804.0	Pass	Fail	
21	1-Tu	16	1672.0	Pass	Pass	
22	1-Tu	17	1728.0	Pass	Pass	
23	1-Tu	17	1969.0	Pass	Fail	
24	1-Tu	17	1606.0	Pass	Pass	
25	1-Tu	18	1718.0	Pass	Pass	

- Let’s pretend *Resist* has a USL at 1800
- Use the requirement to be met as the name for a new column (cell E1)
- We want the new column to say “Pass” when *Resist* ≤ 1800 and “Fail” when *Resist* > 1800
- Enter the corresponding IF statement into cell E2
- Copy the formula down to the end of the data set

Percent greater than 1800 (cont’d)

- Run a pivot table on the new column
- Calculate the % greater than 1800
- The total % defective would be 19.4 + 13.3 = 32.7%
- Save your work



B6 =B5/D5

	A	B	C	D	E	F	G	H
1								
2								
3	Count of R <= 1800	R <= 1800						
4		Fail	Pass	Grand Total				
5	Total	63	411	474				
6		13.3%						
7								
8								
9								
10								

Exercise 24.1

Open *Data Sets* → *number & size of defects*. *Max size* is the area of the largest weld repair on a casting.

(a) Create a basic statistical summary for *Max size*.

(b) Create a frequency histogram for *Max size*.

(c) The customer will accept a casting only if *Max size* is less than or equal to 15. Find the percentage of castings that exceed 15.

(d) Save your work.

Exercise 24.2

Open *Data Sets* → *quotation process current state*. TAT is the turnaround time in business days for each quote.

(a) Create a basic statistical summary of TAT. Update the charter[*] by entering the baseline average TAT. Enter 1.5 days as the goal for that metric.

(b) Create a frequency histogram of TAT.

(c) Customers have been told quotes will be turned around in 3 days or less. Find the percentage of quotes that do not satisfy this expectation. Update the charter by entering this as the baseline value. Enter 10% as the goal for that metric.

(d) Calculate the purchase order hit rate (% Yes in the PO column). Update the charter by entering this as the baseline value.

(e) Save your work.

---

[*] *Student Files* → *quotation process charter*

Exercise 24.3

Open the file *Data Sets* → *MBDP current state*.

a) Create a basic statistical summary of PO-PD. Update the charter[*] by entering the average PO-PD as the baseline value.

b) Create a frequency histogram of PO-PD.

c) Find the % of orders for which PO-PD exceeds 30 days. Update the charter by entering this as the baseline value.

d) Find the % of orders for which MFG is not happy. Update the charter by entering this as the baseline value.

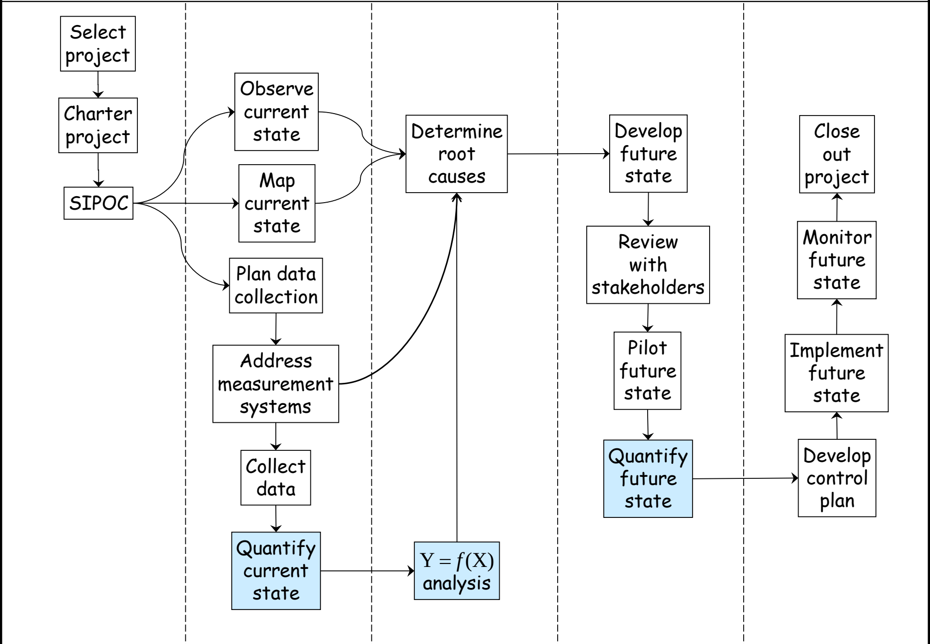
e) Save your work.

---

[*] *Student Files* → *MBDP charter*

Notes

25 Plotting Data Over Time



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Why plot data over time?

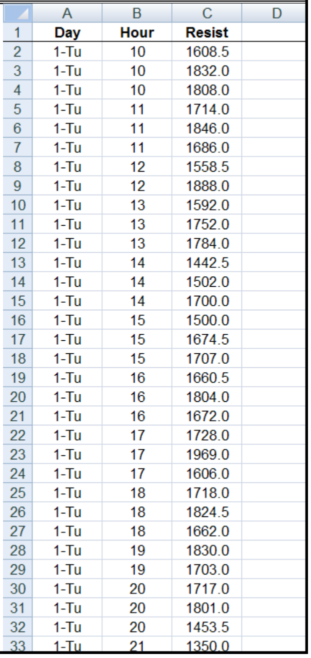
By plotting data in time sequence, we can see how the process is performing over time. We can quickly see:

- the amount of variation and whether it changes over time
- upward or downward trends
- unusual data points
- cycles or other patterns in the data

Example 1: Plotting quantitative data

Data Sets → DI water

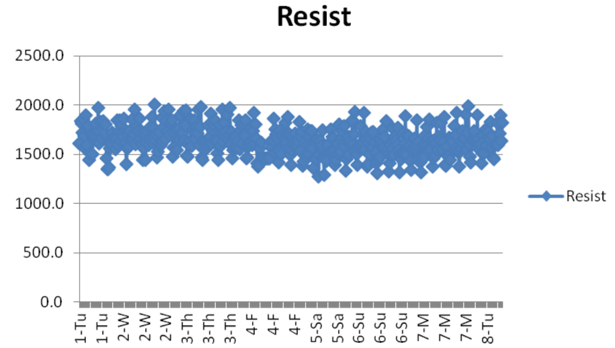
- De–ionized water is used in machining and cutting operations
- Y = electrical resistivity (*Resist*)
- Want lower conductivity, so higher Y is better
- Baseline data was collected over 8 days, 3 measurements per hour
- Want to make a time plot



	A	B	C	D
1	**Day**	**Hour**	**Resist**	
2	1-Tu	10	1608.5	
3	1-Tu	10	1832.0	
4	1-Tu	10	1808.0	
5	1-Tu	11	1714.0	
6	1-Tu	11	1846.0	
7	1-Tu	11	1686.0	
8	1-Tu	12	1558.5	
9	1-Tu	12	1888.0	
10	1-Tu	13	1592.0	
11	1-Tu	13	1752.0	
12	1-Tu	13	1784.0	
13	1-Tu	14	1442.5	
14	1-Tu	14	1502.0	
15	1-Tu	14	1700.0	
16	1-Tu	15	1500.0	
17	1-Tu	15	1674.5	
18	1-Tu	15	1707.0	
19	1-Tu	16	1660.5	
20	1-Tu	16	1804.0	
21	1-Tu	16	1672.0	
22	1-Tu	17	1728.0	
23	1-Tu	17	1969.0	
24	1-Tu	17	1606.0	
25	1-Tu	18	1718.0	
26	1-Tu	18	1824.5	
27	1-Tu	18	1662.0	
28	1-Tu	19	1830.0	
29	1-Tu	19	1703.0	
30	1-Tu	20	1717.0	
31	1-Tu	20	1801.0	
32	1-Tu	20	1453.5	
33	1-Tu	21	1350.0	

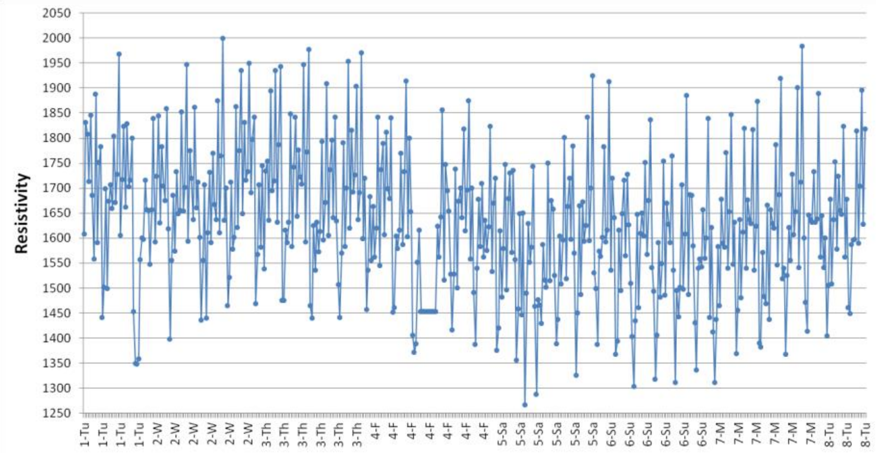
Example 1 (cont'd)

1. Select column C, then select column A while holding down the **Ctrl** key
2. Insert a line chart ("Line with Markers")
3. Behold: your typically terrible default Excel chart
4. Desperately needs "graphical 5S"



Example 1 (cont’d)

5. With a single data series the legend is pointless — delete it
6. Format the vertical axis as shown below: more data, less empty space
7. Format the data series to reduce the size of the markers and lines



Example 1 (cont’d)

- Good graphics are “lean” graphics

- General principle for lean graphics:

Reduce the ink-to-data ratio!

- There are a couple of interesting observations about the data plotted above — what are they?

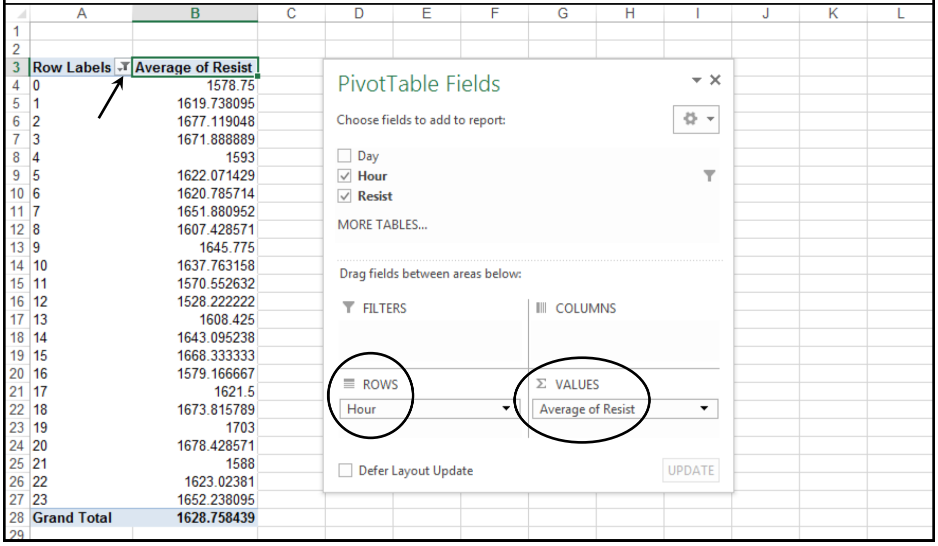
Example 2

- Can also plot *summary statistics* by time period
- Average, % too high, % too low, etc.
- May give a clearer picture of certain patterns of variation

---

Example 2 (cont'd)

1. Let's plot average resistivity by hour of day
2. Insert a pivot table, set it up as shown below



Row Labels	Average of Resist
0	1578.75
1	1619.738095
2	1677.119048
3	1671.888889
4	1593
5	1622.071429
6	1620.785714
7	1651.880952
8	1607.428571
9	1645.775
10	1637.763158
11	1570.552632
12	1528.222222
13	1608.425
14	1643.095238
15	1668.333333
16	1579.166667
17	1621.5
18	1673.815789
19	1703
20	1678.428571
21	1588
22	1623.02381
23	1652.238095
Grand Total	**1628.758439**

PivotTable Fields

Choose fields to add to report:

☐ Day
☑ **Hour**
☑ **Resist**

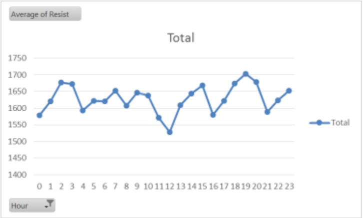
Drag fields between areas below:

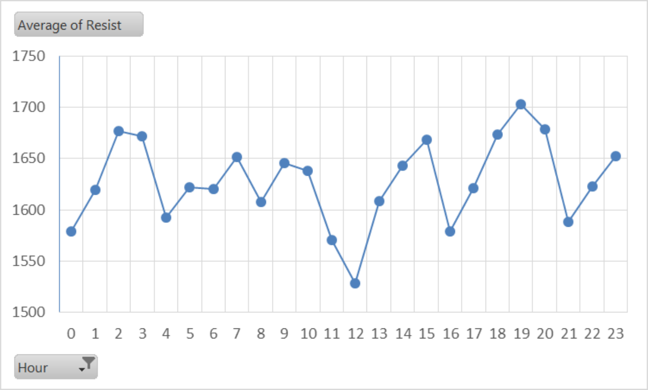
ROWS: Hour
VALUES: Average of Resist

☐ Defer Layout Update

Example 2 (cont'd)

With the *Pivot Table Fields* dialog still showing, select *Insert* ribbon → *Line Chart*



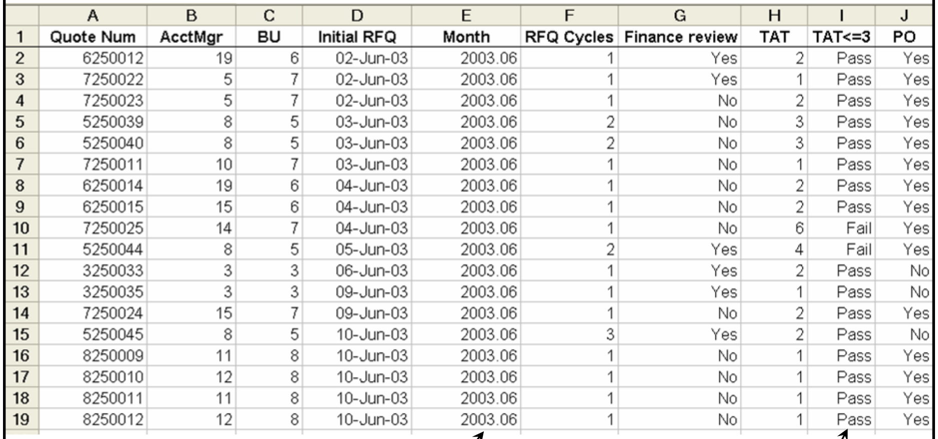


- There was a cyclical daily pattern, most pronounced from noon to midnight
- It was caused by everyone taking lunch and breaks at the same time

---

Example 3

Open *Data Sets* → *quotation process current state*



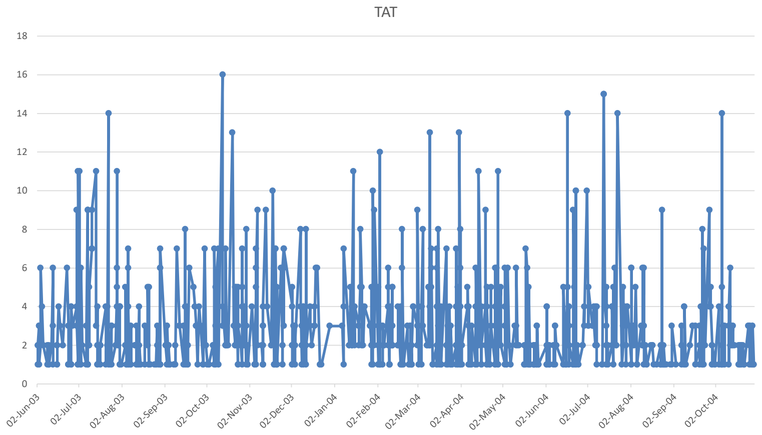
	A	B	C	D	E	F	G	H	I	J
1	Quote Num	AcctMgr	BU	Initial RFQ	Month	RFQ Cycles	Finance review	TAT	TAT<=3	PO
2	6250012	19	6	02-Jun-03	2003.06	1	Yes	2	Pass	Yes
3	7250022	5	7	02-Jun-03	2003.06	1	Yes	1	Pass	Yes
4	7250023	5	7	02-Jun-03	2003.06	1	No	2	Pass	Yes
5	5250039	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes
6	5250040	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes
7	7250011	10	7	03-Jun-03	2003.06	1	No	1	Pass	Yes
8	6250014	19	6	04-Jun-03	2003.06	1	No	2	Pass	Yes
9	6250015	15	6	04-Jun-03	2003.06	1	No	2	Pass	Yes
10	7250025	14	7	04-Jun-03	2003.06	1	No	6	Fail	Yes
11	5250044	8	5	05-Jun-03	2003.06	2	Yes	4	Fail	Yes
12	3250033	3	3	06-Jun-03	2003.06	1	Yes	2	Pass	No
13	3250035	3	3	09-Jun-03	2003.06	1	Yes	1	Pass	No
14	7250024	15	7	09-Jun-03	2003.06	1	No	2	Pass	Yes
15	5250045	8	5	10-Jun-03	2003.06	3	Yes	2	Pass	No
16	8250009	11	8	10-Jun-03	2003.06	1	No	1	Pass	Yes
17	8250010	12	8	10-Jun-03	2003.06	1	No	1	Pass	Yes
18	8250011	11	8	10-Jun-03	2003.06	1	No	1	Pass	Yes
19	8250012	12	8	10-Jun-03	2003.06	1	No	1	Pass	Yes

=YEAR(D2)+MONTH(D2)/100

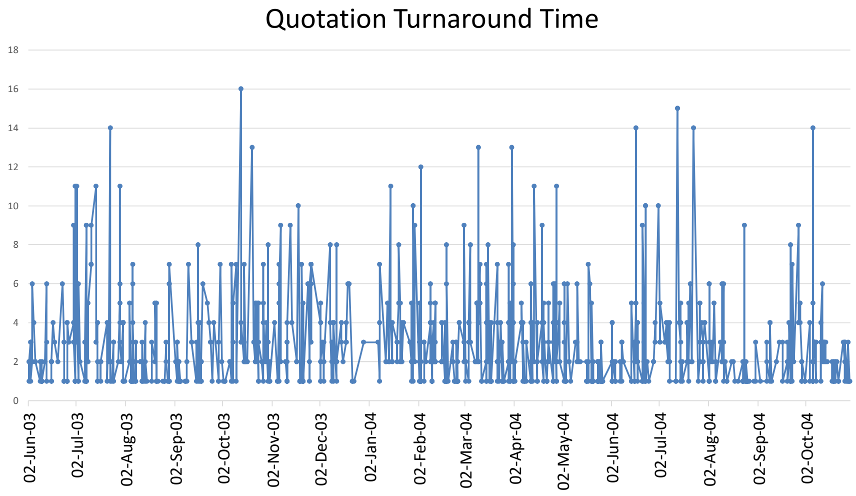
=IF(H2>3,"Fail","Pass")

Example 3 (cont'd)

1. Select column H, then select column D while holding down the **Ctrl** key
2. Insert a line chart ("Line with Markers")



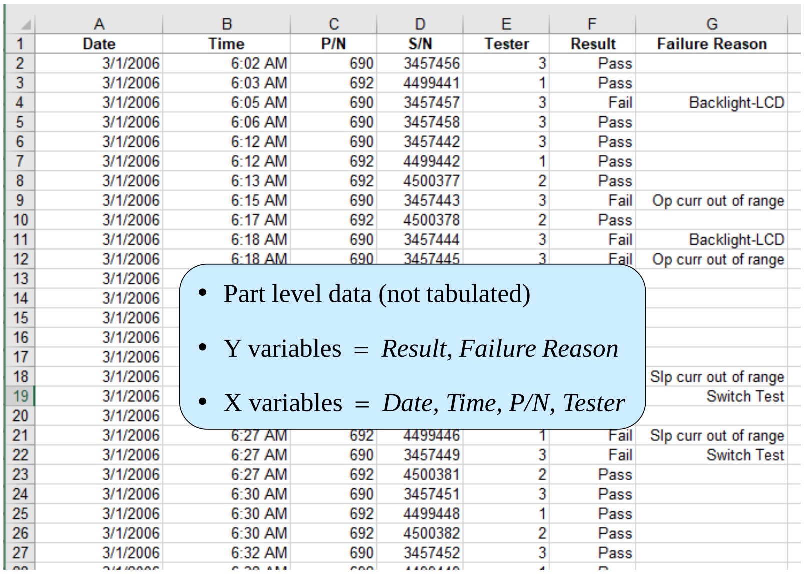
Example 3 (cont'd)



Changes in variation, no discernable changes in the mean

Example 4: plotting pass/fail data

Open *Data Sets* → *ATE Mar & Apr*



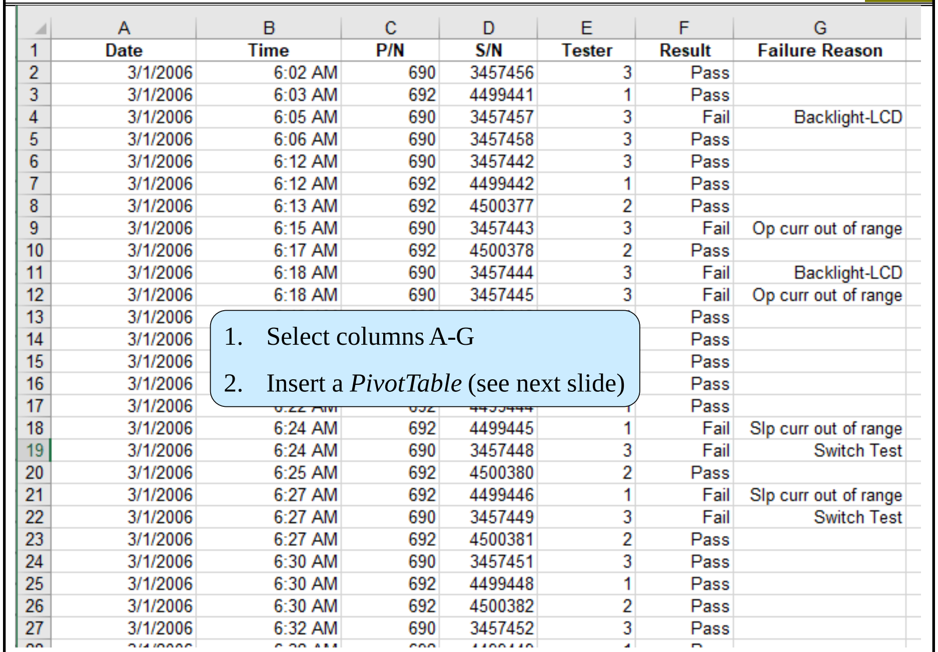
	A	B	C	D	E	F	G
1	Date	Time	P/N	S/N	Tester	Result	Failure Reason
2	3/1/2006	6:02 AM	690	3457456	3	Pass	
3	3/1/2006	6:03 AM	692	4499441	1	Pass	
4	3/1/2006	6:05 AM	690	3457457	3	Fail	Backlight-LCD
5	3/1/2006	6:06 AM	690	3457458	3	Pass	
6	3/1/2006	6:12 AM	690	3457442	3	Pass	
7	3/1/2006	6:12 AM	692	4499442	1	Pass	
8	3/1/2006	6:13 AM	692	4500377	2	Pass	
9	3/1/2006	6:15 AM	690	3457443	3	Fail	Op curr out of range
10	3/1/2006	6:17 AM	692	4500378	2	Pass	
11	3/1/2006	6:18 AM	690	3457444	3	Fail	Backlight-LCD
12	3/1/2006	6:18 AM	690	3457445	3	Fail	Op curr out of range
13	3/1/2006						
14	3/1/2006						
15	3/1/2006						
16	3/1/2006						
17	3/1/2006						
18	3/1/2006						Slp curr out of range
19	3/1/2006						Switch Test
20	3/1/2006						
21	3/1/2006	6:27 AM	692	4499446	1	Fail	Slp curr out of range
22	3/1/2006	6:27 AM	690	3457449	3	Fail	Switch Test
23	3/1/2006	6:27 AM	692	4500381	2	Pass	
24	3/1/2006	6:30 AM	690	3457451	3	Pass	
25	3/1/2006	6:30 AM	692	4499448	1	Pass	
26	3/1/2006	6:30 AM	692	4500382	2	Pass	
27	3/1/2006	6:32 AM	690	3457452	3	Pass	

- Part level data (not tabulated)
- Y variables = *Result, Failure Reason*
- X variables = *Date, Time, P/N, Tester*

Example 4 (cont’d)

- Medical devices are tested for 20 or so failure modes by automated test equipment (ATE)
- Every time a unit is tested, a new record is added to the database
- This is part level data — one part for each row
- Let’s say we want plot the daily % failing

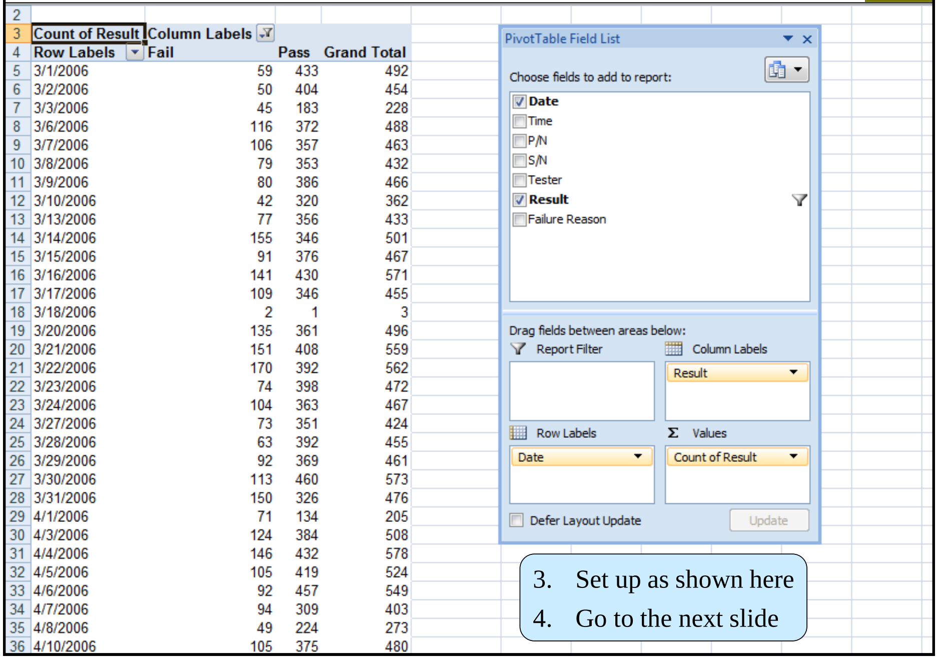
Example 4: (cont'd)



	A	B	C	D	E	F	G
1	Date	Time	P/N	S/N	Tester	Result	Failure Reason
2	3/1/2006	6:02 AM	690	3457456	3	Pass	
3	3/1/2006	6:03 AM	692	4499441	1	Pass	
4	3/1/2006	6:05 AM	690	3457457	3	Fail	Backlight-LCD
5	3/1/2006	6:06 AM	690	3457458	3	Pass	
6	3/1/2006	6:12 AM	690	3457442	3	Pass	
7	3/1/2006	6:12 AM	692	4499442	1	Pass	
8	3/1/2006	6:13 AM	692	4500377	2	Pass	
9	3/1/2006	6:15 AM	690	3457443	3	Fail	Op curr out of range
10	3/1/2006	6:17 AM	692	4500378	2	Pass	
11	3/1/2006	6:18 AM	690	3457444	3	Fail	Backlight-LCD
12	3/1/2006	6:18 AM	690	3457445	3	Fail	Op curr out of range
13	3/1/2006					Pass	
14	3/1/2006					Pass	
15	3/1/2006					Pass	
16	3/1/2006					Pass	
17	3/1/2006					Pass	
18	3/1/2006	6:24 AM	692	4499445	1	Fail	Slp curr out of range
19	3/1/2006	6:24 AM	690	3457448	3	Fail	Switch Test
20	3/1/2006	6:25 AM	692	4500380	2	Pass	
21	3/1/2006	6:27 AM	692	4499446	1	Fail	Slp curr out of range
22	3/1/2006	6:27 AM	690	3457449	3	Fail	Switch Test
23	3/1/2006	6:27 AM	692	4500381	2	Pass	
24	3/1/2006	6:30 AM	690	3457451	3	Pass	
25	3/1/2006	6:30 AM	692	4499448	1	Pass	
26	3/1/2006	6:30 AM	692	4500382	2	Pass	
27	3/1/2006	6:32 AM	690	3457452	3	Pass	

1. Select columns A-G
2. Insert a *PivotTable* (see next slide)

Example 4 (cont'd)



2				
3	Count of Result	Column Labels		
4	Row Labels	Fail	Pass	Grand Total
5	3/1/2006	59	433	492
6	3/2/2006	50	404	454
7	3/3/2006	45	183	228
8	3/6/2006	116	372	488
9	3/7/2006	106	357	463
10	3/8/2006	79	353	432
11	3/9/2006	80	386	466
12	3/10/2006	42	320	362
13	3/13/2006	77	356	433
14	3/14/2006	155	346	501
15	3/15/2006	91	376	467
16	3/16/2006	141	430	571
17	3/17/2006	109	346	455
18	3/18/2006	2	1	3
19	3/20/2006	135	361	496
20	3/21/2006	151	408	559
21	3/22/2006	170	392	562
22	3/23/2006	74	398	472
23	3/24/2006	104	363	467
24	3/27/2006	73	351	424
25	3/28/2006	63	392	455
26	3/29/2006	92	369	461
27	3/30/2006	113	460	573
28	3/31/2006	150	326	476
29	4/1/2006	71	134	205
30	4/3/2006	124	384	508
31	4/4/2006	146	432	578
32	4/5/2006	105	419	524
33	4/6/2006	92	457	549
34	4/7/2006	94	309	403
35	4/8/2006	49	224	273
36	4/10/2006	105	375	480

PivotTable Field List

Choose fields to add to report:

☑ Date
☐ Time
☐ P/N
☐ S/N
☐ Tester
☑ Result
☐ Failure Reason

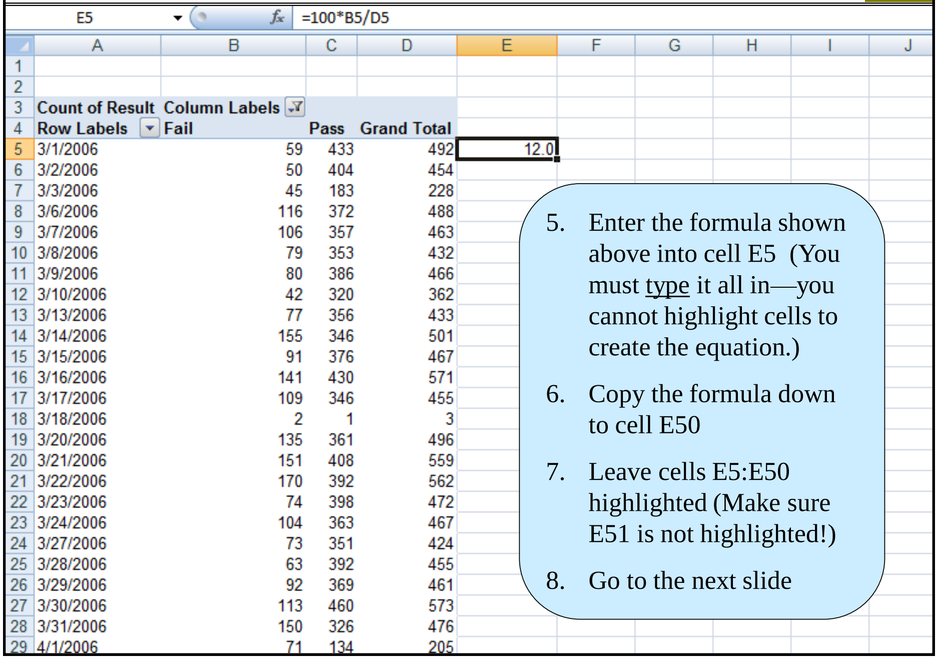
Drag fields between areas below:

Report Filter:
Column Labels: Result
Row Labels: Date
Values: Count of Result

☐ Defer Layout Update

3. Set up as shown here
4. Go to the next slide

Example 4 (cont'd)

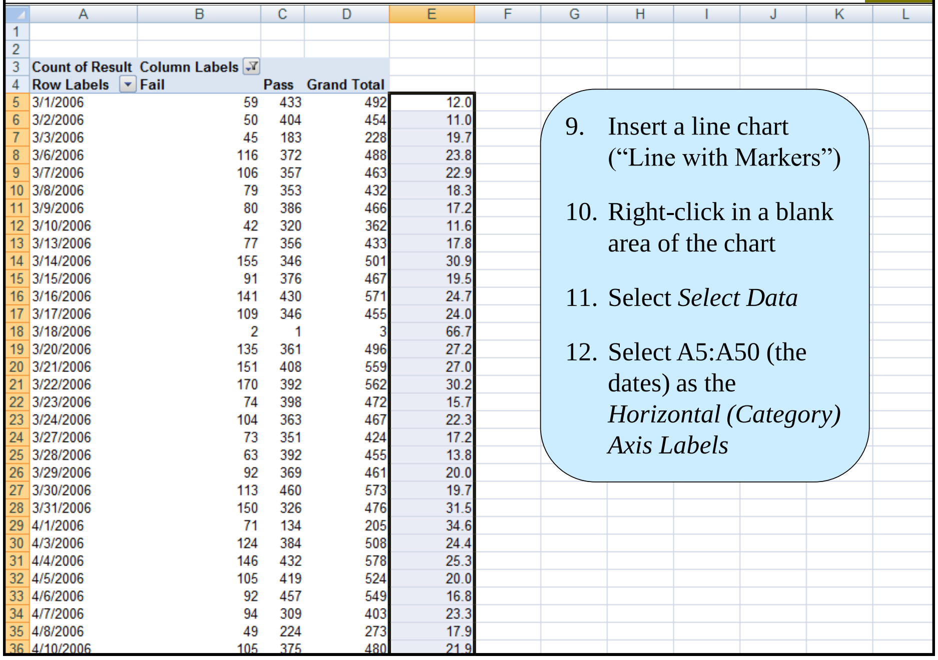


E5 =100*B5/D5

	A	B	C	D	E
1					
2					
3	Count of Result	Column Labels			
4	Row Labels	Fail	Pass	Grand Total	
5	3/1/2006	59	433	492	12.0
6	3/2/2006	50	404	454	
7	3/3/2006	45	183	228	
8	3/6/2006	116	372	488	
9	3/7/2006	106	357	463	
10	3/8/2006	79	353	432	
11	3/9/2006	80	386	466	
12	3/10/2006	42	320	362	
13	3/13/2006	77	356	433	
14	3/14/2006	155	346	501	
15	3/15/2006	91	376	467	
16	3/16/2006	141	430	571	
17	3/17/2006	109	346	455	
18	3/18/2006	2	1	3	
19	3/20/2006	135	361	496	
20	3/21/2006	151	408	559	
21	3/22/2006	170	392	562	
22	3/23/2006	74	398	472	
23	3/24/2006	104	363	467	
24	3/27/2006	73	351	424	
25	3/28/2006	63	392	455	
26	3/29/2006	92	369	461	
27	3/30/2006	113	460	573	
28	3/31/2006	150	326	476	
29	4/1/2006	71	134	205	

5. Enter the formula shown above into cell E5 (You must type it all in—you cannot highlight cells to create the equation.)
6. Copy the formula down to cell E50
7. Leave cells E5:E50 highlighted (Make sure E51 is not highlighted!)
8. Go to the next slide

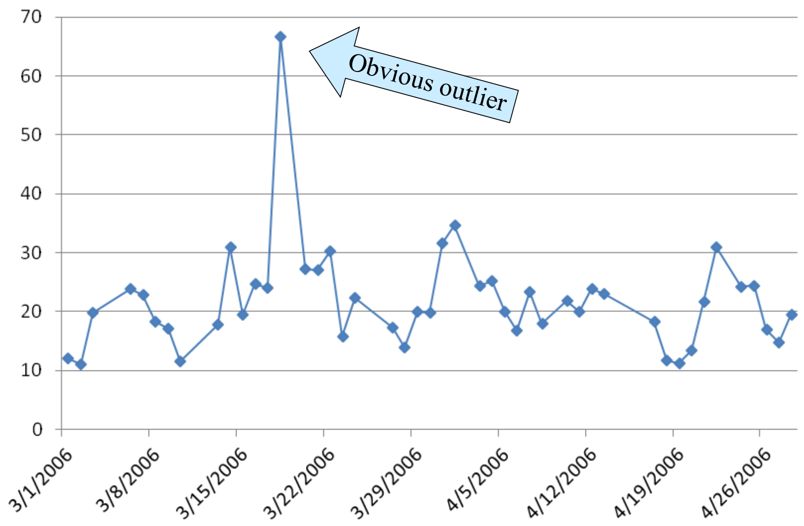
Example 4 (cont'd)



	A	B	C	D	E
1					
2					
3	Count of Result	Column Labels			
4	Row Labels	Fail	Pass	Grand Total	
5	3/1/2006	59	433	492	12.0
6	3/2/2006	50	404	454	11.0
7	3/3/2006	45	183	228	19.7
8	3/6/2006	116	372	488	23.8
9	3/7/2006	106	357	463	22.9
10	3/8/2006	79	353	432	18.3
11	3/9/2006	80	386	466	17.2
12	3/10/2006	42	320	362	11.6
13	3/13/2006	77	356	433	17.8
14	3/14/2006	155	346	501	30.9
15	3/15/2006	91	376	467	19.5
16	3/16/2006	141	430	571	24.7
17	3/17/2006	109	346	455	24.0
18	3/18/2006	2	1	3	66.7
19	3/20/2006	135	361	496	27.2
20	3/21/2006	151	408	559	27.0
21	3/22/2006	170	392	562	30.2
22	3/23/2006	74	398	472	15.7
23	3/24/2006	104	363	467	22.3
24	3/27/2006	73	351	424	17.2
25	3/28/2006	63	392	455	13.8
26	3/29/2006	92	369	461	20.0
27	3/30/2006	113	460	573	19.7
28	3/31/2006	150	326	476	31.5
29	4/1/2006	71	134	205	34.6
30	4/3/2006	124	384	508	24.4
31	4/4/2006	146	432	578	25.3
32	4/5/2006	105	419	524	20.0
33	4/6/2006	92	457	549	16.8
34	4/7/2006	94	309	403	23.3
35	4/8/2006	49	224	273	17.9
36	4/10/2006	105	375	480	21.9

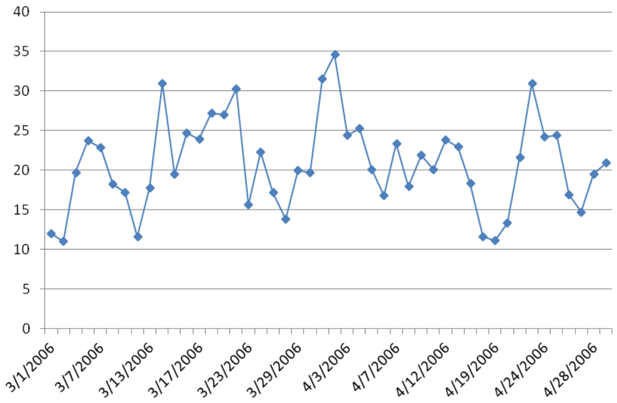
9. Insert a line chart ("Line with Markers")
10. Right-click in a blank area of the chart
11. Select *Select Data*
12. Select A5:A50 (the dates) as the *Horizontal (Category) Axis Labels*

Example 4 (cont'd)



Example 4 (cont'd)

- The outlier is 3/18/06, a Saturday
- The plant is closed on weekends — an engineer came in to troubleshoot one of the testers
- De-select 3/18/2006 in the pivot table
- Looks like steady variation around a mean of about 20%.
- Close and save the data set



Exercise 25.1

Open *Data Sets* → *quotation process current state*. Create the following charts. Make them look the way they should.

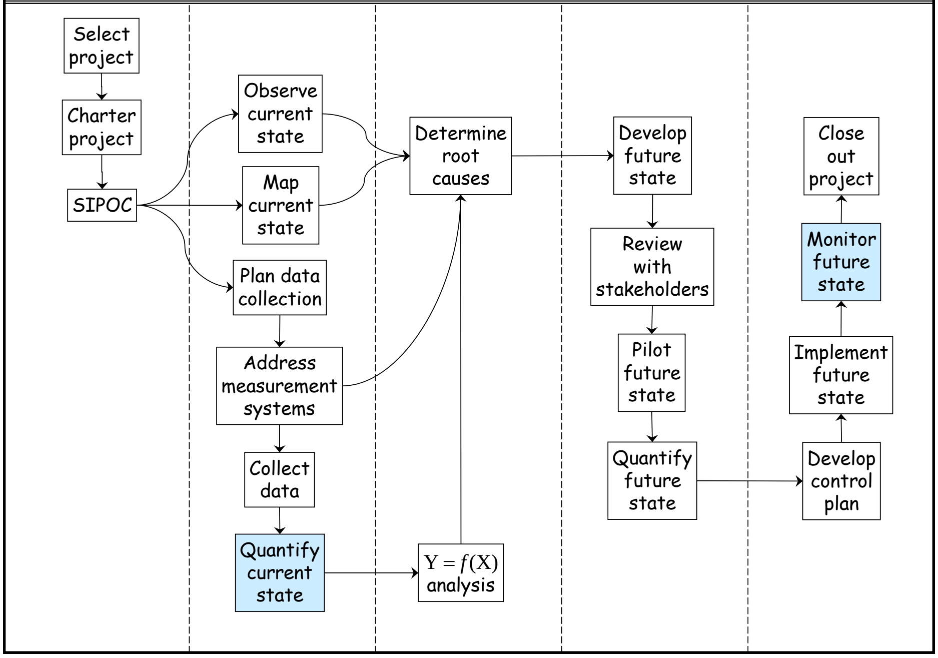
a) Monthly % TAT > 3.

b) Monthly PO hit rate (% Yes).

c) Close and save the data set.

Notes

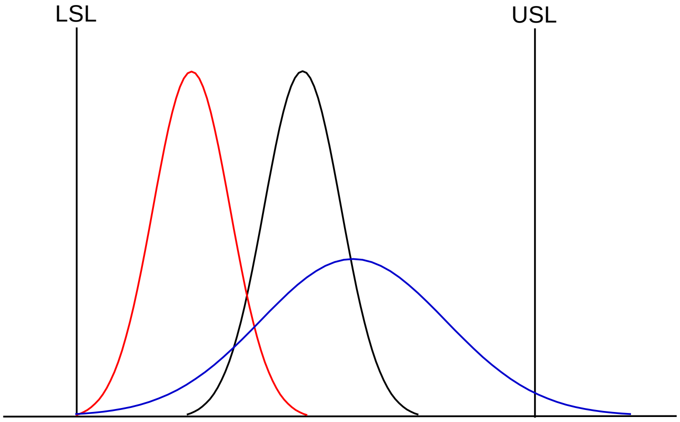
26 Process Capability Indices



Topics

- Purpose of Process Capability Indices
- Commonly used indices
- Important assumptions for validity

Process capability indices



- Some industries focus on “capability indices” instead of DPPM or DPMO
- These are calculated from the specification limit(s) and a fitted distribution
- Back in the day, the distribution was always assumed to be Normal

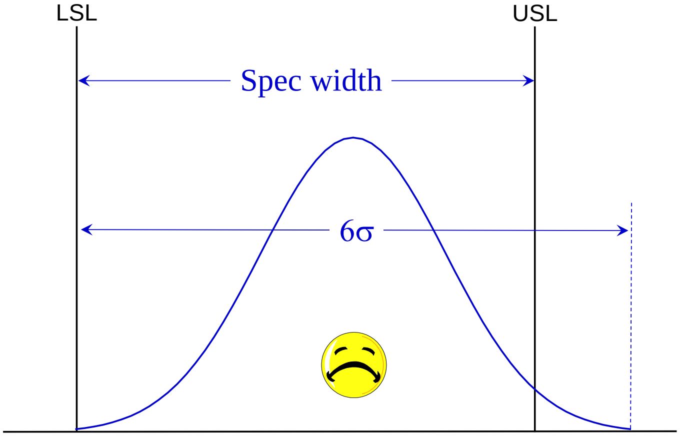
---

Process capability indices (cont’d)

- Do your organization’s external customers ask for process capability reporting?
- Are there internal requirements or needs for process capability reporting?

C_p index

$$C_p = \frac{\text{Spec width}}{6\sigma}$$



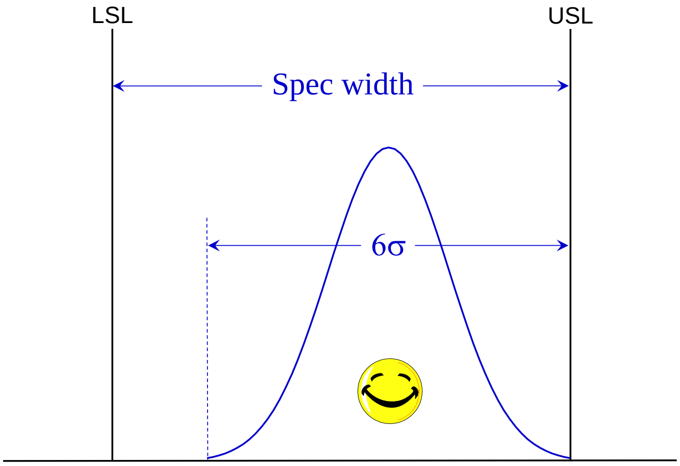
In this case, C_p is less than 1

C_p (cont'd)

The C_p index was historically the first to be used. It is defined as the specification width (USL – LSL) divided by the process spread (6σ). It set the precedent for capability indices to be defined so that "higher is better."

In the example above, the process spread is greater than the spec width, so C_p is less than 1. It is common for customers to push suppliers to achieve index values of 1.33 or higher for key Y variables.

C_p (cont'd)



In this case, C_p is greater than 1, but what's a potential problem here?

C_p (cont'd)

In the example above, the process spread is less than the spec width, so C_p is greater than 1.

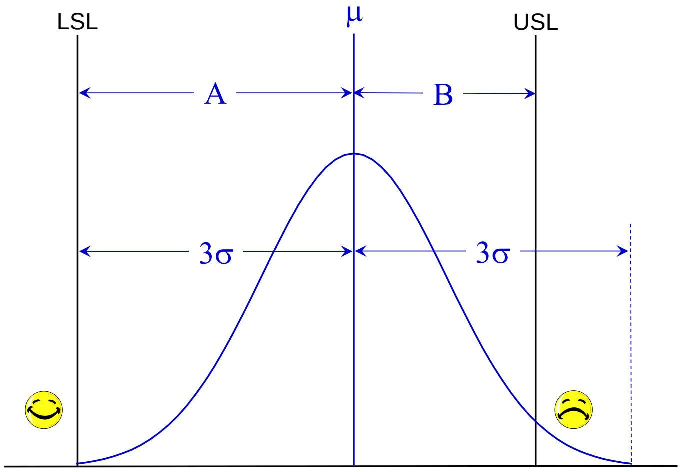
The limitation of C_p is that it doesn't depend on the process mean. If the process mean is equal to the midpoint of the specification range, then C_p is directly related to first pass yield.

If the process mean does not equal the midpoint of the specification range, C_p represents the capability that could be attained by moving the process mean to the midpoint.

C_{pl} and C_{pu} indices

$$C_{pl} = \text{"}C_p \text{ lower"} = \frac{A}{3\sigma}$$

$$C_{pu} = \text{"}C_p \text{ upper"} = \frac{B}{3\sigma}$$

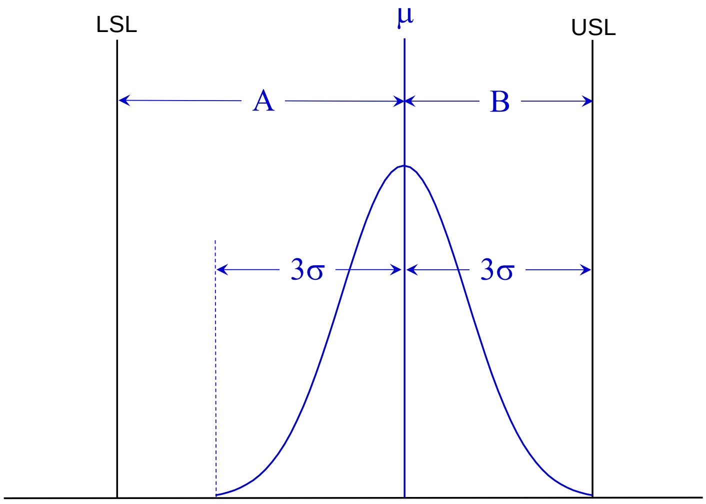


C_{pl} and C_{pu} (cont'd)

The indices C_{pl} and C_{pu}, pronounced "C_p lower" and "C_p upper", were introduced to overcome the deficiency of C_p. They depend on both the mean and standard deviation of the process. If we know both C_{pl} and C_{pu} we can determine the first pass yield of the process.

Like the C_p index, C_{pl} and C_{pu} are defined so that "higher is better." In the example shown above, the main problem is on the high side, with C_{pk} less than 1.

C_{pl} and C_{pu} (cont'd)



C_{pl} is greater than 1, C_{pu} is equal to 1

C_{pl} and C_{pu} (cont'd)

C_{pk} is equal to 1 in the example above. If improvement is needed, the opportunity is on the high side.

Many people have asked what the *k* in C_{pk} stands for. To everyone's great disappointment, the *k* seems to have been chosen arbitrarily and may not stand for anything.

There is, however, a bit of historical trivia that may give us a clue:

- C_{pk} was first popularized by a man named Victor Kane.
- Is it possible Victor simply used the first letter of his last name?

Guidelines

- Use C_{pl} if you have only a lower spec limit
- Use C_{pu} if you have only an upper spec limit
- Use C_{pk} (smaller of C_{pl} and C_{pu}) if you have both lower and upper spec limits
- As noted previously, C_p indicates what C_{pk} would be if the process mean were equal to the midpoint of the spec range.
  - If this is not the case, C_p represents a potential capability.
  - Centering a process at this midpoint may not always be desirable.

Important assumptions in Process Capability

For Process Capability indices to be valid, the following must be true:

- The process is in statistical control (we will cover this during the Control phase)
- The measurement data is normally distributed*
- The sampling method used is representative of day-to-day process operation

There are times when we want to calculate process capability before the process is under control, for example to set an initial baseline or make a rough prediction.

- The purpose of a process capability study should always be communicated along with the numbers.

**Handling situations when the data is not normally distributed is beyond the scope of this course. Some statistical software packages offer options for calculating Process Capability for non-Normal distributions, along with indices for other special cases.*

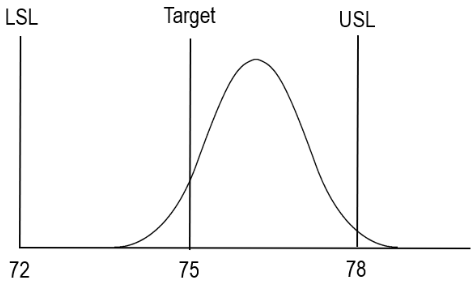
Formulas (Normal distribution)

$$C_{pl} = \frac{\mu - LSL}{3\sigma} \qquad C_{pu} = \frac{USL - \mu}{3\sigma}$$

$$C_p = \frac{C_{pl} + C_{pu}}{2} = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = \min\left(C_{pl}, C_{pu}\right)$$

Example: Calculating Process Capability indices



For this distribution, the mean = 76 and the standard deviation = 1.

$$C_p = \frac{USL-LSL}{6\sigma} = \frac{78-72}{6*1} = \frac{6}{6} = 1.0$$

$$C_{pl} = \frac{\mu-LSL}{3\sigma} = \frac{76-72}{3*1} = \frac{4}{3} = 1.33$$

$$C_{pu} = \frac{USL-\mu}{3\sigma} = \frac{78-76}{3*1} = \frac{2}{3} = 0.67$$

$$C_{pk} = \min\left(C_{pu}, C_{pl}\right) = 0.67$$

Exercise 26.1

(a) Calculate C_p and C_{pk} for a process with mean = 55, standard deviation = 1, USL = 60 and LSL = 50.
Sketch the distribution.

(b) Calculate C_p and C_{pk} for a process with mean = 100.20, standard deviation = 0.20, USL = 101.00 and LSL = 100.00.
Sketch the distribution.

What is "good" process capability?

Capability	How good is this?	Sigma Level
$C_p = 1.0$	Marginally capable	3 sigma
$C_p = 1.33$	Good	4 sigma
$C_p = 2.0$	World-class	6 sigma

The indices C_p and C_{pk} are assumed to be measures of the long-term capability of the process. Therefore,

- the data needs to be gathered over a long enough period of time to capture all regular contributors to process variation,
- *and* a sample size of at least 70 is needed, with 100 preferred.

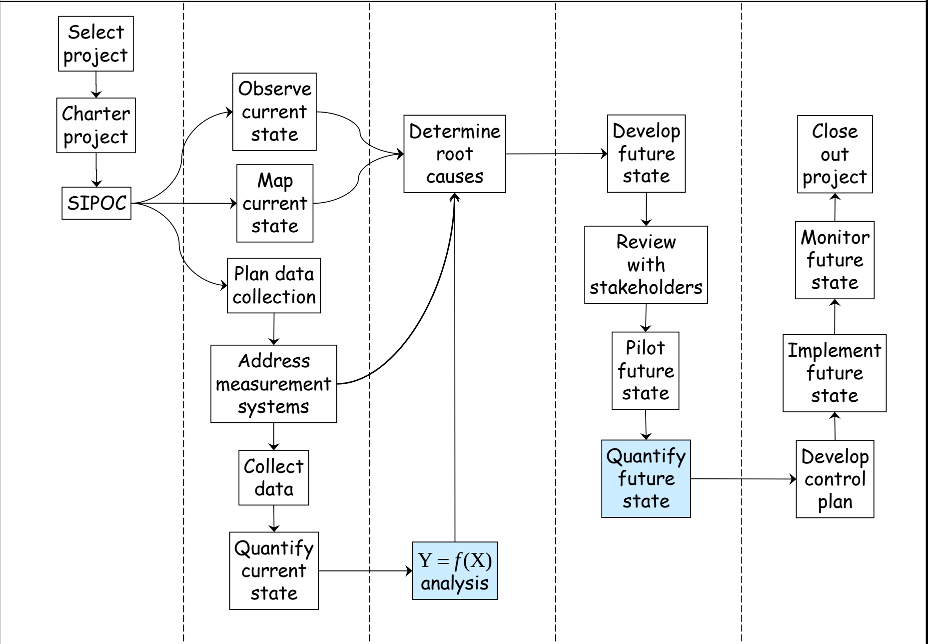
Predicting defects

C_p, C_{pk} Value	C_p Fallout (centered)	C_{pk} Fallout (not centered)
.5	133,620 PPM	66,810 PPM
.6	71,860	35,930
.7	35,720	17,860
.8	16,400	8,200
.9	6,940	3,470
1.0	2,700	1,350
1.1	966	483
1.2	318	159
1.3	96	48
1.33	66	33
1.4	26	13
1.5	7	3
1.6	2	800 PPB
1.7	340 PPB	170
1.8	60	30
1.9	12	6
2.0	2	1

PPM = Parts Per Million
PPB = Parts Per Billion
Note: 1%=10,000 PPM

Notes

27 Testing for Statistical Significance



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Topics

- Comparing populations with quantitative Y
- Comparing populations with categorical (pass/fail) Y
- Correlating quantitative X and Y variables

Comparing populations with quantitative Y

Example	Is there a difference between molding machines A and B with respect to average diameter of molded parts?
Required data	Diameters for representative samples of parts molded on machines A and B.
Y variable	Diameter — quantitative
X variable	Machine (A or B)

Comparing populations with categorical (pass/fail) Y

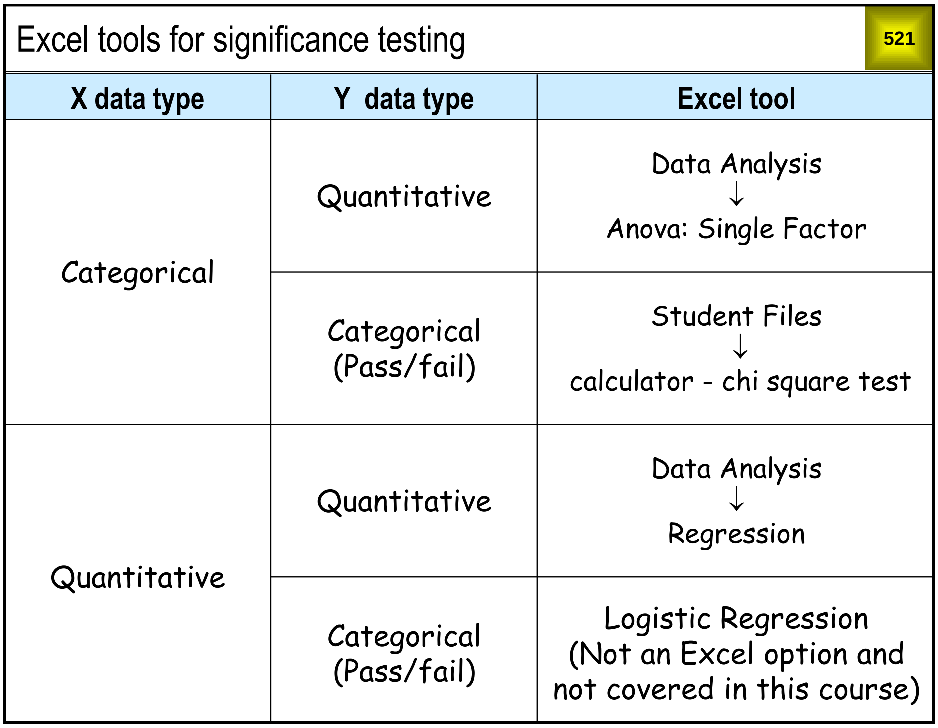
Example	Is there a difference between molding machines A and B with respect to the percentage of parts with cosmetic defects?
Required data	Defective (yes/no) for representative samples of parts molded on machines A and B.
Y variable	Defective (yes/no)
X variable	Machine (A or B)

Correlating quantitative Y and X variables

Example	If we reduce our billing lead time, will we get paid sooner?
Required data	Days in accounts receivable and billing lead times for a representative sample of invoices.
Y variable	Days in accounts receivable
X variable	Billing lead time

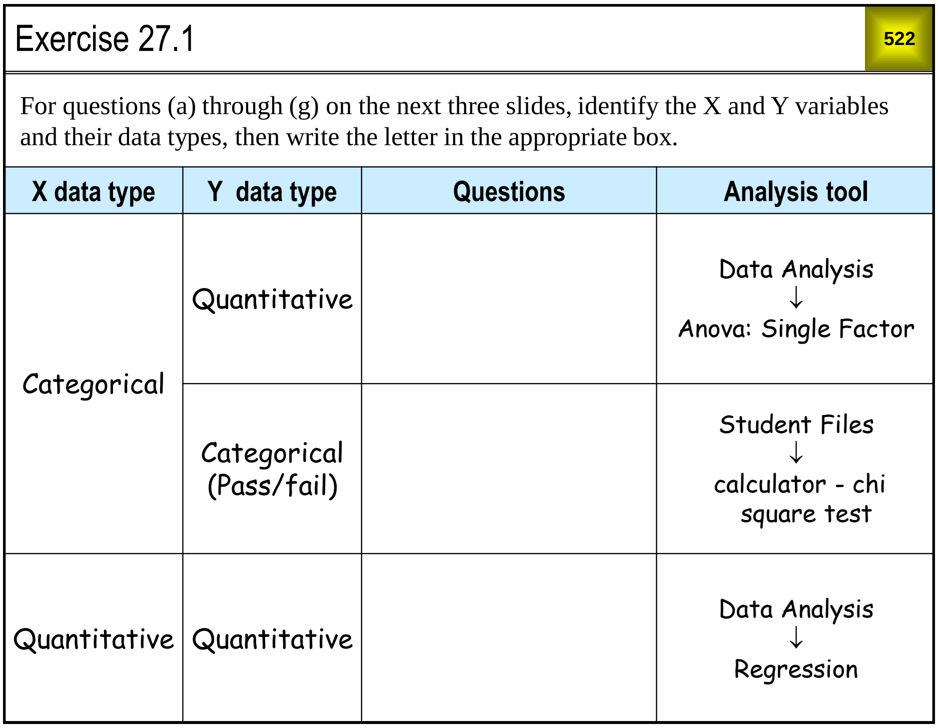
The role of the X variable in significance testing

X data type	Analysis type	The X column contains . . .
Categorical	Comparing populations	• Labels identifying logical subgroups (strata) within the current state data, or • Labels distinguishing the current state data from the future state pilot data • Each group must contain multiple rows (Y data values)
Quantitative	Correlating variables	• Quantitative measurements • The data consists of (X, Y) pairs (values in the same row) • Don't need to have multiple Y values for each X value



Excel tools for significance testing

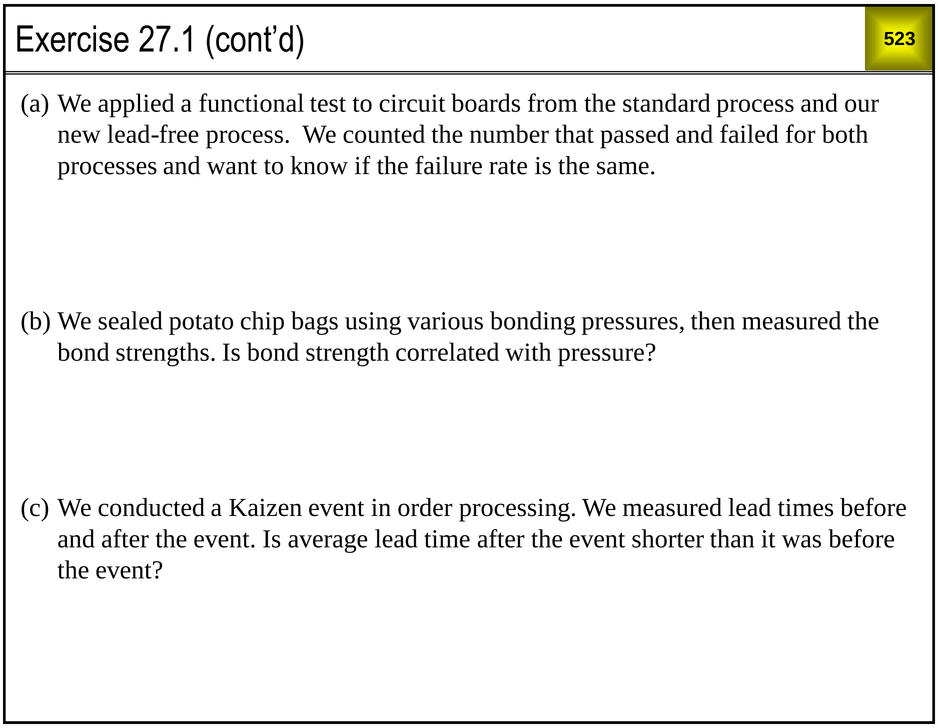
X data type	Y data type	Excel tool
Categorical	Quantitative	Data Analysis ↓ Anova: Single Factor
	Categorical (Pass/fail)	Student Files ↓ calculator - chi square test
Quantitative	Quantitative	Data Analysis ↓ Regression
	Categorical (Pass/fail)	Logistic Regression (Not an Excel option and not covered in this course)



Exercise 27.1

For questions (a) through (g) on the next three slides, identify the X and Y variables and their data types, then write the letter in the appropriate box.

X data type	Y data type	Questions	Analysis tool
Categorical	Quantitative		Data Analysis ↓ Anova: Single Factor
	Categorical (Pass/fail)		Student Files ↓ calculator - chi square test
Quantitative	Quantitative		Data Analysis ↓ Regression

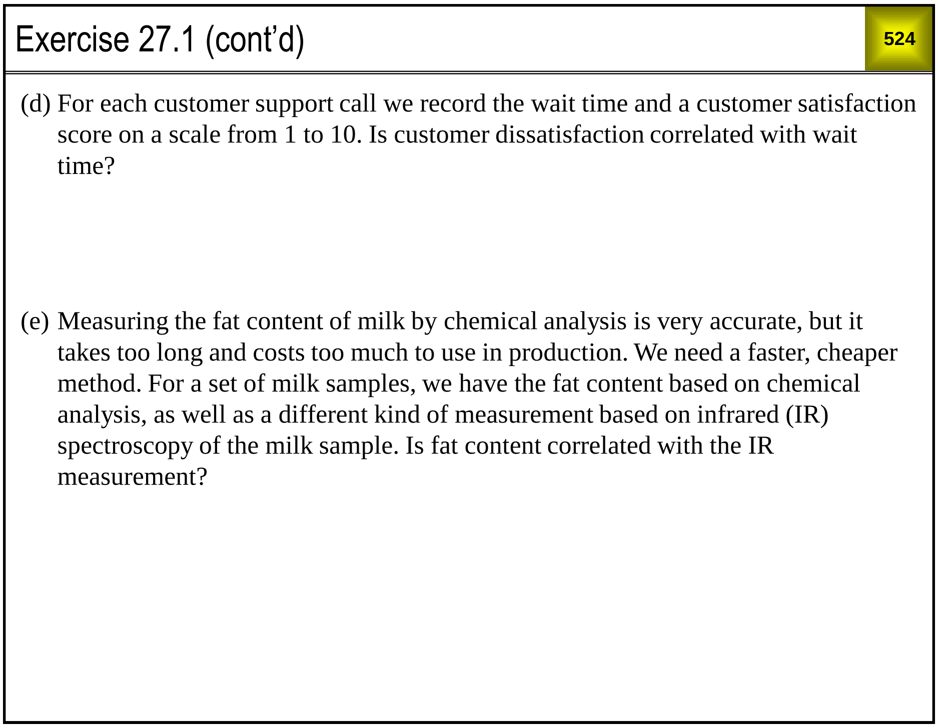


Exercise 27.1 (cont'd)

(a) We applied a functional test to circuit boards from the standard process and our new lead-free process. We counted the number that passed and failed for both processes and want to know if the failure rate is the same.

(b) We sealed potato chip bags using various bonding pressures, then measured the bond strengths. Is bond strength correlated with pressure?

(c) We conducted a Kaizen event in order processing. We measured lead times before and after the event. Is average lead time after the event shorter than it was before the event?



Exercise 27.1 (cont'd)

(d) For each customer support call we record the wait time and a customer satisfaction score on a scale from 1 to 10. Is customer dissatisfaction correlated with wait time?

(e) Measuring the fat content of milk by chemical analysis is very accurate, but it takes too long and costs too much to use in production. We need a faster, cheaper method. For a set of milk samples, we have the fat content based on chemical analysis, as well as a different kind of measurement based on infrared (IR) spectroscopy of the milk sample. Is fat content correlated with the IR measurement?

Exercise 27.1 (cont’d)

f) Engineers complete change orders which are then sent back to the customer for approval. Each change order has been counted as being complete and accurate or not based on the customer’s approval. Are there differences among the engineers in their change orders’ “complete and accurate” rate?

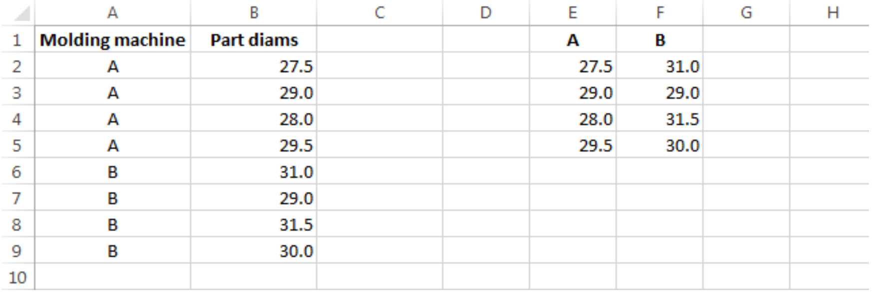
g) We use several different machines to seal potato chip bags. Do the machines give the same average bond strength?

Significance testing: example 1

Comparing samples with quantitative Y

Standard data matrix format ↓

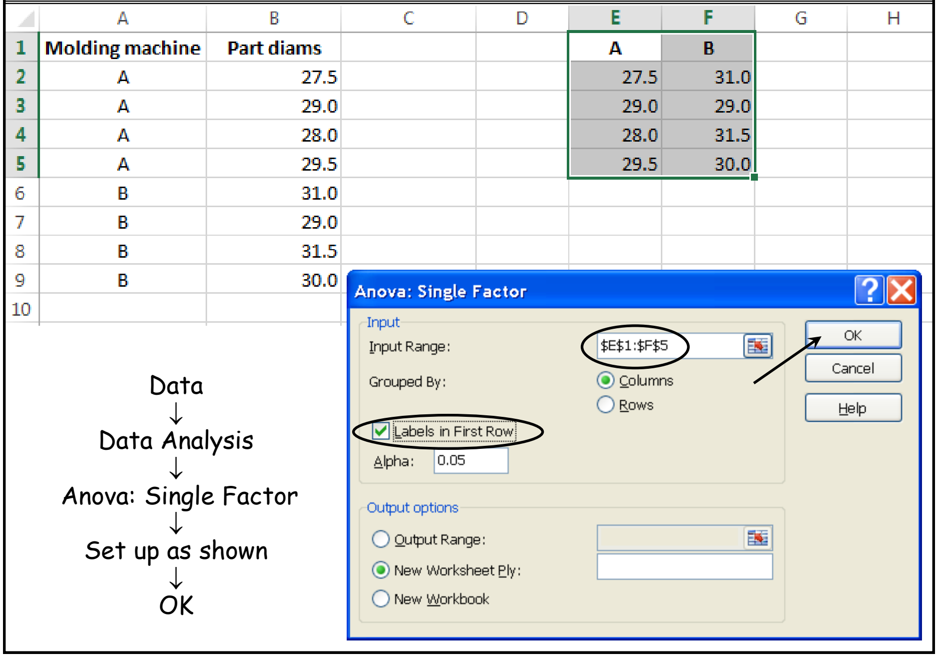
Data format required for Anova: Single Factor ↓



	A	B	C	D	E	F	G	H
1	**Molding machine**	**Part diams**			**A**	**B**		
2	A	27.5			27.5	31.0		
3	A	29.0			29.0	29.0		
4	A	28.0			28.0	31.5		
5	A	29.5			29.5	30.0		
6	B	31.0						
7	B	29.0						
8	B	31.5						
9	B	30.0						
10								

- Open *Data Sets* → *significance testing examples*
- We want to determine whether or not there a significant difference between machines A and B.
- Reformat the data into columns A and B, as shown, to perform ANOVA.

Significance testing: example 1 (cont'd)



	A	B	C	D	E	F	G	H
1	Molding machine	Part diams			A	B		
2	A	27.5			27.5	31.0		
3	A	29.0			29.0	29.0		
4	A	28.0			28.0	31.5		
5	A	29.5			29.5	30.0		
6	B	31.0						
7	B	29.0						
8	B	31.5						
9	B	30.0						
10								

Anova: Single Factor

Input

Input Range: $E$1:$F$5

Grouped By: ● Columns ○ Rows

☑ Labels in First Row

Alpha: 0.05

Output options

○ Output Range:

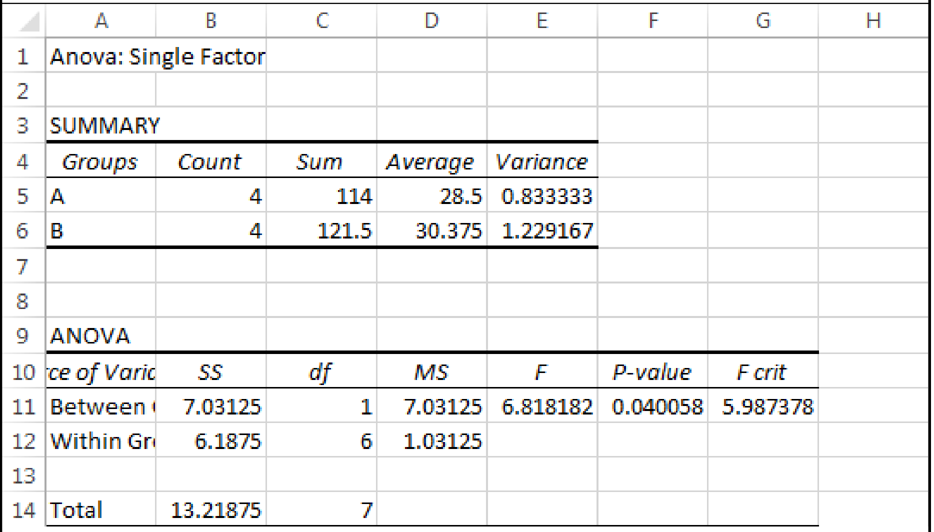
● New Worksheet Ply:

○ New Workbook

Data
↓
Data Analysis
↓
Anova: Single Factor
↓
Set up as shown
↓
OK

Significance testing: example 1 (cont'd)

Default Excel output

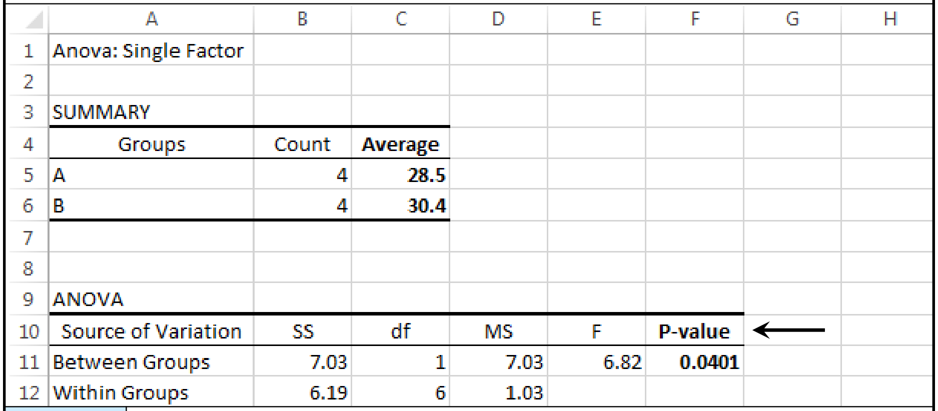


	A	B	C	D	E	F	G	H
1	Anova: Single Factor							
2								
3	SUMMARY							
4	*Groups*	*Count*	*Sum*	*Average*	*Variance*			
5	A	4	114	28.5	0.833333			
6	B	4	121.5	30.375	1.229167			
7								
8								
9	ANOVA							
10	*ce of Varic*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*	
11	Between (	7.03125	1	7.03125	6.818182	0.040058	5.987378	
12	Within Gr	6.1875	6	1.03125				
13								
14	Total	13.21875	7					

Go to the next slide

Significance testing: example 1 (cont'd)

Cleaned up Excel output



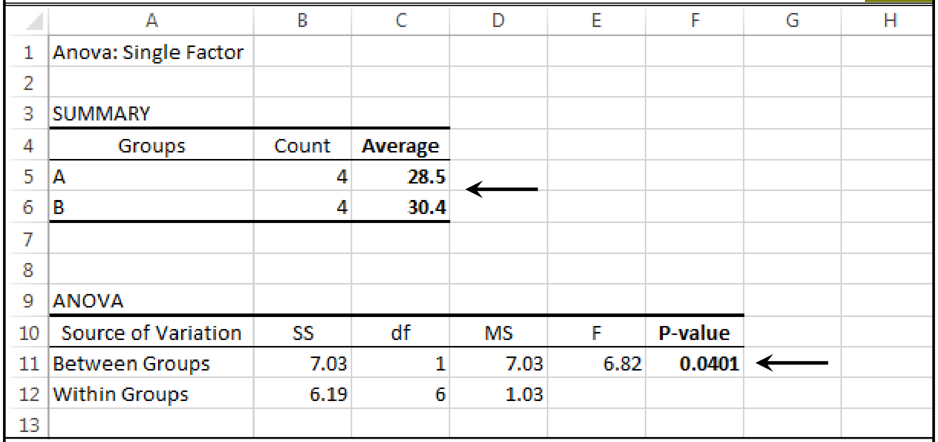
	A	B	C	D	E	F	G	H
1	Anova: Single Factor							
2								
3	SUMMARY							
4	Groups	Count	**Average**					
5	A	4	**28.5**					
6	B	4	**30.4**					
7								
8								
9	ANOVA							
10	Source of Variation	SS	df	MS	F	**P-value**	←	
11	Between Groups	7.03	1	7.03	6.82	**0.0401**		
12	Within Groups	6.19	6	1.03				

P value	The probability that the sample's mean difference would be this large if they were from the same population
	The probability that machines A and B produce the same average diameter. The sample is used to infer a difference in the machine's performance.

Interpreting P values - "Standard of Evidence"

P value	Evidence that samples are different, or variables are correlated	Confidence level (CL)
1.00 0.15	None	None
0.15 0.05	Some	$85\% \leq CL < 95\%$
0.05 0.01	Strong	$95\% \leq CL < 99\%$
0.01 0.0001	Very strong	$CL \geq 99\%$

Significance testing: example 1 (cont'd)



	A	B	C	D	E	F	G	H
1	Anova: Single Factor							
2								
3	SUMMARY							
4	Groups	Count	**Average**					
5	A	4	**28.5**	←				
6	B	4	**30.4**					
7								
8								
9	ANOVA							
10	Source of Variation	SS	df	MS	F	**P-value**		
11	Between Groups	7.03	1	7.03	6.82	**0.0401**	←	
12	Within Groups	6.19	6	1.03				
13								

- In this example, the P value is 0.0401
- There is *strong evidence* of a difference between the samples
- Based on this analysis, we expect that parts molded on machine B will have larger diameters than parts molded on machine A

Notes on p-values, confidence, and false-positives

Even people that work with data regularly often misinterpret the meaning of a p-value. The technical definition of a p-value is:

- The odds that the difference between samples would be this large or larger if the two samples were taken from the same population.

This unwieldy definition means that we try to think of the p-value in a way that makes more sense in the context of what we are studying. People will often think of the p-value as meaning "The odds that the difference I'm seeing isn't real". They think a p-value of 0.05 means that there is only a 5% chance that what they've measured isn't a real difference between populations, or that there is a 95% chance that the difference is real. This is a mostly harmless short-hand, but other misinterpretations are more problematic.

Notes on p-values, confidence, and false-positives (cont'd)

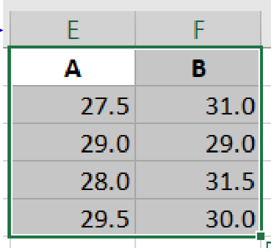
Sometimes people believe that a p-value of 0.05 means that there is only a 5% chance that their result is a false-positive. Here's an example to explain why that is dangerous.

Say you are working on a process that is having a quality problem. You have no idea what the source of the problem is so you decide to study all of the variables you can identify, and you come up with 20. When the analysis is finished, you identify 4 with a p-value of 0.05 or less. That seems really great, but remember, since you were looking for p-values of 0.05 or better, you would expect to get 0.05*20 = 1 significant variable by chance alone. Since you found 4 significant variables, you can expect a false positive rate of ¼ = 25%. If these variables are difficult, expensive, or risky to change, you'll want to know which one isn't real.

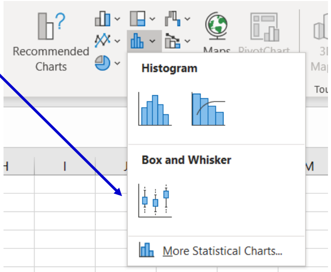
Key take-away
If in doubt, always repeat your study with another sample set!

Displaying the data graphically using Box and Whisker Plots

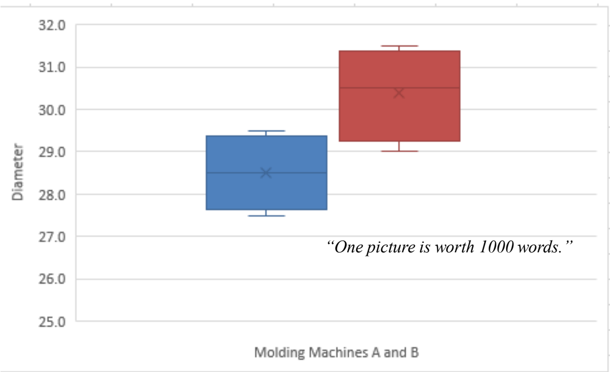
1. Highlight the two columns for molding Machines A&B
2. Navigate to the Insert Ribbon and then the Charts section
3. Choose the Insert Statistics Chart dropdown and then the Box and Whisker plot



E	F
A	**B**
27.5	31.0
29.0	29.0
28.0	31.5
29.5	30.0



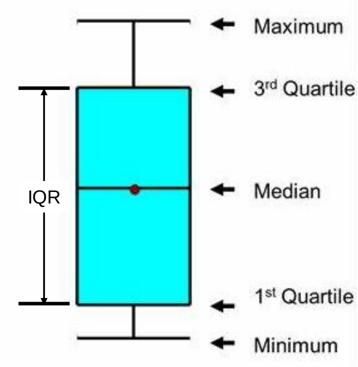
Displaying the data graphically Using Box and Whisker Plots



"One picture is worth 1000 words."

- Edit legends, titles, etc. as desired.
- Rule of thumb – if the median line for one data set is outside of the box of the other data set, then the two samples are significantly different
- If we wanted to reduce the overall variation in diameter, would we focus on within or between machine variation first? What follow up action is needed here?

Anatomy of a Box and Whisker Plot



- Box and Whisker plots display data distributions based on Quartiles.
- The data is divided in four equal parts, with the Box drawn from Q1 (25%) to Q3 (75%).
- The Median is drawn at Q2 (50%).
- The Mean (aka Average) may also be marked.
- The Inner Quartile Range (IQR) provides a robust measure of spread.
- Outliers are defined as data falling outside the range Q1 – (1.5)IQR and Q3 + (1.5)IQR.

Significance testing: example 2

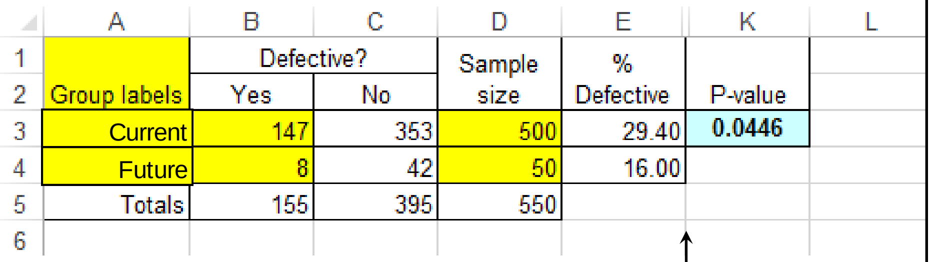
Comparing samples with pass/fail Y

- Our project objective was to reduce % defective by 50%
- Based on the data, it looks like we didn't quite make it
- But did we make a statistically significant improvement?

Process	Sample size	No. Failed	% Defective
Current state	500	147	29.4%
Future state pilot	50	8	16.0%

Significance testing: example 2 (cont'd)

- Open *Student Files* → *calculator - chi square test*
- Fill out the *2 groups* sheet as shown



	A	B	C	D	E	K	L
1		Defective?		Sample size	% Defective	P-value	
2	Group labels	Yes	No				
3	Current	147	353	500	29.40	0.0446	
4	Future	8	42	50	16.00		
5	Totals	155	395	550			
6							

Hid columns F-I

- Strong evidence of an improvement!

Interpreting P values - “Standard of Evidence”

P value

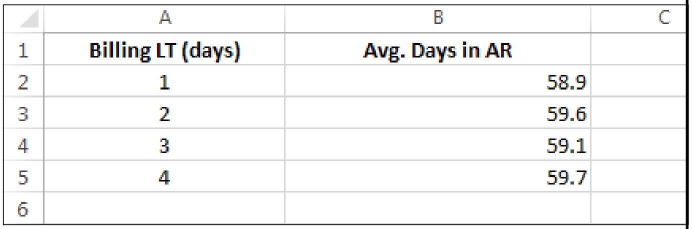
	Evidence that samples are different or variables are correlated	Confidence level (CL)
1.00		
	None	None
0.15		
	Some	85% ≤ CL ‹ 95%
0.05		
	Strong	95% ≤ CL ‹ 99%
0.01		
	Very strong	CL ≥ 99%
0.0001		

Significance testing: example 3

Correlating quantitative X and Y variables

If we reduce our billing lead time, will we get paid sooner?

1. *Open Data Sets → significance testing examples*
2. Highlight column B



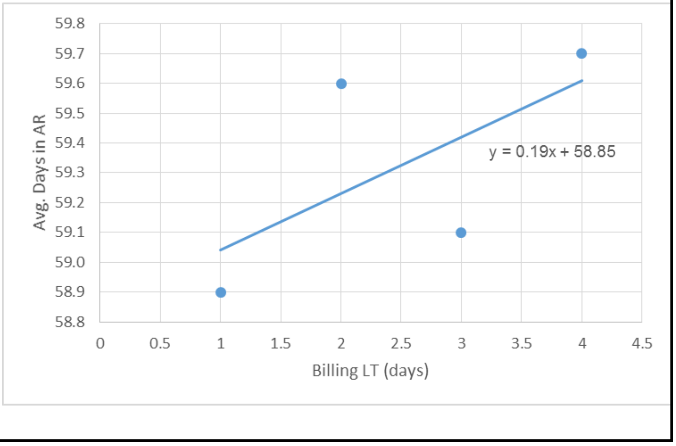
	A	B	C
1	Billing LT (days)	Avg. Days in AR	
2	1	58.9	
3	2	59.6	
4	3	59.1	
5	4	59.7	
6			

3. Highlight column A while holding down the **Shift** key
4. **Insert → Scatter plot**
5. Right click on a data point → ***Add Trendline*** → **Fill & Line** (looks like a bucket) → Solid line → Dash type → Solid → **Trendline Options** (looks like a bar chart) → Display equation on chart
6. See next slide

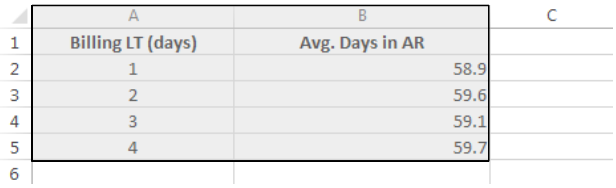
Significance testing: example 3 (cont'd)

7. Click on the graph, select **Chart Tools** → **Design**
8. Select **Add Chart Element** → **Axis Titles** → **Primary Horizontal** and **Primary Vertical**

- It looks like there may be a correlation, but appearances can be deceiving!
- We need to calculate the P value before we know for sure

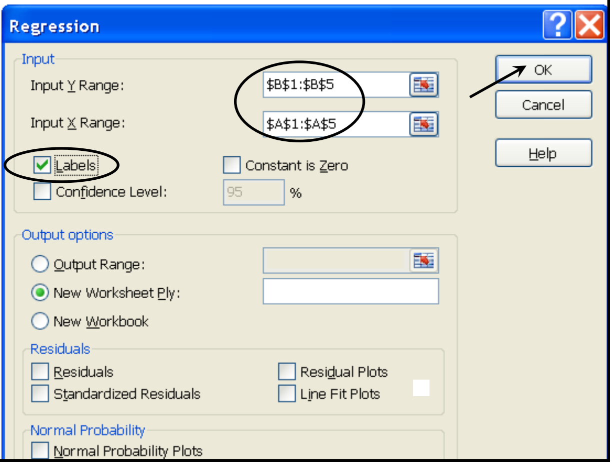


Significance testing: example 3 (cont'd)



	A	B	C
1	Billing LT (days)	Avg. Days in AR	
2	1	58.9	
3	2	59.6	
4	3	59.1	
5	4	59.7	
6			

Data
↓
Data Analysis
↓
Regression
↓
set up as shown
↓
OK



Input

Input Y Range: $B$1:$B$5

Input X Range: $A$1:$A$5

☑ Labels ☐ Constant is Zero

☐ Confidence Level: 95 %

Output options

○ Output Range:

● New Worksheet Ply:

○ New Workbook

Residuals

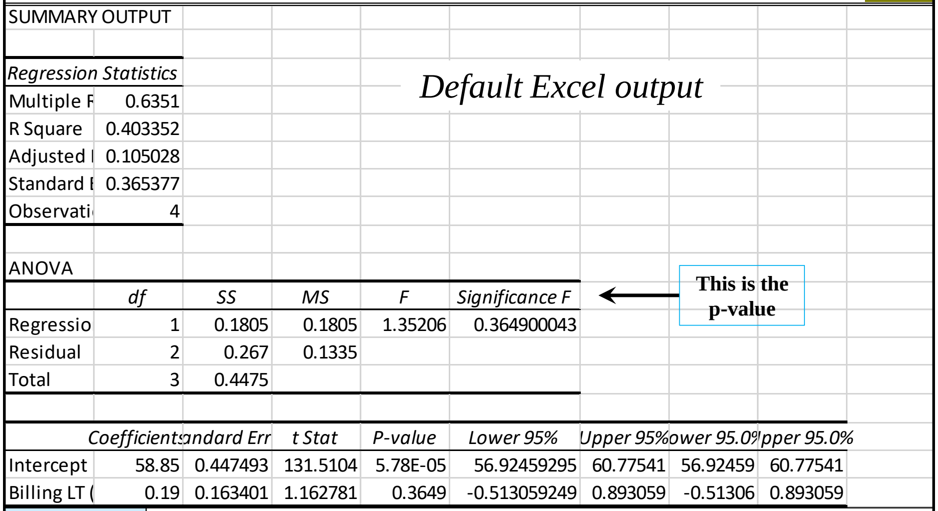
☐ Residuals ☐ Residual Plots

☐ Standardized Residuals ☐ Line Fit Plots

Normal Probability

☐ Normal Probability Plots

Significance testing: example 3 (cont'd)



Default Excel output

```
SUMMARY OUTPUT

Regression Statistics
Multiple F      0.6351
R Square      0.403352
Adjusted I    0.105028
Standard I    0.365377
Observati            4

ANOVA
                df        SS        MS         F   Significance F
Regressio        1    0.1805    0.1805   1.35206      0.364900043
Residual         2     0.267    0.1335
Total            3    0.4475

          Coefficientsandard Err  t Stat   P-value     Lower 95%  Upper 95%ower 95.0%pper 95.0%
Intercept      58.85  0.447493  131.5104  5.78E-05   56.92459295   60.77541   56.92459   60.77541
Billing LT (    0.19  0.163401  1.162781    0.3649  -0.513059249   0.893059   -0.51306   0.893059
```

This is the p-value

P value	
	The probability that the slope of the line for the sample would be this large if there was truly no relationship (i.e. if the real slope is zero)
	The probability of no correlation between billing lead time and days in accounts receivable

Interpreting P values - "Standard of Evidence"

P value	**Evidence that samples are different or variables are correlated**	**Confidence level (CL)**
1.00	None	None
0.15	Some	85% ≤ CL < 95%
0.05	Strong	95% ≤ CL < 99%
0.01 0.0001	Very strong	CL ≥ 99%

Interpreting P values (and other stuff)

SUMMARY OUTPUT

Regression Statistics	
Adjusted R Square	**0.1050**
Residual standard deviation	**0.3654**
Observations	4

- In this example, only 10.5% of the variation in Y is caused by variation in X
- This is one standard deviation of the data variation above and below the trend line

ANOVA

	df	SS	MS	F	**P value**
Regression	1	0.18	0.18	1.35	**0.3649**
Residual	2	0.27	0.13		
Total	3	0.45			

- The P value is 0.3649
- There is no evidence of a correlation between billing lead time and days in AR
- The trend line is of no use when there is no evidence of a correlation

Exercise 27.2

Open *Data Sets* → *DPPM vs dwell time*. Is DPPM correlated with *dwell time*?

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

c) Create an appropriate chart to illustrate the analysis.

d) Describe an appropriate follow up to this analysis.

e) Close and save the data set.

Exercise 27.3

Open *Data Sets* → *defects per unit*. Is the average DPU for March the same as it was for February?

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

c) Close and save the data set.

Exercise 27.4

Open *Data Sets* → *number & size of defects*. Someone hypothesizes that *Max size* (the size of the largest weld repair area) depends on *# Defects* (the number of weld repair areas).

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

c) Create an appropriate chart to illustrate the analysis.

d) Go to the next exercise, but keep the data set open.

Exercise 27.5

Is there a significant difference in *Max size* between welders A and B?

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

c) Close and save the data set.

Exercise 27.6

Based on the data given below, did our project achieve a significant reduction in % defective?

	Sample size	No. defective	% Defective
Current state	500	147	29.4%
Future state pilot	10	1	10.0%

a) Perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

Exercise 27.7

Open *Data Sets* → *computer chips*. Is Y correlated with X?

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

b) Give the P value and its interpretation in terms of standards of evidence.

c) Create an appropriate chart to illustrate the analysis.

d) Close and save the data set.

Exercise 27.8

Open *Data Sets* → *lead time*. Did our project achieve a significant reduction in average lead time?

a) Identify the data types for the X and Y variables, then perform the appropriate analysis.

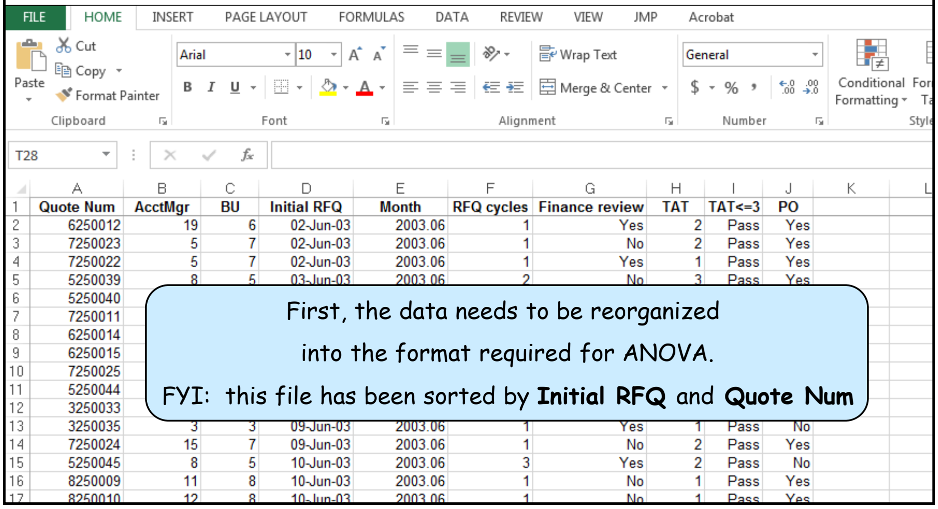
b) Give the P value and its interpretation in terms of standards of evidence.

c) Close and save the data set.

28 Stratification Analysis — Quantitative Y

We want to test for significant differences among the business units (BUs) with respect to turnaround time (TAT)

Open *Data Sets* → *unstacked quotation process current state*



	A	B	C	D	E	F	G	H	I	J
1	Quote Num	AcctMgr	BU	Initial RFQ	Month	RFQ cycles	Finance review	TAT	TAT<=3	PO
2	6250012	19	6	02-Jun-03	2003.06	1	Yes	2	Pass	Yes
3	7250023	5	7	02-Jun-03	2003.06	1	No	2	Pass	Yes
4	7250022	5	7	02-Jun-03	2003.06	1	Yes	1	Pass	Yes
5	5250039	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes
6	5250040									
7	7250011									
8	6250014									
9	6250015									
10	7250025									
11	5250044									
12	3250033									
13	3250035	3	3	09-Jun-03	2003.06	1	Yes	1	Pass	No
14	7250024	15	7	09-Jun-03	2003.06	1	No	2	Pass	Yes
15	5250045	8	5	10-Jun-03	2003.06	3	Yes	2	Pass	No
16	8250009	11	8	10-Jun-03	2003.06	1	No	1	Pass	Yes
17	8250010	12	8	10-Jun-03	2003.06	1	No	1	Pass	Yes

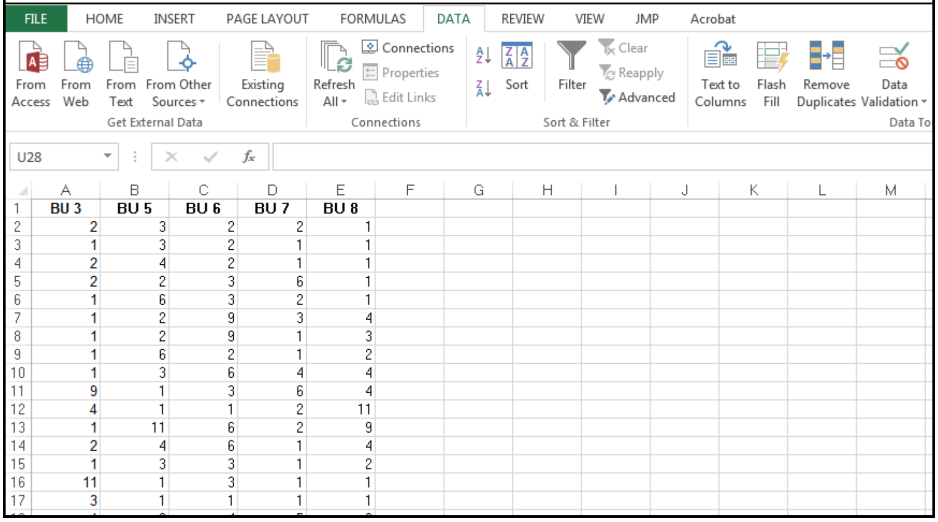
First, the data needs to be reorganized

into the format required for ANOVA.

FYI: this file has been sorted by **Initial RFQ** and **Quote Num**

Stratification with quantitative Y (cont'd)

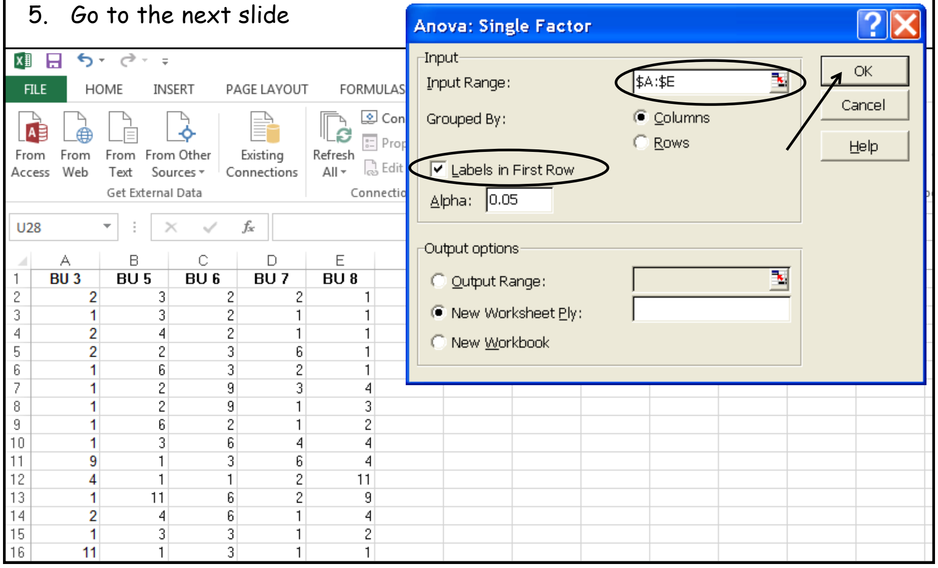
1. Click on tab "TAT by BU" to find this worksheet of reorganized data. (For your reference, instructions for creating this worksheet can be found at the end of this section.)
2. Go to the next slide



	A	B	C	D	E
1	BU 3	BU 5	BU 6	BU 7	BU 8
2	2	3	2	2	1
3	1	3	2	1	1
4	2	4	2	1	1
5	2	2	3	6	1
6	1	6	3	2	1
7	1	2	9	3	4
8	1	2	9	1	3
9	1	6	2	1	2
10	1	3	6	4	4
11	9	1	3	6	4
12	4	1	1	2	11
13	1	11	6	2	9
14	2	4	6	1	4
15	1	3	3	1	2
16	11	1	3	1	1
17	3	1	1	1	1

Stratification with quantitative Y (cont’d)

3. Go to the **Data** ribbon, select **Data Analysis**, select **Anova: Single Factor**
4. Fill out as shown here, click OK
5. Go to the next slide



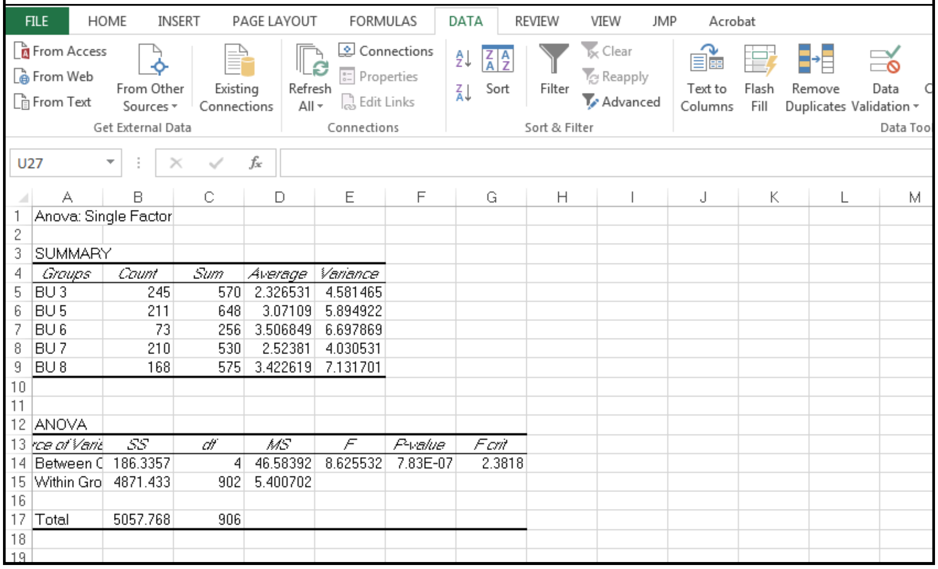
	A	B	C	D	E
1	BU 3	BU 5	BU 6	BU 7	BU 8
2	2	3	2	2	1
3	1	3	2	1	1
4	2	4	2	1	1
5	2	2	3	6	1
6	1	6	3	2	1
7	1	2	9	3	4
8	1	2	9	1	3
9	1	6	2	1	2
10	1	3	6	4	4
11	9	1	3	6	4
12	4	1	1	2	11
13	1	11	6	2	9
14	2	4	6	1	4
15	1	3	3	1	2
16	11	1	3	1	1

Input
Input Range: $A:$E
Grouped By: ● Columns ○ Rows
☑ Labels in First Row
Alpha: 0.05

Output options
○ Output Range:
● New Worksheet Ply:
○ New Workbook

Stratification with quantitative Y (cont’d)

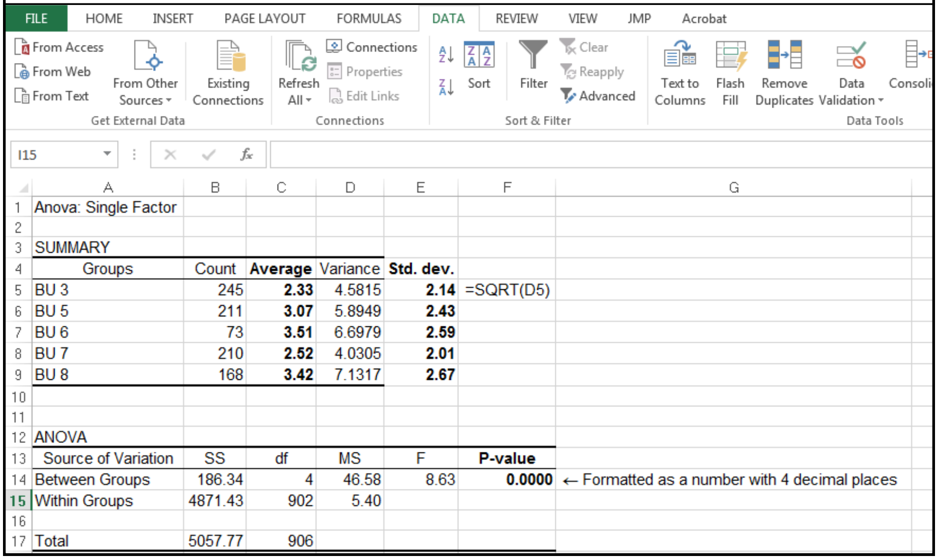
6. Here is the unedited default output
7. Go to the next slide for the cleaned-up output



	A	B	C	D	E	F	G
1	Anova: Single Factor						
2							
3	SUMMARY						
4	*Groups*	*Count*	*Sum*	*Average*	*Variance*		
5	BU 3	245	570	2.326531	4.581465		
6	BU 5	211	648	3.07109	5.894922		
7	BU 6	73	256	3.506849	6.697869		
8	BU 7	210	530	2.52381	4.030531		
9	BU 8	168	575	3.422619	7.131701		
10							
11							
12	ANOVA						
13	*rce of Varia*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
14	Between C	186.3357	4	46.58392	8.625532	7.83E-07	2.3818
15	Within Gro	4871.433	902	5.400702			
16							
17	Total	5057.768	906				
18							
19							

Stratification with quantitative Y (cont'd)

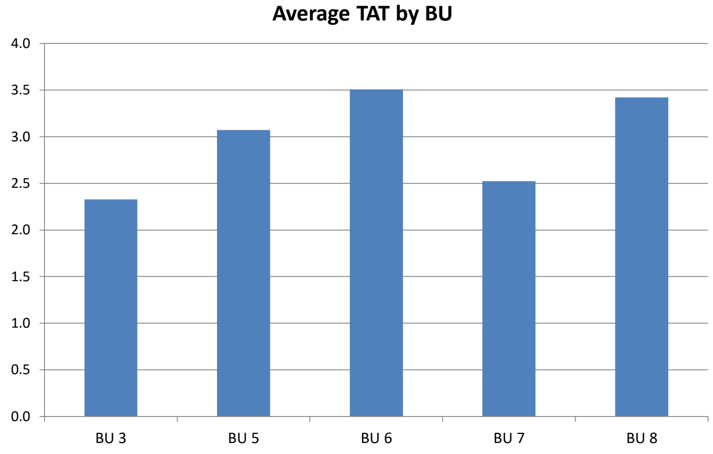
8. Very strong evidence of differences among the five BUs with respect to TAT
9. See next slide for a column chart of the averages



	A	B	C	D	E	F	G
1	Anova: Single Factor						
2							
3	SUMMARY						
4	Groups	Count	**Average**	Variance	**Std. dev.**		
5	BU 3	245	**2.33**	4.5815	**2.14**	=SQRT(D5)	
6	BU 5	211	**3.07**	5.8949	**2.43**		
7	BU 6	73	**3.51**	6.6979	**2.59**		
8	BU 7	210	**2.52**	4.0305	**2.01**		
9	BU 8	168	**3.42**	7.1317	**2.67**		
10							
11							
12	ANOVA						
13	Source of Variation	SS	df	MS	F	**P-value**	
14	Between Groups	186.34	4	46.58	8.63	**0.0000**	← Formatted as a number with 4 decimal places
15	Within Groups	4871.43	902	5.40			
16							
17	Total	5057.77	906				

Stratification with quantitative Y (cont'd)

10. BUs 3 and 7 represent best practice. Follow up: find out what they are doing and make it the standard for all BUs.
11. Close and save your workbook .



Exercise 28.1

Open *Data Sets* → *alignment process*. Three alignment tools of the same type are used to attach orifice plates to chips. We want to know if there are significant differences among the three tools in terms of radial alignment error *R dev*.

(a) Test for significant differences in average *R dev* among the 3 aligners. (Data is arranged for ANOVA under tab *R dev by Aligner*.) Give the P value and its interpretation in terms of standards of evidence.

(b) Smaller *R dev* is better. Which aligner represents best practice? Describe the appropriate follow up action.

(c) Close and save the data set.

Exercise 28.2

Open *Data Sets* → *casting dimensions*. Metal parts are cast from wax patterns molded on machines A or B. We want to know if there is a significant difference in average casting dimensions depending on which machine molded the pattern.

a) Test for a significant difference in average *length* between machines A and B. Give the P value and its interpretation in terms of standards of evidence.

b) The target value for *length* is 600. Which machine is closer to target?

c) Test for a significant difference in average *diam* between machines A and B. Give the P value and its interpretation in terms of standards of evidence.

Exercise 28.2 (cont’d)

d) The target value for *diam* is 50. Which machine is closer to target?

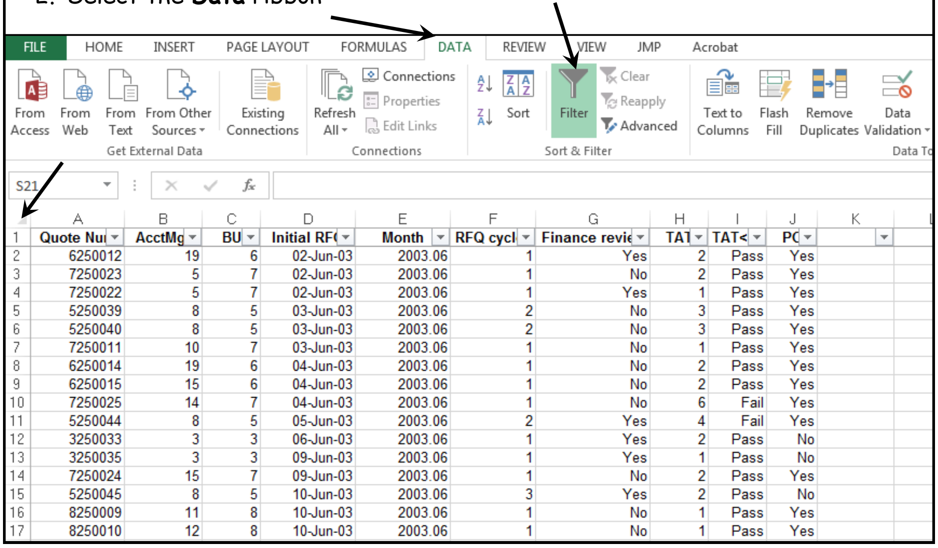
e) Describe an appropriate follow up action.

f) Close and save the data set.

Example: Unstacking Data using Filtering

For reference only:

1. Highlight BU column
2. Select the **Data** ribbon
3. Select **Filter**
4. Go to the next slide

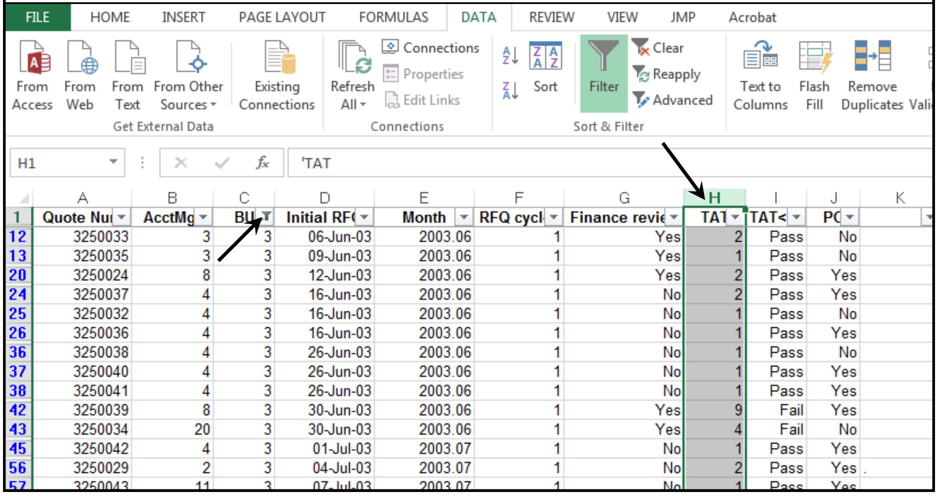


	A	B	C	D	E	F	G	H	I	J	K
1	Quote Nu	AcctMg	BU	Initial RF	Month	RFQ cycl	Finance revie	TAT	TAT<	PC	
2	6250012	19	6	02-Jun-03	2003.06	1	Yes	2	Pass	Yes	
3	7250023	5	7	02-Jun-03	2003.06	1	No	2	Pass	Yes	
4	7250022	5	7	02-Jun-03	2003.06	1	Yes	1	Pass	Yes	
5	5250039	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes	
6	5250040	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes	
7	7250011	10	7	03-Jun-03	2003.06	1	No	1	Pass	Yes	
8	6250014	19	6	04-Jun-03	2003.06	1	No	2	Pass	Yes	
9	6250015	15	6	04-Jun-03	2003.06	1	No	2	Pass	Yes	
10	7250025	14	7	04-Jun-03	2003.06	1	No	6	Fail	Yes	
11	5250044	8	5	05-Jun-03	2003.06	2	Yes	4	Fail	Yes	
12	3250033	3	3	06-Jun-03	2003.06	1	Yes	2	Pass	No	
13	3250035	3	3	09-Jun-03	2003.06	1	Yes	1	Pass	No	
14	7250024	15	7	09-Jun-03	2003.06	1	No	2	Pass	Yes	
15	5250045	8	5	10-Jun-03	2003.06	3	Yes	2	Pass	No	
16	8250009	11	8	10-Jun-03	2003.06	1	No	1	Pass	Yes	
17	8250010	12	8	10-Jun-03	2003.06	1	No	1	Pass	Yes	

Example: Unstacking Data using Filtering (cont'd)

For reference only:

5. Highlight the TAT column (H)
6. Click on the arrowhead next to the BU header in column C
7. Deselect all but BU 3 → OK
8. Right click on the TAT column
9. Select **Copy**
10. Go to the next slide



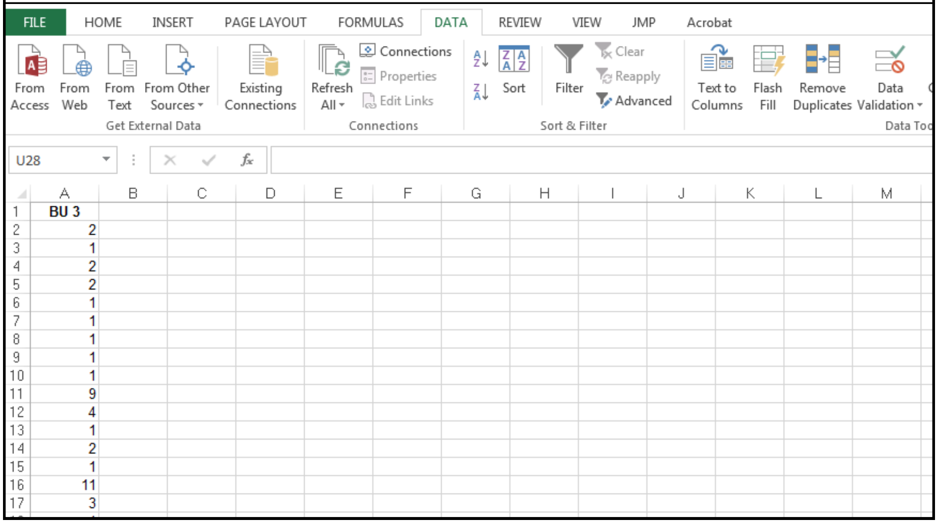
H1 'TAT

	A	B	C	D	E	F	G	H	I	J	K
1	Quote Nu	AcctMg	BU	Initial RF(	Month	RFQ cycl	Finance revie	TAT	TAT<	PC	
12	3250033	3	3	06-Jun-03	2003.06	1	Yes	2	Pass	No	
13	3250035	3	3	09-Jun-03	2003.06	1	Yes	1	Pass	No	
20	3250024	8	3	12-Jun-03	2003.06	1	Yes	2	Pass	Yes	
24	3250037	4	3	16-Jun-03	2003.06	1	No	2	Pass	Yes	
25	3250032	4	3	16-Jun-03	2003.06	1	No	1	Pass	No	
26	3250036	4	3	16-Jun-03	2003.06	1	No	1	Pass	Yes	
36	3250038	4	3	26-Jun-03	2003.06	1	No	1	Pass	No	
37	3250040	4	3	26-Jun-03	2003.06	1	No	1	Pass	Yes	
38	3250041	4	3	26-Jun-03	2003.06	1	No	1	Pass	Yes	
42	3250039	8	3	30-Jun-03	2003.06	1	Yes	9	Fail	Yes	
43	3250034	20	3	30-Jun-03	2003.06	1	Yes	4	Fail	No	
45	3250042	4	3	01-Jul-03	2003.07	1	No	1	Pass	Yes	
56	3250029	2	3	04-Jul-03	2003.07	1	No	2	Pass	Yes	
57	3250043	11	3	07-Jul-03	2003.07	1	No	1	Pass	Yes	

Example: Unstacking Data using Filtering (cont'd)

For reference only:

11. Create a blank worksheet, **Paste** in cell A1
12. Change the header in cell A1 as shown below
13. Repeat steps 7 through 12 for BUs 5, 6, 7, and 8



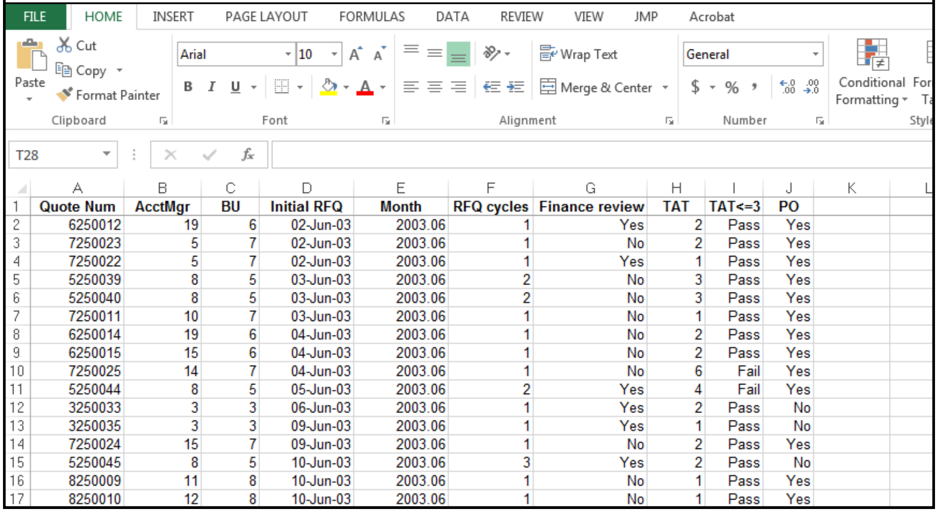
U28

	A
1	BU 3
2	2
3	1
4	2
5	2
6	1
7	1
8	1
9	1
10	1
11	9
12	4
13	1
14	2
15	1
16	11
17	3

29 Stratification Analysis — Pass/fail Y

Open *Data Sets → quotation process current state*

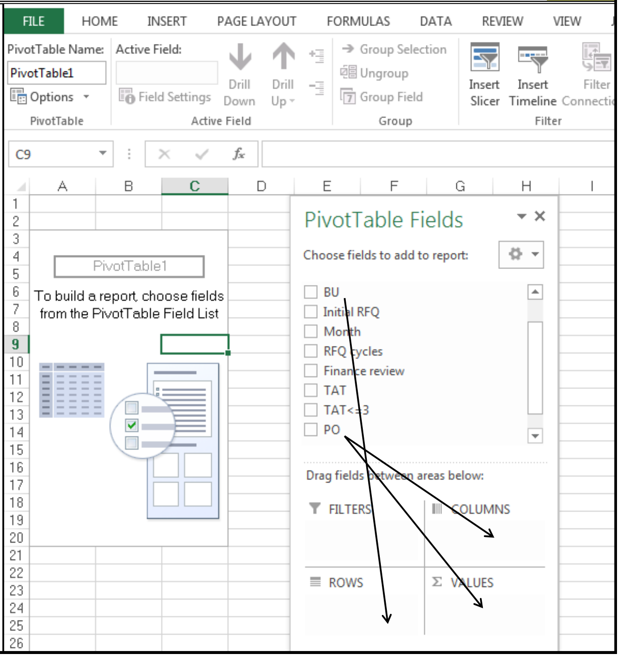
We want to test for significant differences among the business units (BUs) with respect to PO hit rate



	A	B	C	D	E	F	G	H	I	J
1	Quote Num	AcctMgr	BU	Initial RFQ	Month	RFQ cycles	Finance review	TAT	TAT<=3	PO
2	6250012	19	6	02-Jun-03	2003.06	1	Yes	2	Pass	Yes
3	7250023	5	7	02-Jun-03	2003.06	1	No	2	Pass	Yes
4	7250022	5	7	02-Jun-03	2003.06	1	Yes	1	Pass	Yes
5	5250039	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes
6	5250040	8	5	03-Jun-03	2003.06	2	No	3	Pass	Yes
7	7250011	10	7	03-Jun-03	2003.06	1	No	1	Pass	Yes
8	6250014	19	6	04-Jun-03	2003.06	1	No	2	Pass	Yes
9	6250015	15	6	04-Jun-03	2003.06	1	No	2	Pass	Yes
10	7250025	14	7	04-Jun-03	2003.06	1	No	6	Fail	Yes
11	5250044	8	5	05-Jun-03	2003.06	2	Yes	4	Fail	Yes
12	3250033	3	3	06-Jun-03	2003.06	1	Yes	2	Pass	No
13	3250035	3	3	09-Jun-03	2003.06	1	Yes	1	Pass	No
14	7250024	15	7	09-Jun-03	2003.06	1	No	2	Pass	Yes
15	5250045	8	5	10-Jun-03	2003.06	3	Yes	2	Pass	No
16	8250009	11	8	10-Jun-03	2003.06	1	No	1	Pass	Yes
17	8250010	12	8	10-Jun-03	2003.06	1	No	1	Pass	Yes

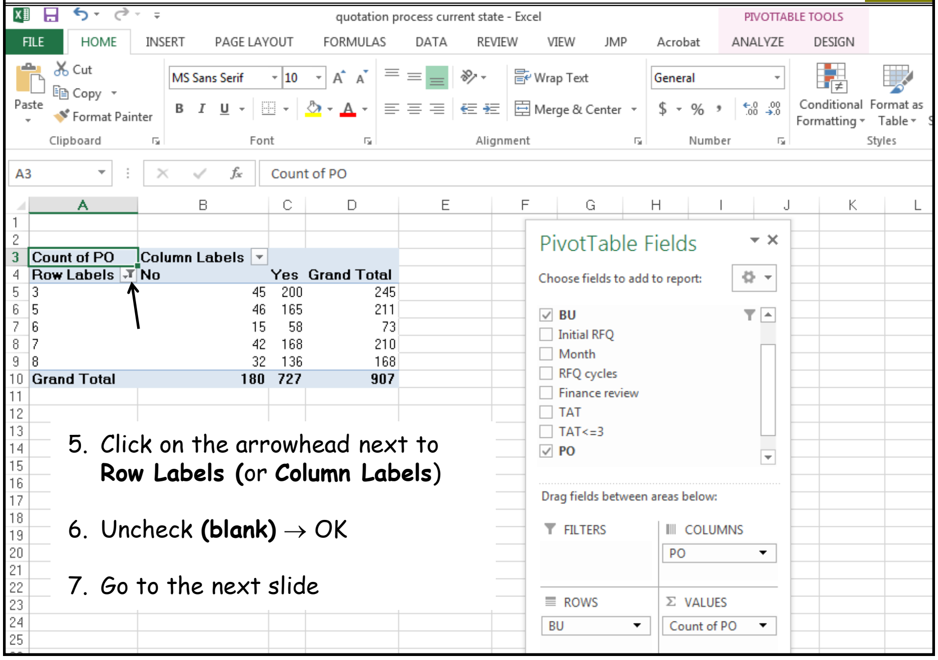
Stratification with pass/fail Y (cont'd)

1. Highlight all columns
2. Insert → PivotTable → OK
3. Drag/drop **BU** to the **Rows** area
4. Drag/drop **PO** to the **Columns** area
5. Drag/drop **PO** to the **Values** area
6. Go to the next slide



☐ BU
☐ Initial RFQ
☐ Month
☐ RFQ cycles
☐ Finance review
☐ TAT
☐ TAT<=3
☐ PO

Stratification with pass/fail Y (cont'd)



A3 Count of PO

Count of PO	Column Labels		
Row Labels	No	Yes	Grand Total
3	45	200	245
5	46	165	211
6	15	58	73
7	42	168	210
8	32	136	168
Grand Total	180	727	907

PivotTable Fields

Choose fields to add to report:

☑ BU
☐ Initial RFQ
☐ Month
☐ RFQ cycles
☐ Finance review
☐ TAT
☐ TAT<=3
☑ PO

Drag fields between areas below:

FILTERS

COLUMNS: PO

ROWS: BU

VALUES: Count of PO

5. Click on the arrowhead next to **Row Labels** (or **Column Labels**)

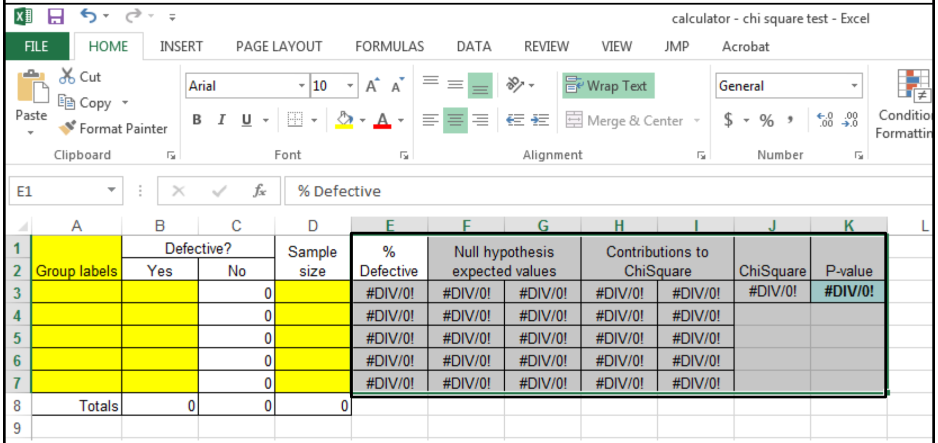
6. Uncheck **(blank)** → OK

7. Go to the next slide

Stratification with pass/fail Y (cont'd)

8. Open ***Student Files*** → ***calculator - chi square test***

9. Select the **5 groups** sheet, select and copy the cell range shown below



E1 % Defective

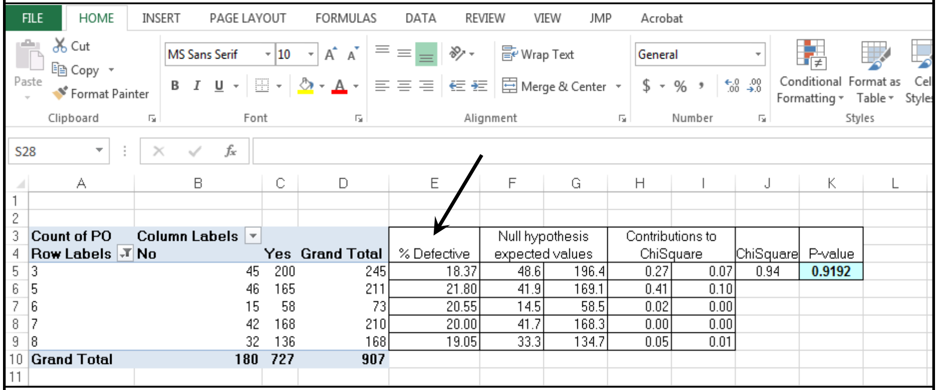
Group labels	Defective?		Sample size	% Defective	Null hypothesis expected values		Contributions to ChiSquare		ChiSquare	P-value
	Yes	No								
		0		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
		0		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
		0		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
		0		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
		0		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
Totals	0	0	0							

10. Go to the worksheet containing your pivot table

11. Go to the next slide

Stratification with pass/fail Y (cont'd)

10. Paste in cell **E3**
11. The P value is 0.9192. There is no evidence of differences among the BUs with respect to PO hit rate.



	A	B	C	D	E	F	G	H	I	J	K
1											
2											
3	Count of PO	Column Labels				Null hypothesis		Contributions to			
4	Row Labels	No	Yes	Grand Total	% Defective	expected values		ChiSquare		ChiSquare	P-value
5	3	45	200	245	18.37	48.6	196.4	0.27	0.07	0.94	0.9192
6	5	46	165	211	21.80	41.9	169.1	0.41	0.10		
7	6	15	58	73	20.55	14.5	58.5	0.02	0.00		
8	7	42	168	210	20.00	41.7	168.3	0.00	0.00		
9	8	32	136	168	19.05	33.3	134.7	0.05	0.01		
10	Grand Total	180	727	907							
11											

12. Note: for this to work, your pivot table has to contain raw counts, **not** percentages of row totals.
13. Close and save your workbook.

Exercise 29.1

Open *Data Sets* → *ATE Mar & Apr*.

a) Test for significant differences in % failing among the four test stations. Give the P value and its interpretation in terms of standards of evidence.

b) Based on the % failing for each test station, which pairs of stations appear to be statistically equivalent? Which pairs appear to be statistically different?

c) Test for a significant difference between the two part numbers (P/N). Give the P value and its interpretation in terms of standards of evidence.

d) Close and save the data set.

Exercise 29.2

Open *Data Sets* → *supplier comparison*. This is pass/fail inspection of raw material lots from suppliers A and B.

a) Test for a difference in % failing between suppliers A and B. Give the P value and its interpretation in terms of standards of evidence.

b) Make a pivot table with *Supplier* as the *Column Label*, *Inspector* as the *Row label*, and either one in the *Values* area. There is something here that casts doubt on your conclusion in (a). What is it?

c) Close and save the data set.

Exercise 29.3 (Read all instructions carefully!)

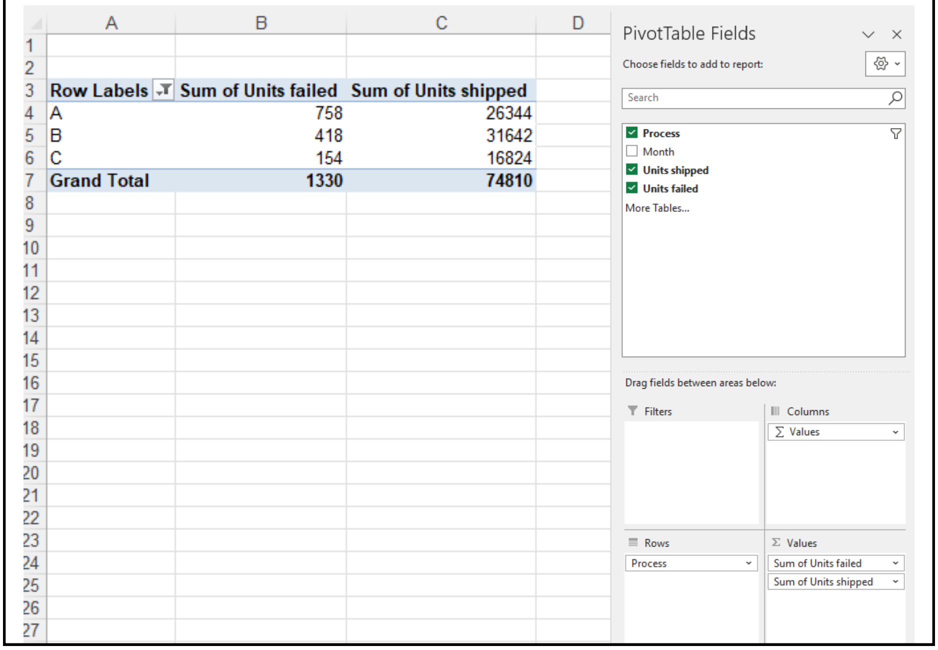
Open *Data Sets* → *out of box failures*. This tabulated pass/fail data. Set up your pivot table as shown on the **next slide**, then enter the values into the appropriate cells in *calculator – chi square test*. **(Pasting from the calculator to the pivot table won’t work in this case because we’re using sums.)**

a) Compare processes A, B, and C in terms of % failing. Give the P value and its interpretation in terms of standards of evidence.

b) Is there a significant difference between processes B and C? Give the P value and its interpretation in terms of standards of evidence.

c) Close and save the data set.

Exercise 29.3 (cont'd)



Row Labels	Sum of Units failed	Sum of Units shipped
A	758	26344
B	418	31642
C	154	16824
Grand Total	**1330**	**74810**

PivotTable Fields

Choose fields to add to report:

- ☑ Process
- ☐ Month
- ☑ Units shipped
- ☑ Units failed

Drag fields between areas below:

Filters:

Columns: Σ Values

Rows: Process

Values: Sum of Units failed, Sum of Units shipped

Exercise 29.4 --Small group exercise

Open *Data Sets* → *unstacked MBDP current state*. In your group, perform the stratification tests indicated in the table on the next slide:

a) Determine the type of Y data (PO-PD and MFG happy)

b) Determine the type of analysis for each. Find examples to follow.

c) Do the first one, the Sales row, together. Make sure everyone in the group knows how to do the analysis for the two types of data.

d) Assign one of the remaining rows to each group member.

e) Each group member performs the analysis on their row. (The fastest in the group can help others or pick up one more row, as needed.)

f) If there is a significant difference ($P \leq 0.15$), identify the process participant with best practice.

g) Share results, so each person has a completed table of results.

h) Discuss the results. Where would you focus your efforts to make improvements?

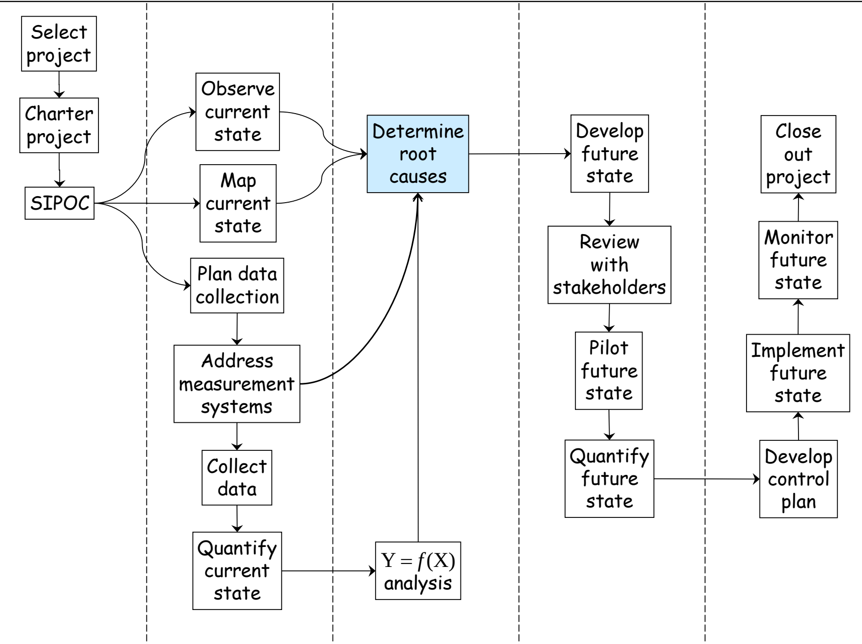
Exercise 29.4 --Small group exercise (cont.)

X's

	Avg. PO-PD (P value)	Best practice (Who)	% MFG ☹ (P value)	Best practice (Who)
Sales				
PE				
ME				
QE				
Drafter				
Proto oper.				
Baseline values:	29.5 days		49.4%	

Notes

30 Root Cause Analysis



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Tools used in Root Cause Analysis

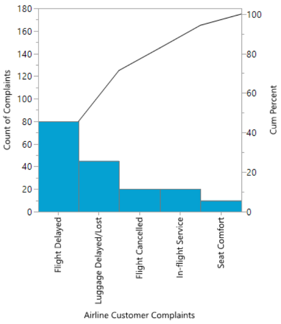
Usually we identify problems while mapping and observing the current state during the *Measure* phase

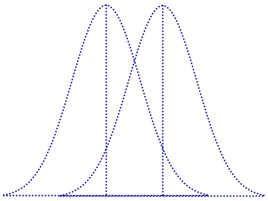
Observed problems

(*a.k.a.* opportunities for improvement)

Tools used in Root Cause Analysis (cont.)

Analyses such as Pareto Charts and Testing for Statistical Significance point us in the direction of the root causes or critical x’s





$H_0: \mu_1 = \mu_2$
$H_1: \mu_1 \neq \mu_2$

But, we usually need to dig deeper . . .

Topics

Additional tools and techniques for identifying root causes:

- Failure Modes and Effects Analysis (FMEA)
- Multi-level Pareto Analysis
- Five whys
- Five whys based on Y = f(X)

Failure Modes and Effects Analysis (FMEA)

FMEA can be used in the Analyze Phase to prioritize x’s

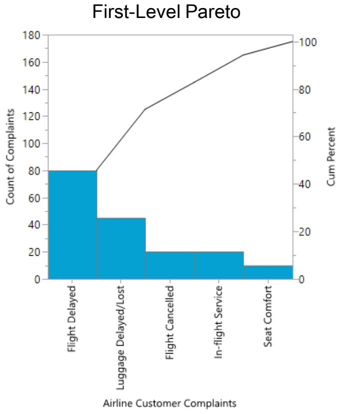
- It is used at the *beginning* of the Analyze Phase:
    - to identify the inputs that are likely to have a significant impact on the primary metric Y, and to remove from consideration those that are deemed trivial
    - data collection and analysis are required for verification of those failure modes with high RPNs, to validate their significant impact on Y, as FMEA is an opinion-based tool
- Actions for remedying failure modes with high RPNs are *not* discussed or taken in Analyze
- We will learn about FMEA in the Improve Phase, when it is used to evaluate risk and prevent problems before they occur in the proposed process, its original application.

Process Functions	Requirements	Failure Modes	Effects	SEV	Causes	OCC	CN	Current Controls	DET	RPN	Actions Planned	Responsible	Due Date	Actions Taken
Reagent lot creation	New lot information distributed to OPS team	Printer malfunction	Delay in distribution to the OPS team	1	Electrical	1	**1**	One printer	1	**1**				
Reagent creation	New reagent created based on processing demand	Operator error during manufacture of reagent	Processing delay, wasted sub-reagents, time lost, labor money	5	Did not use trained witness	1	**5**	SOP requires trained witness for procedure	1	**5**				
Reagent storage	Storage of new reagent at point of use (laboratory)	Insufficent storage space in freezer or fridge	Reagent stock-out	4	Freezer space not reconciled	5	**20**	No control.	5	**100**				
Material storage	Stocking of materials and reagents in designated location within the functional laboratory	Insufficient shelf space for materials.	Material stock-out	3	Too many items on shelving	3	**9**	Shelving units with four shelves	5	**45**				
		Staff is unclear where material items should be stored	Materials not stocked in designated location within the functional area	2	Insufficent labeling system to designate material and reagent locations	3	**6**	Labels on shelving only	3	**18**				
Material Distribution	Distribution of materials based on MIN/MAX forecasting	MIN/MAX values not accurate	Material shortage	2	Forecasting not accurate	3	**6**	Master Science Forecasting	5	**30**				

Multi-Level Pareto Analysis

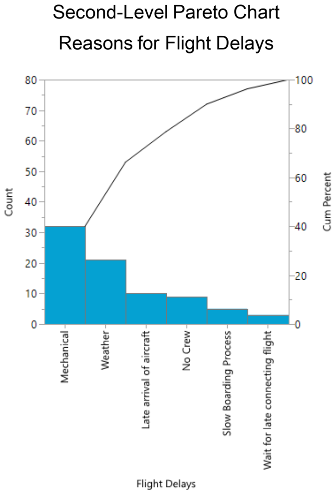
We can drill down to root causes using a series of Pareto Charts

- From a first-level Pareto Chart, we can see which categories are contributing the most to our problem



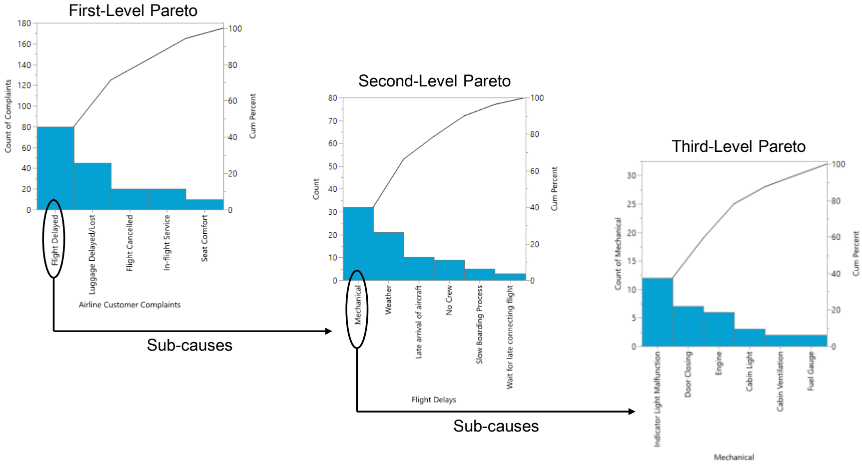
Second-Level Pareto Chart

The highest bar(s) from the first-level Pareto can be broken down further into a second-level Pareto Chart:

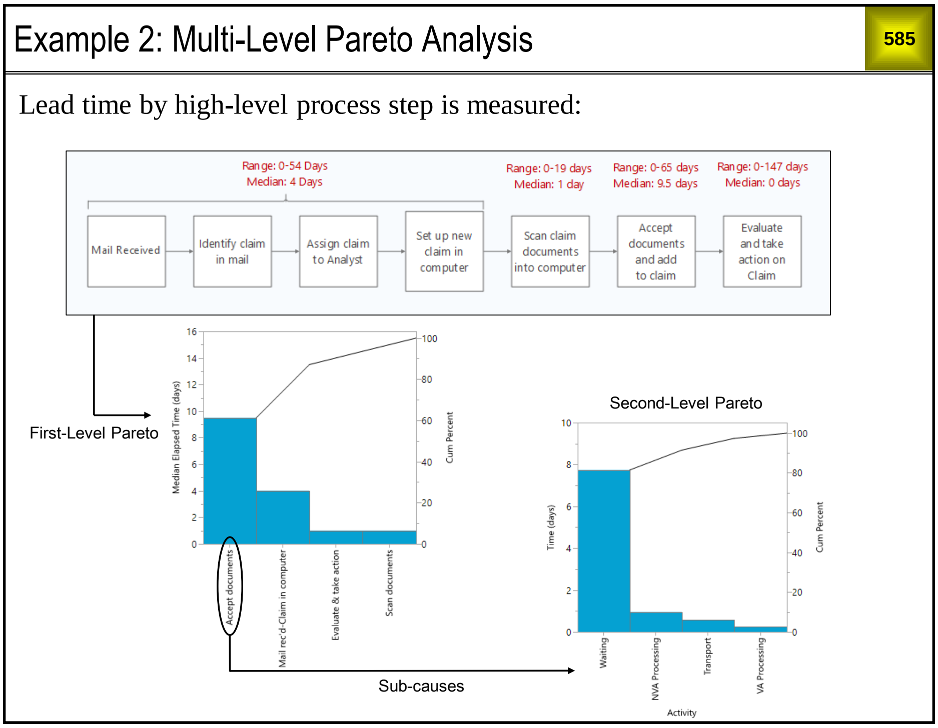


Multi-Level Pareto Analysis (cont.)

By continuing to drill down, we can determine root causes of most frequently occurring defects.

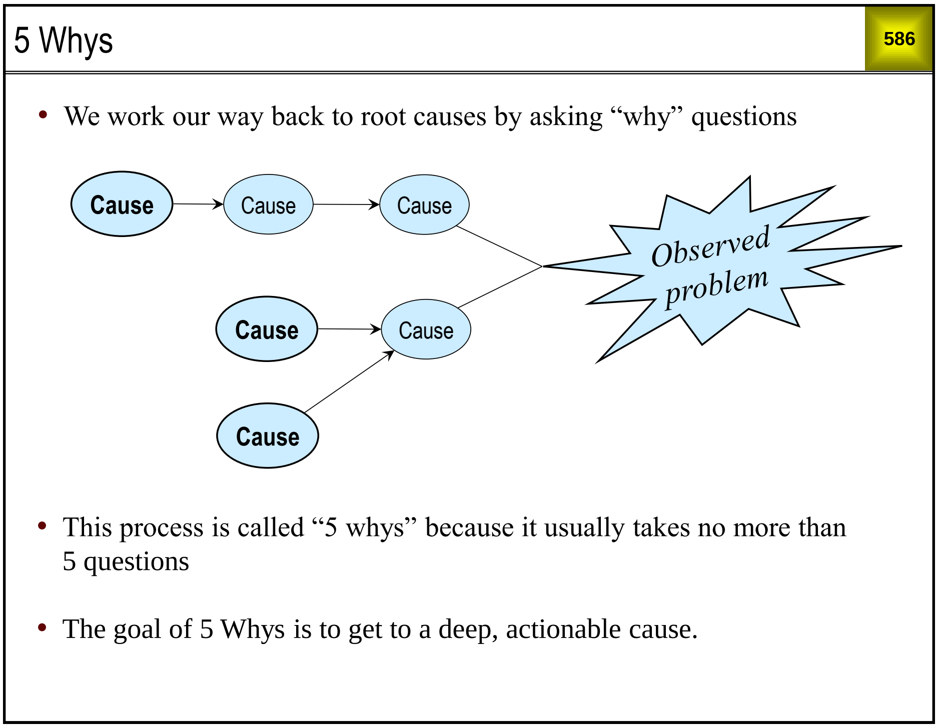


When data is not available for multi-level Pareto analysis, use the first-level Pareto Chart with 5 Whys to determine root causes.



Example 2: Multi-Level Pareto Analysis

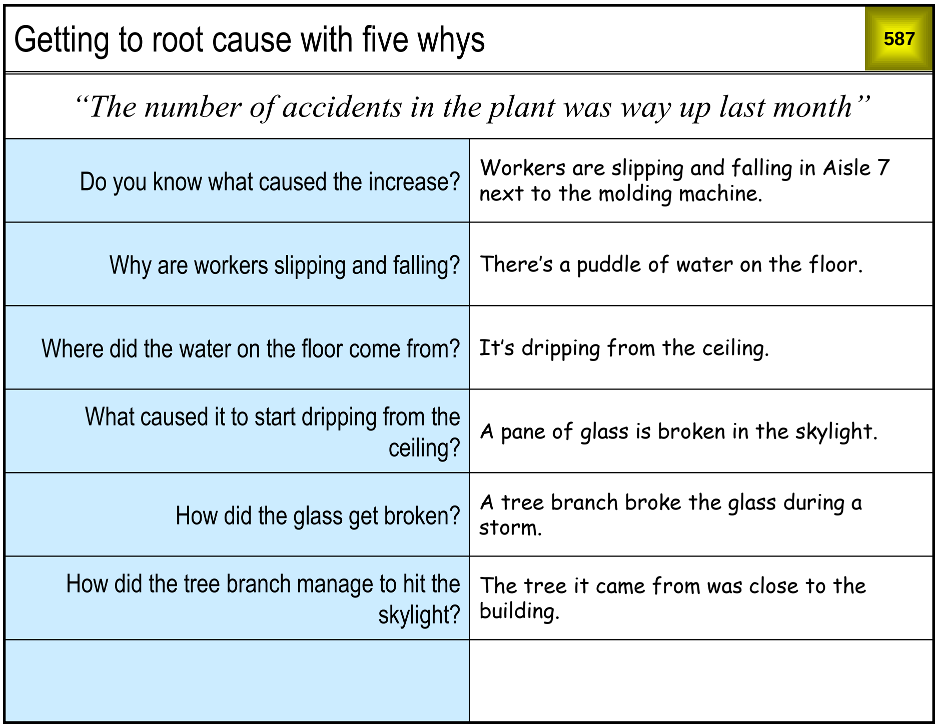
Lead time by high-level process step is measured:



5 Whys

- We work our way back to root causes by asking "why" questions

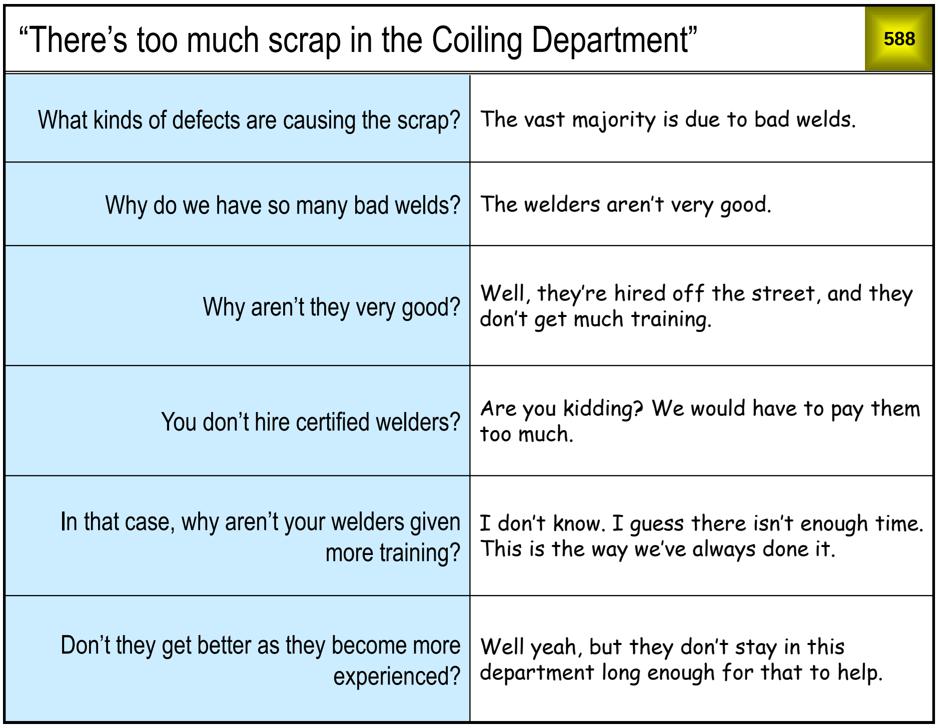
- This process is called "5 whys" because it usually takes no more than 5 questions
- The goal of 5 Whys is to get to a deep, actionable cause.



Getting to root cause with five whys

"The number of accidents in the plant was way up last month"

Do you know what caused the increase?	Workers are slipping and falling in Aisle 7 next to the molding machine.
Why are workers slipping and falling?	There's a puddle of water on the floor.
Where did the water on the floor come from?	It's dripping from the ceiling.
What caused it to start dripping from the ceiling?	A pane of glass is broken in the skylight.
How did the glass get broken?	A tree branch broke the glass during a storm.
How did the tree branch manage to hit the skylight?	The tree it came from was close to the building.



"There's too much scrap in the Coiling Department"

What kinds of defects are causing the scrap?	The vast majority is due to bad welds.
Why do we have so many bad welds?	The welders aren't very good.
Why aren't they very good?	Well, they're hired off the street, and they don't get much training.
You don't hire certified welders?	Are you kidding? We would have to pay them too much.
In that case, why aren't your welders given more training?	I don't know. I guess there isn't enough time. This is the way we've always done it.
Don't they get better as they become more experienced?	Well yeah, but they don't stay in this department long enough for that to help.

(cont'd)

Why do they leave this department so soon?	There's another department where welders are used. As soon as there's an opening over there, everybody here applies for it.
Why are they so eager to work in the other department?	For one thing, the working conditions over there are much better. We have the highest accident rate in the company.
Is there another reason?	Over there they pay a dollar an hour more than here.

"I was late for work today."

Why were you late for work today?	I overslept.
Why did you oversleep?	My alarm didn't go off.
Why didn't your alarm go off?	The power went out last night.
Why did the power go out last night?	There was a thunderstorm.

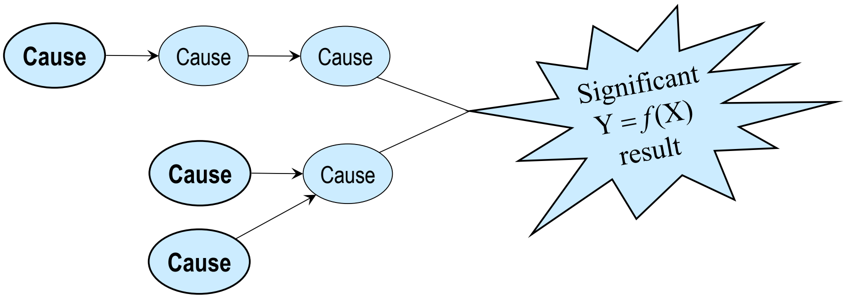
What is wrong with this 5 Whys path?

If you get to a non-actionable root cause, back up and try to find a different path to an answer.

Five whys based on $Y = f(X)$ analysis

591

- Data analysis provides the basis for penetrating questions
- After we have completed our $Y = f(X)$ analyses, we should interview process participants again to determine the causes of significant comparisons or correlations.
- 5 Whys and Cause and Effect (Fishbone) Diagrams are helpful “interviewing” tools.



Want to reduce external failures

592

Q “There is a significant correlation between dwell time and DPPM. What causes the variation in dwell time?”

A “The dwell time stretches out when operators are called away to do other things while they’re getting ready to mold parts.”

Q “Isn’t there an upper spec on the dwell time?”

A “Yes. The operators are supposed to purge the tank if the dwell time gets too long, but they don’t always do that.”

Q . . .

Whenever we can collect data to verify the root cause found through 5 Whys, that should be done.

Want to reduce turnaround time

Q “The turnaround time is significantly longer for some account managers than for others. What do you think causes that?”

A “They don’t all use the same quotation preparation process.”

Q “Why not?”

A “There is no standard process. They have all developed their own way of doing it.”

Q . . .

Whenever observation can verify the root cause found through 5 Whys, that should be done

(cont’d)

Q “The turnaround time is significantly longer for some business units than for others. What do you think causes that?”

A “Some of the business units aren’t using the automated configuration tool.”

Q “Why not?”

A . . .

Whenever observation or data collection can verify the root cause found through 5 Whys, that should be done.

Want to improve internal customer satisfaction

Q “The tool development process often results in slow line speeds and overweight material. What causes that?”

A “The testers slow the line down and increase the weight to get the dimensions on target.”

Q “Why do they use weight and line speed instead of other variables?”

A “They’re usually in a hurry. They’ve discovered that manipulating weight and line speed is the fastest way.”

Q . . .

Whenever observation or data collection can verify the root cause found through 5 Whys, that should be done.

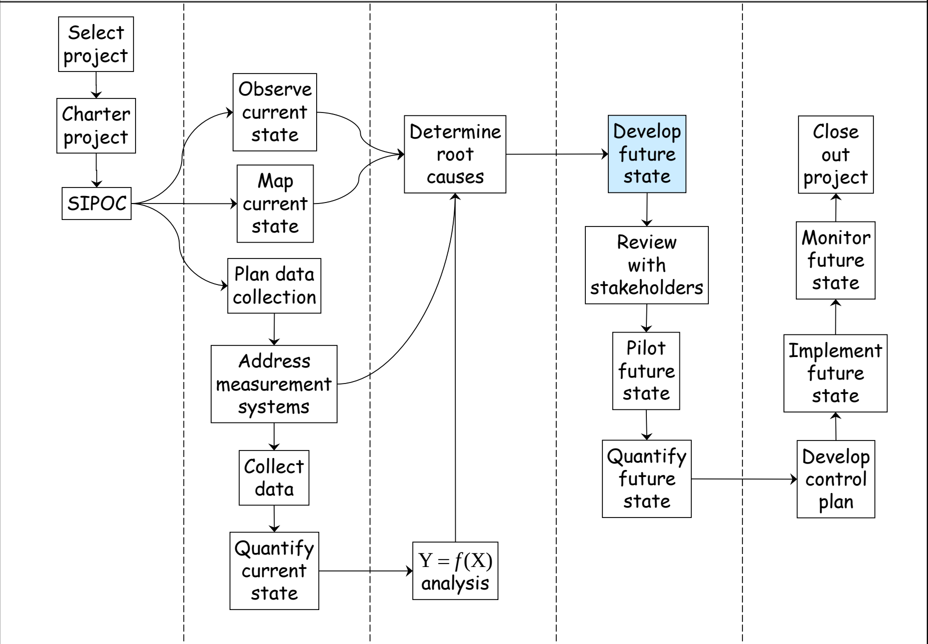
Identifying root causes

At the conclusion of the Analyze Phase, the team must list those specific root causes or critical x’s to be acted upon during the Improve Phase

- Review the analyses completed to:
    - ✓ determine those critical x’s and root causes that have been validated as significant contributors to unsatisfactory performance in the primary metric
    - ✓ list those that are no longer under consideration

- The team should show the analyses that support their decision on which opportunities to address in the Improve Phase

31 Developing and Prioritizing Solutions



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

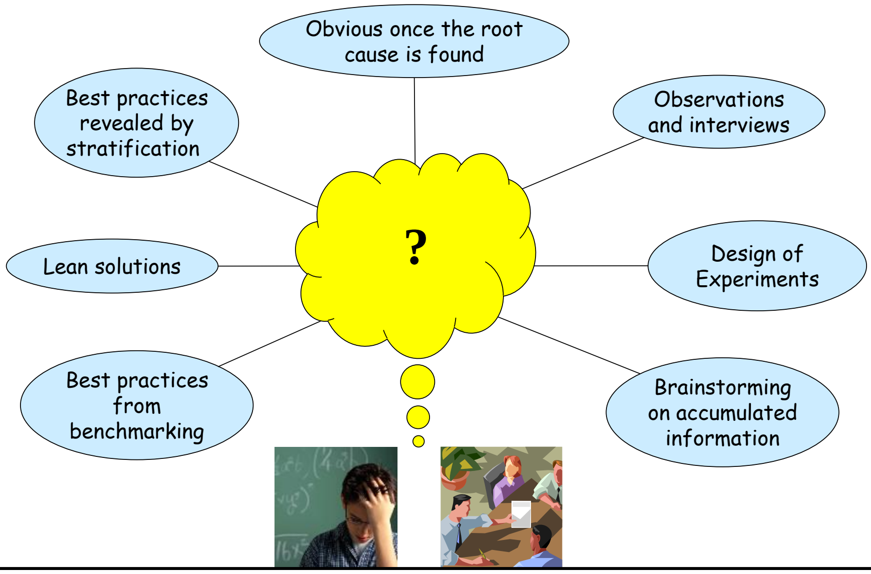
Monitor future state

Implement future state

Develop control plan

Developing solutions

Solutions come from many sources



Obvious once the root cause is found

Best practices revealed by stratification

Observations and interviews

Lean solutions

Design of Experiments

Best practices from benchmarking

Brainstorming on accumulated information

Developing solutions (cont'd)

Improvement ideas can come from many sources. Some ideas will contribute more to the success of the future state than others. The greater the number of ideas, the greater the probability of discovering successful solutions. The team should generate as many improvement ideas as possible.

The nature of this process is that the initial list gets shorter. Some ideas are discarded along the way, others are retained intact, still others are modified or combined. This process leads to a future state that is likely to be best available within the constraints of the project.

Common solution categories

- Technology upgrades
- Lean solutions (we'll learn more about these in the next section of the course)
- Standardization
- Modification of procedures
- Optimization of processes or products (DOE)
- "Just do it" solutions that haven't yet been implemented

Solution categories (cont'd)

LSS projects address problems for which solutions are not known. Nevertheless, there are commonly occurring categories.

A common example of technology upgrade would be switching to a better measurement system.

We don't need a LSS project to tell us that Lean is good. But what if the organization lacks consensus on the benefits of these methods? A high priority LSS project that makes significant improvements by applying Lean solutions could help the organization recognize the value of Lean across the board.

The same applies for "just do it" solutions. Everyone knows what needs to be done, but it isn't getting done. A LSS project identifying and quantifying the need for the "just do it" solution might get some high level attention, cut through the lethargy, and stimulate action on the issue.

Prioritizing solutions

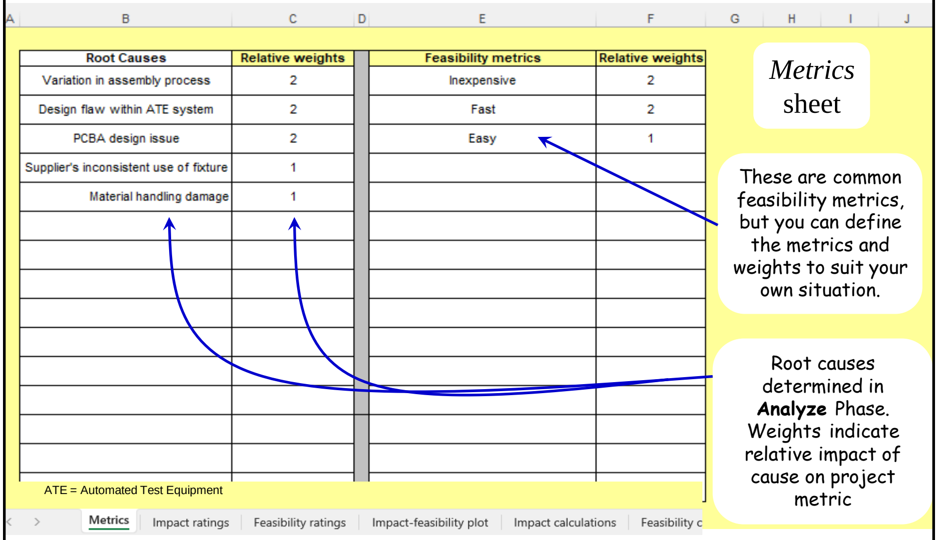
- Uses the impact/feasibility method — same as prioritizing projects
- Defines "impact" as addressing the root causes identified by the project team
- Gives the organization a basis for making sound decisions in light of project findings
  - ✓ Opportunity to expedite implementation of solutions with high impact or high feasibility
  - ✓ Opportunity to postpone implementation of solutions with low impact and low feasibility

Instructions for prioritizing solutions

1. Open *Student Files* → *blank C&E matrix* - *impact & feasibility*.
2. In the *Metrics* sheet, change *Impact metrics* to *Root causes*.
3. List your prioritized root causes and relative weights (overall rankings).
4. List your feasibility metrics and relative weights.
5. Go to the *Impact ratings* sheet, change *Items to be ranked* to *Solutions*.
6. List the solutions you wish to rank.
7. Rate each solution for impact on each root cause.
8. Go to the *Feasibility ratings* sheet, rate each solution for each feasibility metric.
9. Go to the sheet *Impact* - *feasibility plot* to evaluate the results.

Student Files → *prioritizing solutions - exercise*

Root causes of Long Lead Time



Root Causes	Relative weights	Feasibility metrics	Relative weights
Variation in assembly process	2	Inexpensive	2
Design flaw within ATE system	2	Fast	2
PCBA design issue	2	Easy	1
Supplier's inconsistent use of fixture	1		
Material handling damage	1		

ATE = Automated Test Equipment

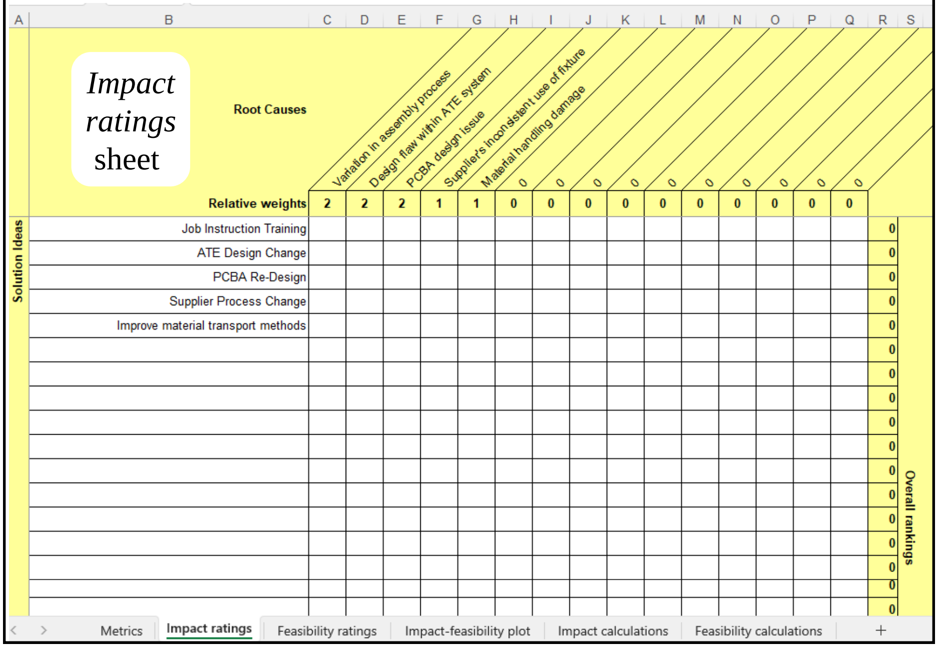
Metrics sheet

These are common feasibility metrics, but you can define the metrics and weights to suit your own situation.

Root causes determined in **Analyze** Phase. Weights indicate relative impact of cause on project metric

Prioritizing solutions (cont'd)

605



Impact ratings sheet

Solution Ideas

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Root Causes	Variation in assembly process	Design flaw within ATE system	PCBA design issue	Supplier's inconsistent use of fixture	Material handling damage	0	0	0	0	0	0	0	0	0	0	
Relative weights	2	2	2	1	1	0	0	0	0	0	0	0	0	0	0	
Job Instruction Training																0
ATE Design Change																0
PCBA Re-Design																0
Supplier Process Change																0
Improve material transport methods																0
																0
																0
																0
																0
																0
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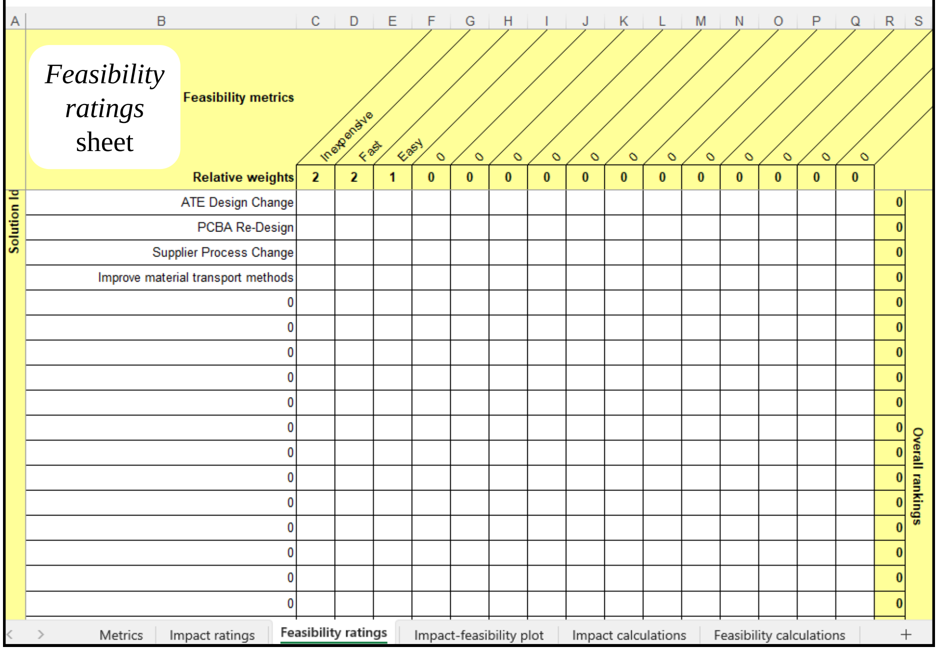
Overall rankings

605

Prioritizing solutions (cont'd)

606



Feasibility ratings sheet

Solution Id

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Feasibility metrics	Inexpensive	Fast	Easy	0	0	0	0	0	0	0	0	0	0	0	0	
Relative weights	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	
ATE Design Change																0
PCBA Re-Design																0
Supplier Process Change																0
Improve material transport methods																0
0																0
0																0
0																0
0																0
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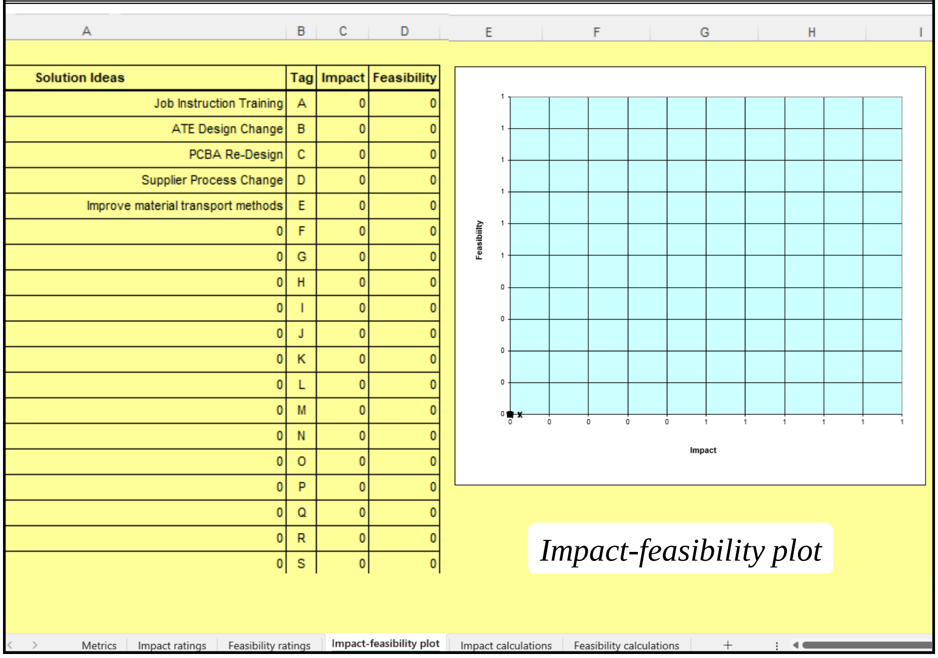
Overall rankings

606

Prioritizing solutions (cont'd)



Solution Ideas	Tag	Impact	Feasibility
Job Instruction Training	A	0	0
ATE Design Change	B	0	0
PCBA Re-Design	C	0	0
Supplier Process Change	D	0	0
Improve material transport methods	E	0	0
0	F	0	0
0	G	0	0
0	H	0	0
0	I	0	0
0	J	0	0
0	K	0	0
0	L	0	0
0	M	0	0
0	N	0	0
0	O	0	0
0	P	0	0
0	Q	0	0
0	R	0	0
0	S	0	0

Impact-feasibility plot

Exercise 31.1

Open *Student Files → prioritizing solutions - exercise*.

Use the root causes and solution ideas as provided. Note that the first row of each sheet is frozen for ease of use during ranking.

Use your knowledge and experience to complete the following tasks:

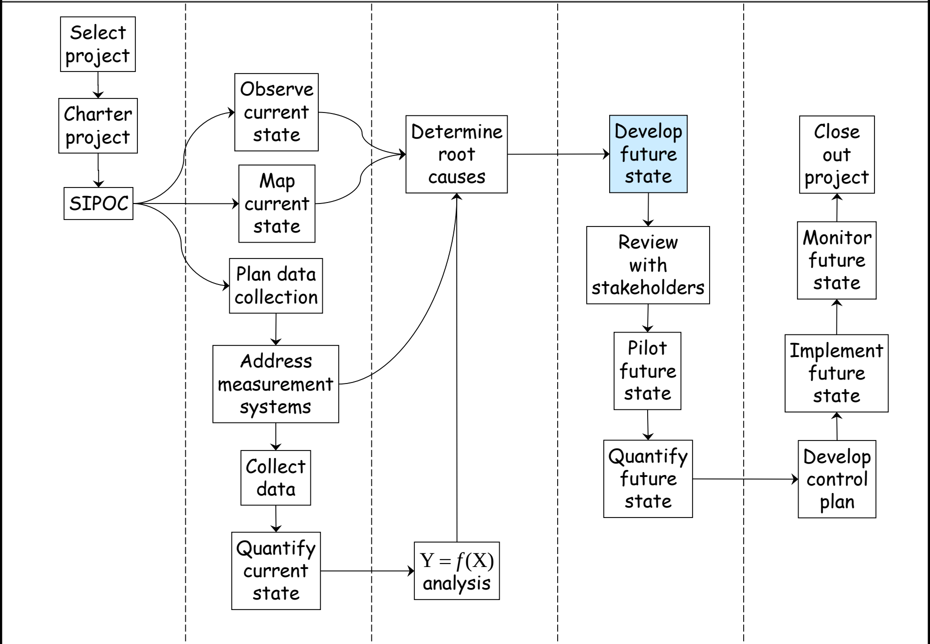
a) Change the relative weights for the feasibility metrics as you see fit.

b) Fill out the *Impact ratings* sheet using H, M, L or blank.

c) Fill out the *Feasibility ratings* sheet using H, M, or L.

d) Use your impact-feasibility plot to decide which solution ideas should be implemented sooner, which should be implemented later, and perhaps, which should not be implemented.

32 Lean Solutions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$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

Monitor future state

Close out project

Commonly used Lean solutions

5S

Stop & fix

Pull system

Standardization

Mistake proofing

Reduce batch sizes

Value stream teams

Visual management

Changeover reduction

Work balancing (leveling)

.
.
.

The 5S Vision

A Workplace that is:

- Clean, organized, orderly
- Safe
- Efficient and pleasant
- The foundation for all other improvement activities

Resulting In:

- Fewer accidents
- Improved efficiency
- Improved quality
- Workplace control

And therefore:

- Reduced waste
- Reduced cost

5S

- Sort – Sort through and Sort out
    - Keep what is needed – Eliminate what is not
    - Reduce quantity of items to what is needed

- Set in Order – A place for everything and everything in its place
    - Identify best location and relocate out-of-place items
    - Make locations visually identified – easy to see missing items
    - Set height, quantity, and size limits
    - Organize for safety

- Shine – Shine and Inspect through cleaning
    - Filthy work environments lead to poor morale
    - Spills and debris are safety hazards
    - Its easier to identify a maintenance need on clean equipment

- Standardize
    - Build the framework for maintaining Sort, Set in Order, and Shine
    - Clarity about what is and is not normal with simple action plans

- Sustain
    - Incorporate 5S into the daily work cycle

Pull systems for supply replenishment

- Material usage should be first-in-first-out (FIFO)
- Supply orders are triggered by *kanbans* (cards, empty bins, or other signals)
- The objective is to minimize stock-outs without keeping excessive supply quantities on hand

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Kanban card for supply items

- An order is triggered when the minimum quantity is reached*
- A kanban card goes with the order, returns with the delivery
- The minimum quantity should represent what is needed to span the delivery cycle time

Item Name ________________________

Max. Quantity __________

Min. Quantity __________

Re-order Qty. __________ **(Max – Min)**

Vendor ___________________________

Catalog Pg. No. ________

- The maximum quantity should represent a desired upper bound for supply quantity on hand

*What can cause this system to fail?

Example: two-bin kanban system

- Two bins for each item (see next slide)
- Amount in each bin = min. quantity = order quantity
- Order when top bin is empty, move bottom bin to top
- Visual system, easy to use
- The max and min quantities can be determined by trial and error
- If usage data is available, there is a better way

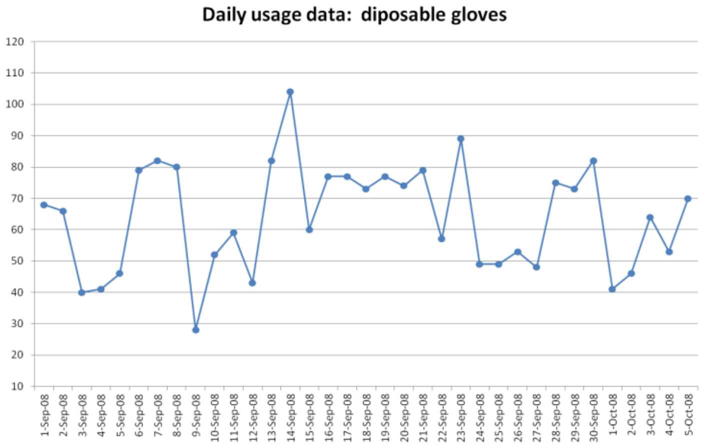
Two-bin system (cont'd)

Using data to set max/min values

- Required inputs
  - ✓ Time basis for usage data (hourly, each shift, daily, weekly, . . .)
  - ✓ Average usage per time period
  - ✓ Standard deviation of usage per time period
  - ✓ Minimum order quantity
  - ✓ Min. value (number of orders)
  - ✓ Max. value (number of orders)
- Values calculated in the simulation
  - ✓ Starting quantity for each period
  - ✓ Quantity received during each period
  - ✓ Quantity used during each period
  - ✓ Ending quantity for each period
  - ✓ Quantity ordered during each period

Setting max/min values (cont'd)

Data Sets → usage of disposable gloves

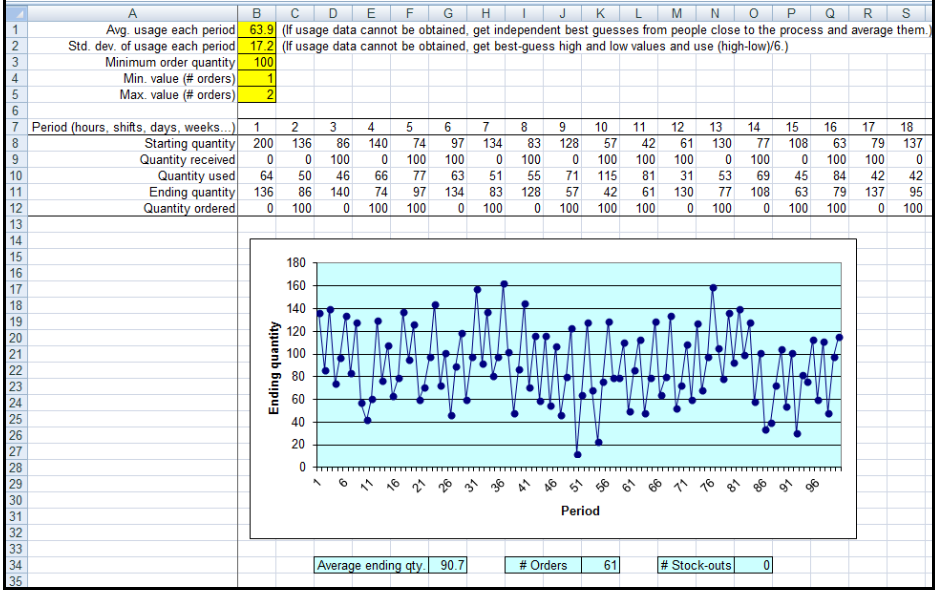


Average = 63.9

Std. dev. = 17.2

Setting max/min values (cont'd)

Student Files → kanban setup

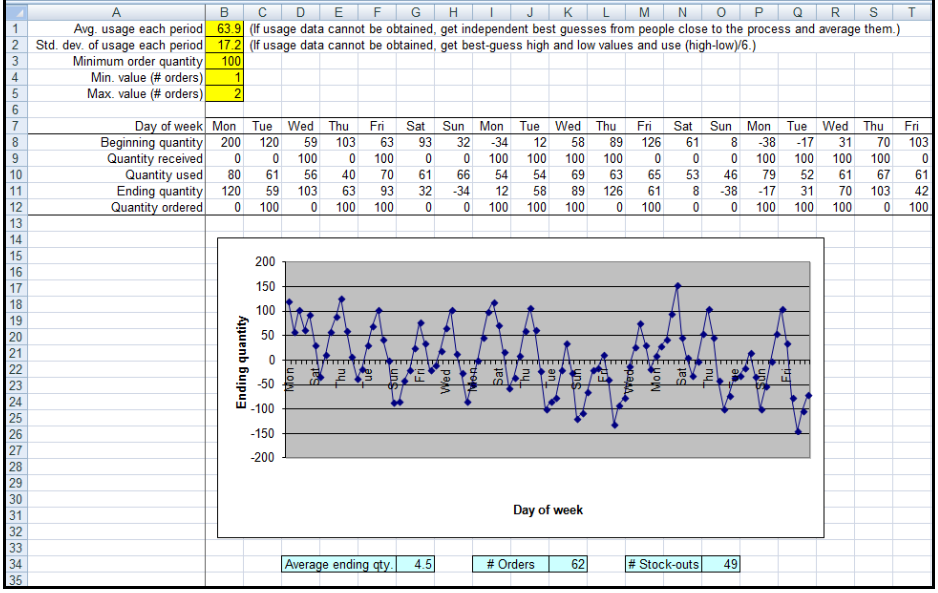


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Avg. usage each period	63.9	(If usage data cannot be obtained, get independent best guesses from people close to the process and average them.)																
2	Std. dev. of usage each period	17.2	(If usage data cannot be obtained, get best-guess high and low values and use (high-low)/6.)																
3	Minimum order quantity	100																	
4	Min. value (# orders)	1																	
5	Max. value (# orders)	2																	
6																			
7	Period (hours, shifts, days, weeks...)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
8	Starting quantity	200	136	86	140	74	97	134	83	128	57	42	61	130	77	108	63	79	137
9	Quantity received	0	0	100	0	100	100	0	100	0	100	100	100	0	100	0	100	100	0
10	Quantity used	64	50	46	66	77	63	51	55	71	115	81	31	53	69	45	84	42	42
11	Ending quantity	136	86	140	74	97	134	83	128	57	42	61	130	77	108	63	79	137	95
12	Quantity ordered	0	100	0	100	100	0	100	0	100	100	100	0	100	0	100	100	0	100

Average ending qty.	90.7	# Orders	61	# Stock-outs	0

Setting max/min values (cont'd)

Student Files → kanban setup - weekdays only



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Avg. usage each period	63.9	(If usage data cannot be obtained, get independent best guesses from people close to the process and average them.)																	
2	Std. dev. of usage each period	17.2	(If usage data cannot be obtained, get best-guess high and low values and use (high-low)/6.)																	
3	Minimum order quantity	100																		
4	Min. value (# orders)	1																		
5	Max. value (# orders)	2																		
6																				
7	Day of week	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri
8	Beginning quantity	200	120	59	103	63	93	32	-34	12	58	89	126	61	8	-38	-17	31	70	103
9	Quantity received	0	0	100	0	100	0	0	100	100	100	100	0	0	0	100	100	100	100	0
10	Quantity used	80	61	56	40	70	61	66	54	54	69	63	65	53	46	79	52	61	67	61
11	Ending quantity	120	59	103	63	93	32	-34	12	58	89	126	61	8	-38	-17	31	70	103	42
12	Quantity ordered	0	100	0	100	100	0	0	100	100	100	0	100	0	0	100	100	100	0	100

Average ending qty.	4.5	# Orders	62	# Stock-outs	49

Examples of mistake-proofing (Poke Yoke)

- Designing connecting cables and ports so that a cable cannot be plugged into the wrong port
- Programming software so that the user cannot proceed unless necessary information is filled in
- Auto fill of previously entered information on electronic forms
- Pull down menus in computer programs — especially for data entry
- Using feedback control systems and alarms on equipment
- Fixturing to prevent incorrect placement and hold things in place

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Reduce batch sizes (keep the work moving)

Don't do things in batches.
The ideal is to do one thing at a time.
Come as close to this as you can.

- Wait a minute — batching is supposed to be "efficient"
- Maybe, but here are some problems with batching:
  - ✓ A customer who wants just one item has to wait for a whole batch to be completed
  - ✓ Reduces flexibility in building different products.
  - ✓ Items accumulate until the batch quantity is reached — wastes space, creates opportunities for defects

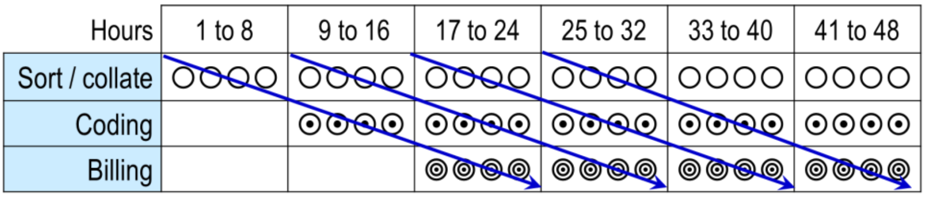
Reduce batch sizes (cont’d)

Of course, there can be a legitimate problem with reducing batch sizes: it increases the number of changeovers.

Fortunately, this is a problem for which Lean has excellent solutions. Lean projects have reduced changeover times by 80% or more.

Current state: daily batching

3 operations
2 hours per transaction per operation

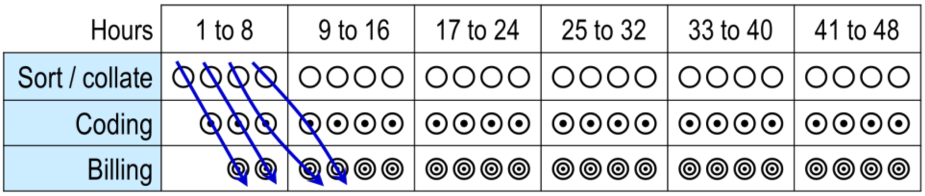


Hours	1 to 8	9 to 16	17 to 24	25 to 32	33 to 40	41 to 48
Sort / collate	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Coding		⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙
Billing			◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎

Lead time = 24 hours (3 days)

Future state: continuous flow

3 operations
2 hours per transaction per operation



Hours	1 to 8	9 to 16	17 to 24	25 to 32	33 to 40	41 to 48
Sort / collate	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Coding	⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙
Billing	◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎

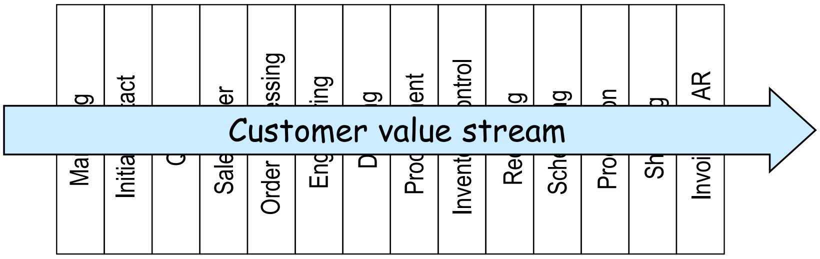
Lead time = 6 hours (less than one day)

Organizing by value stream

Sales	Initial contact	Quote	Sales order	Order processing	Engineering	Drawing	Procurement	Inventory control	Receiving	Scheduling	Production	Shipping	Invoicing / AR

- Departmental boundaries create "silos"
- Vestige of industrial revolution — need for specialization
- Silos are "islands" of responsibility
- Hand offs between silos are opportunities for poor communication and lack of coordination

Organizing by value stream (cont'd)



- Customer value stream spans all silos
- Often, no single entity has overall responsibility for customer satisfaction

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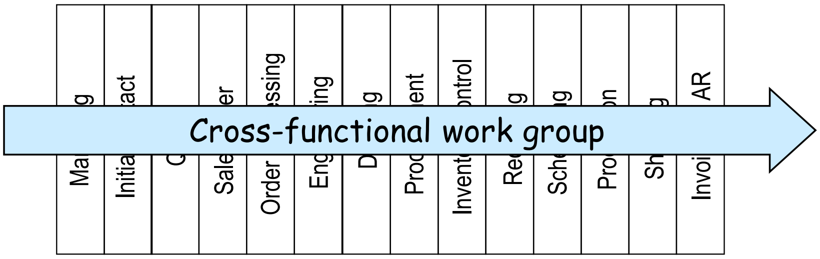
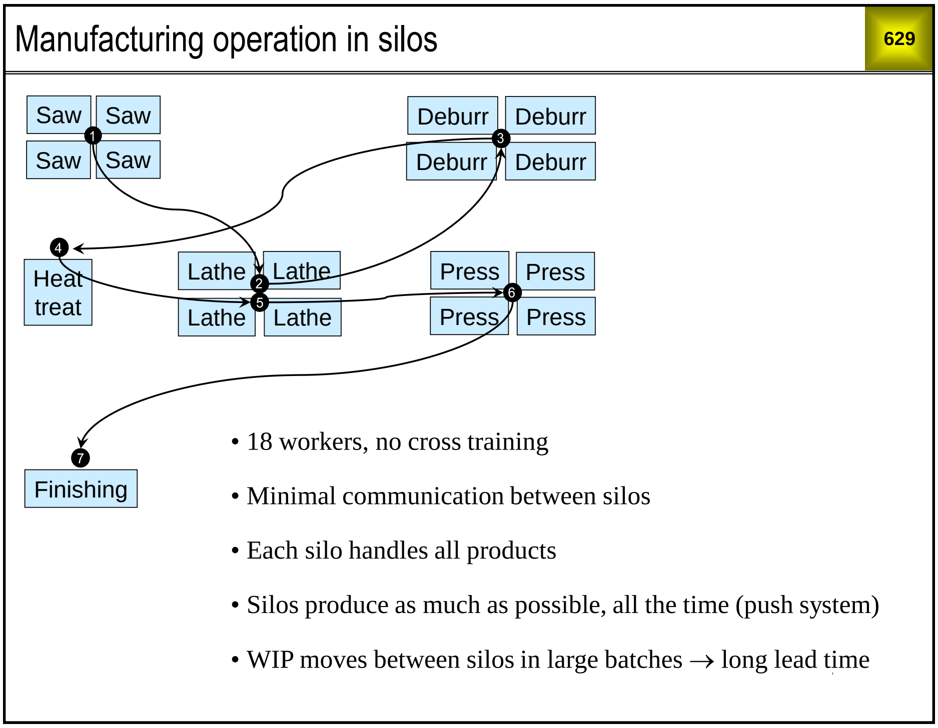
Organizing by value stream (cont'd)

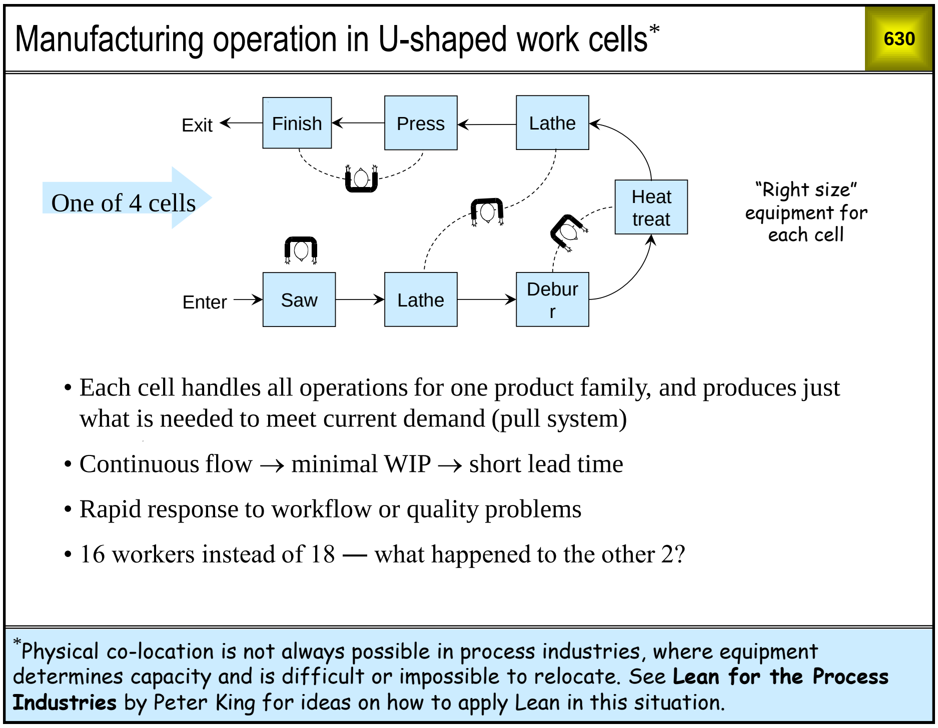


- Responsible for entire value stream for a product/service "family"
- Physical co–location is ideal
- Alternative: "value stream team"
- Stand-up meetings: every day, shift, or other frequent interval
- Alternative: virtual meetings



Manufacturing operation in silos

- 18 workers, no cross training
- Minimal communication between silos
- Each silo handles all products
- Silos produce as much as possible, all the time (push system)
- WIP moves between silos in large batches → long lead time

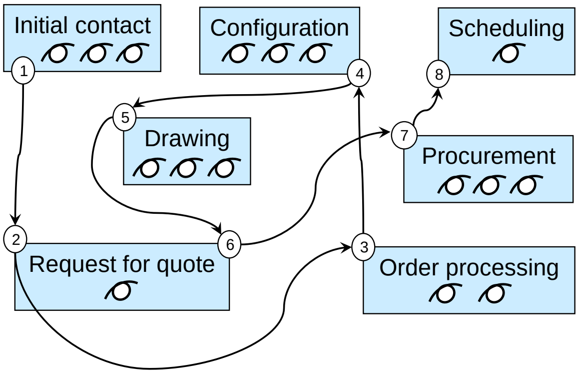


Manufacturing operation in U-shaped work cells*

- Each cell handles all operations for one product family, and produces just what is needed to meet current demand (pull system)
- Continuous flow → minimal WIP → short lead time
- Rapid response to workflow or quality problems
- 16 workers instead of 18 — what happened to the other 2?

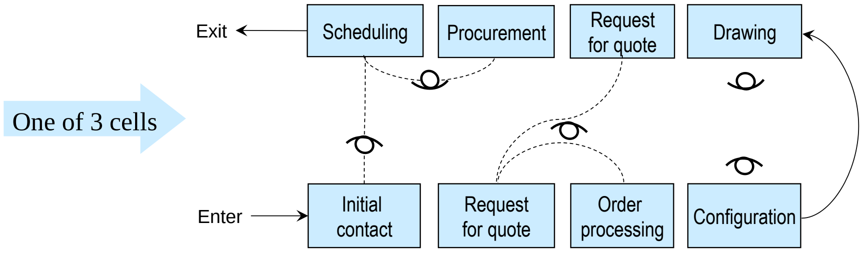
*Physical co-location is not always possible in process industries, where equipment determines capacity and is difficult or impossible to relocate. See **Lean for the Process Industries** by Peter King for ideas on how to apply Lean in this situation.

Transactional process in silos



- 16 workers (σ), no cross training
- Each silo handles all transactions
- Minimal communication between silos
- Lots of do overs (not shown in diagram)
- Lots of WIP → long turnaround time

Transactional process in U-shaped work cells



- Each cell handles all steps for one transaction family
- Continuous flow → minimal WIP→ short turnaround time
- Rapid response to errors or workflow problems
- 15 workers instead of 16 — what happened to the other one?

Definitions

Available Working Time (AWT)	• The time a process is available to conduct work • AWT excludes time when work isn't occurring such as time for breaks, meetings, lunch, preventative maintenance, estimates of unplanned downtime, change overs, etc.
Throughput (Tput)	• The average number of good parts or transactions completed over a period of time • Typically measured as average over at least several days • Throughput, lead time, and inventory are related through Little's Law

Definitions (cont'd)

Lead time (LT)	• The total elapsed time to produce one defect free product or transaction • The time difference between when a part or transaction enters and leaves a process
Customer Demand Rate (CDR)	• The number of parts or transactions that the customer desires over a period of time (usually a day, week, or month)

Definitions (cont'd)

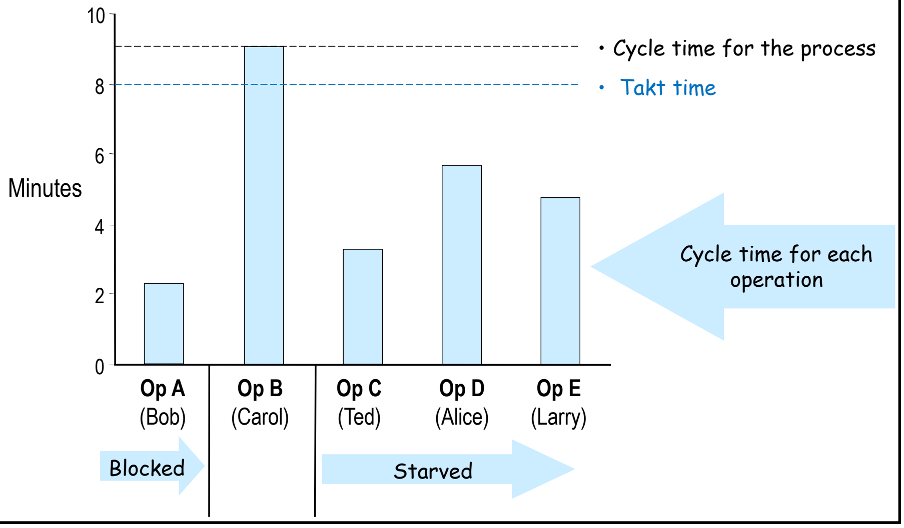
Takt time (TT)	• The pace at which an operation should complete products or transactions in order to meet customer demand during the Available Working Time. • Available working time during a period divided by the number of products or transactions *required* during that same period
Cycle time (CT)	• The fastest repeatable time between part or transaction completions using the current processes and resources • Shows how a process is capable of performing • Combines with AWT to determine capacity

Definitions (cont'd)

Process Cycle Efficiency (PCE)	• The percentage of time that WIP is being transformed by VA activities. In other words, the percentage of lead time that is value added.
Work In Progress (WIP)	• Includes items waiting to be worked on and items actively being worked on. WIP includes all of the inventory in the production system.

Work balancing

- Cycle time for a process = cycle time for the *slowest* operation
- This process is unable to meet the customer’s needs



Work balancing (cont’d)

- Operation A can complete 1 part every 2.2 minutes, operation B can complete 1 part every 9 minutes
- If A runs at full capacity, its output will pile up in front of B
- Common example of waste: overproduction

- Operations C, D, and E can produce faster than B, but their capacity cannot be utilized
- They can complete parts only as fast as B supplies them
- Cycle time for C, D, and E is 9 minutes
- Cycle time for the process is 9 minutes

Improving work balance by adding resources

- Add a second resource (Moe) to operation B
- Together, Carol and Moe can complete 2 parts or transactions every 9 minutes
- New cycle time for operation B is 9 ÷ 2 = 4.5 mins (see next slide)
- New cycle time for the process is 5.8 mins (process time for operation D)

Effect of multiple resources on cycle time

- Remember: the lead time is the time interval between units leaving a process.
- If a resource processes only one unit at a time, then the cycle time for that resource equals the lead time.
- Suppose the cycle time for one resource (machine or person) is 6 minutes and 4 workers (or machines) perform this task.
- Collectively, they can complete 4 parts or transactions every 6 minutes
- Their cycle time is:

(6 mins) / (4 parts or transactions) = 1.5 mins

- Similarly, if a machine processes a batch of 4 parts every 6 minutes, the cycle time is 1.5 minutes.

Effect of multiple resources on cycle time (cont'd)

- For a conveyorized process, the cycle time is the time interval between units exiting the conveyor.
- Imagine a conveyorized wash process that runs at a speed such that parts are washed for 6 minutes. Given its length and conveyor speed, a part exits the machine every 1.5 minutes. Its cycle time is 1.5 minutes.
- If there were two identical wash processes in a production line, their combined cycle time would be 1.5/2 = 0.75 minutes = 45 sec.

Multiple resources (cont'd)

- In general:

Cycle time = (Cycle time of one resource) / (# Resources)

- Calculating number of resources required to meet customer demand:

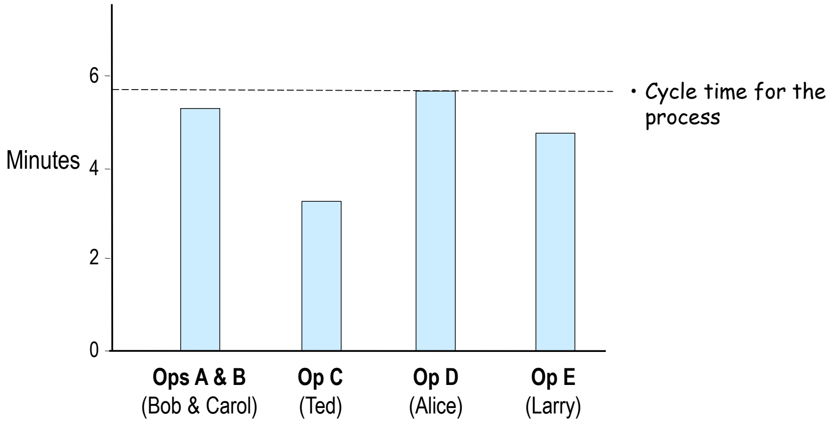
Resources needed = (Cycle time) / (Takt time)

Improving work balance by cross training

- Teach Bob how to do B, teach Carol how to do A, have them both do A & B
- Process time for A & B = 9.0 + 2.2 = 11.2
- New cycle time for A + B = 5.6 mins
- Cycle time is once again 5.8 mins, and we didn't have to add a resource
- Where is the next best opportunity for cross training?

Cross training (cont'd)

A more cost-effective way to meet customer demand.

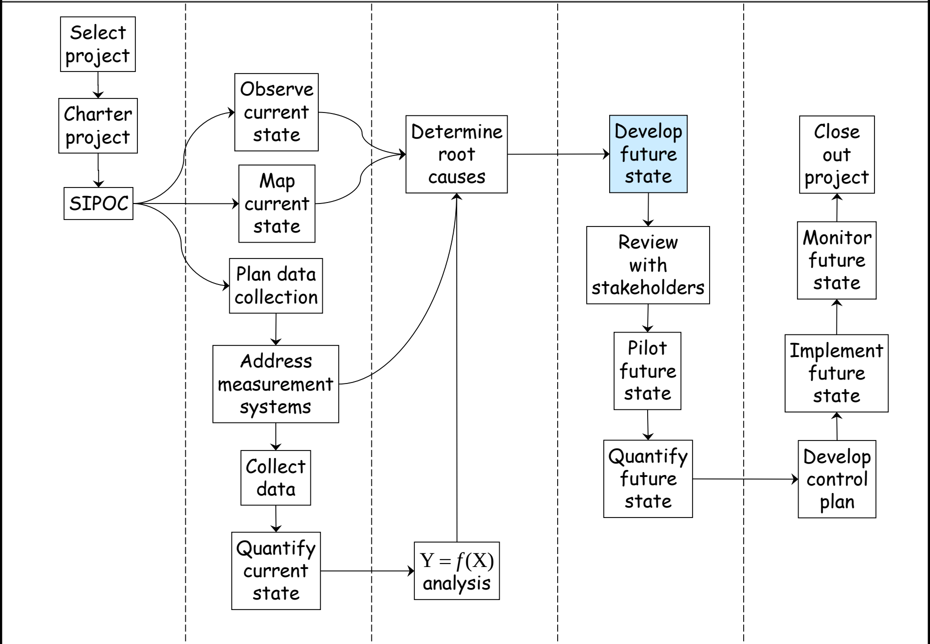


Exercise 32.1 Lean workshop

The Instructor will provide directions for this workshop.

Notes

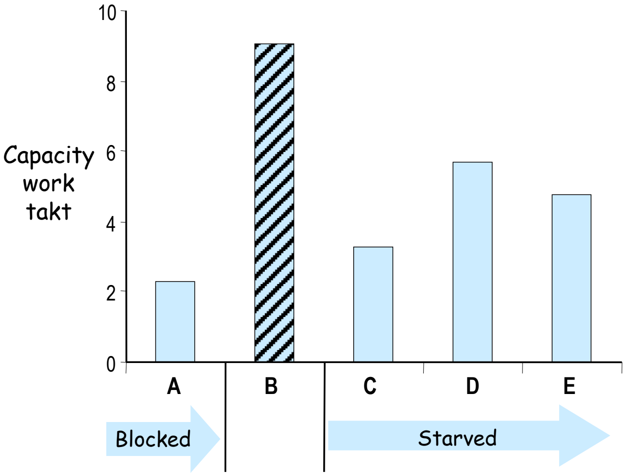
33 Theory of Constraints (TOC)



TOC (cont'd)

What if cross training is not feasible?

What if the bottleneck is machine capacity?

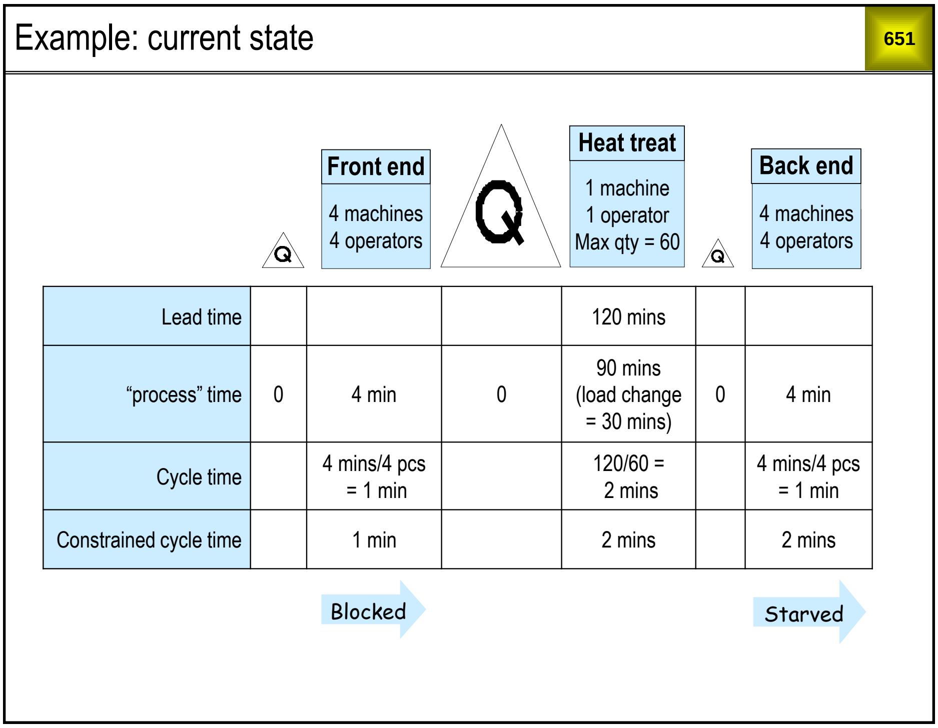


TOC (cont’d)

TOC improvement cycle	Lean terminology
1. *Identify* the system constraint (the “drum”)	Find the bottleneck (“pacemaker”)
2. *Exploit* the identified constraint (includes establishing the “buffer”)	• Move resources to the bottleneck • Minimize NVA at the bottleneck • Maintain needed level of “safety” WIP
3. *Subordinate* everything else to the constraint (establish the “rope”)	Pull system synchronized with the takt time of the bottleneck
4. *Elevate* the constraint	Add enough resources to eliminate the bottleneck
5. Return to step #1	Find the new bottleneck, repeat same steps

Ways to identify the constraint

- Greatest WIP
- Longest cycle time
- Longest process time
- Highest % utilization



Example: current state

Front end
4 machines
4 operators

Heat treat
1 machine
1 operator
Max qty = 60

Back end
4 machines
4 operators

Lead time				120 mins		
"process" time	0	4 min	0	90 mins (load change = 30 mins)	0	4 min
Cycle time		4 mins/4 pcs = 1 min		120/60 = 2 mins		4 mins/4 pcs = 1 min
Constrained cycle time		1 min		2 mins		2 mins

Blocked

Starved

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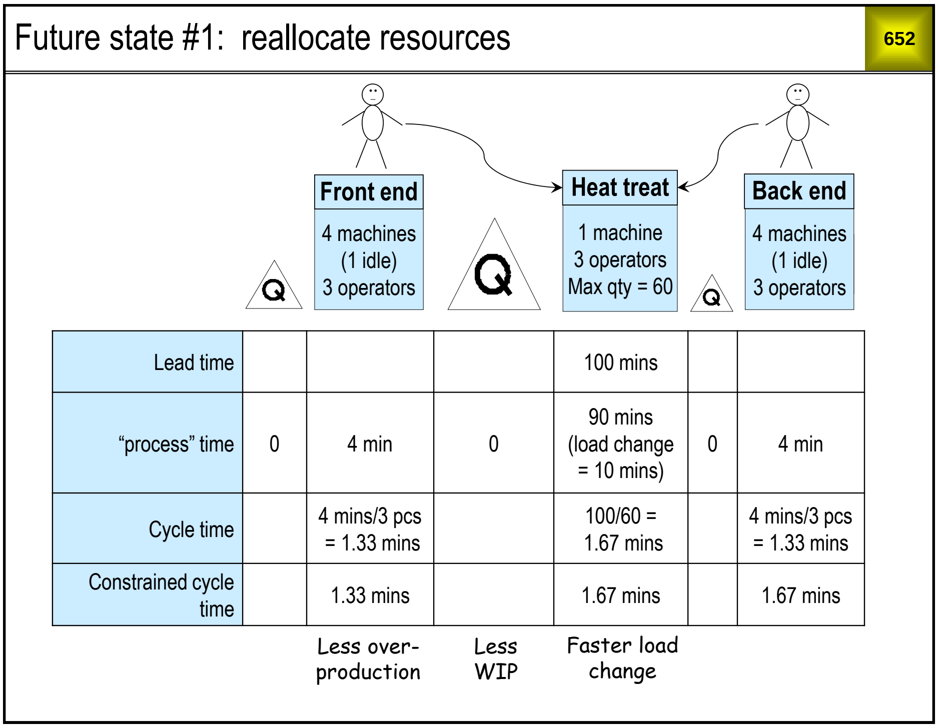

Future state #1: reallocate resources

Front end
4 machines
(1 idle)
3 operators

Heat treat
1 machine
3 operators
Max qty = 60

Back end
4 machines
(1 idle)
3 operators

Lead time				100 mins		
"process" time	0	4 min	0	90 mins (load change = 10 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		100/60 = 1.67 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.33 mins		1.67 mins		1.67 mins

Less over-production

Less WIP

Faster load change

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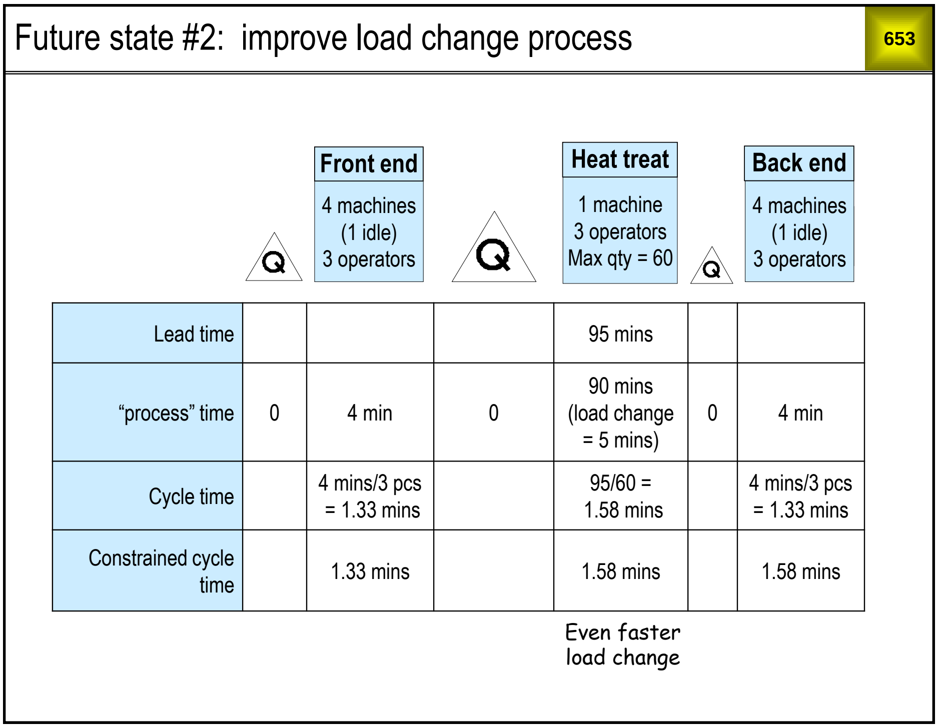

Future state #2: improve load change process

Front end
4 machines
(1 idle)
3 operators

Heat treat
1 machine
3 operators
Max qty = 60

Back end
4 machines
(1 idle)
3 operators

Lead time				95 mins		
"process" time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.33 mins		1.58 mins		1.58 mins

Even faster
load change

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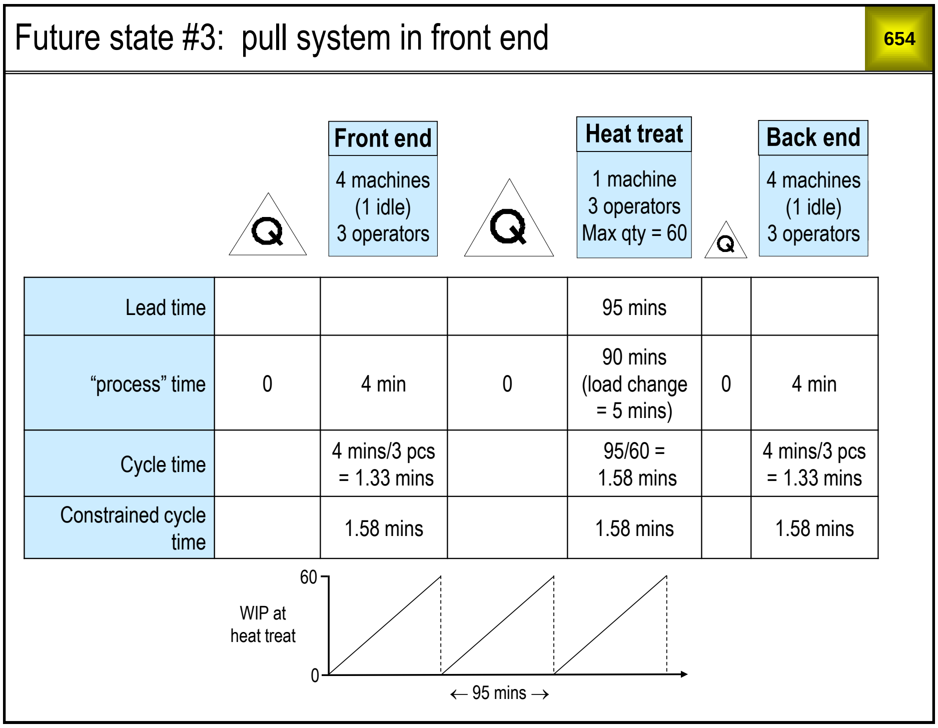

Future state #3: pull system in front end

Front end
4 machines
(1 idle)
3 operators

Heat treat
1 machine
3 operators
Max qty = 60

Back end
4 machines
(1 idle)
3 operators

Lead time				95 mins		
"process" time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.58 mins		1.58 mins		1.58 mins

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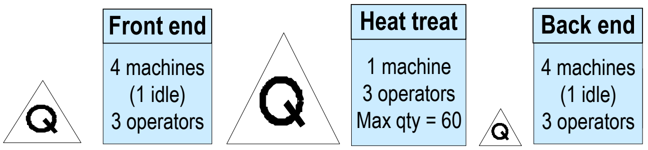
Future state #4: establish and maintain safety WIP

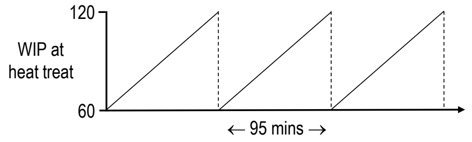


Front end
4 machines
(1 idle)
3 operators

Heat treat
1 machine
3 operators
Max qty = 60

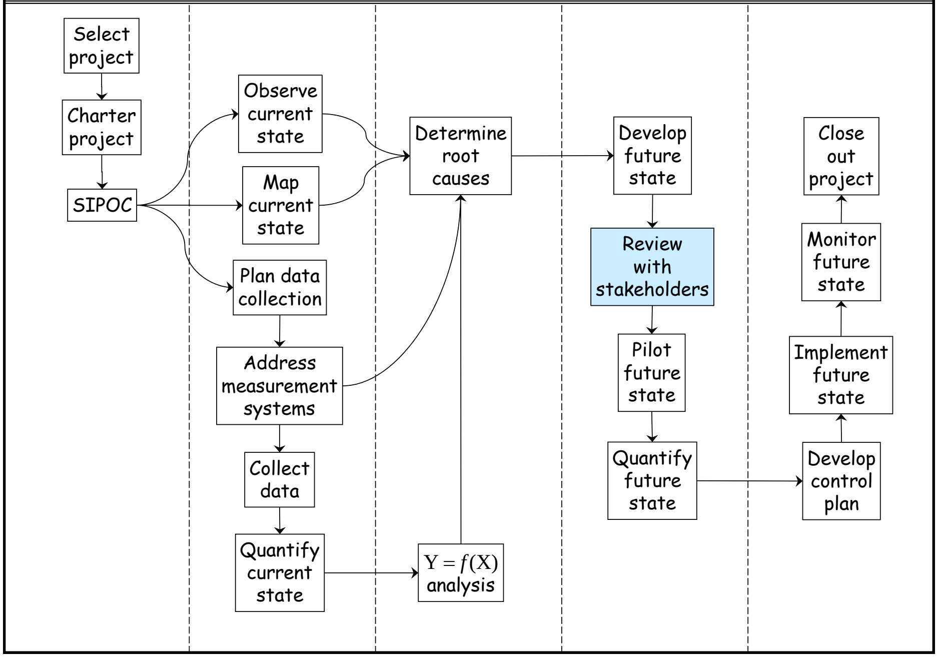
Back end
4 machines
(1 idle)
3 operators

Lead time				95 mins		
"process" time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.58 mins		1.58 mins		1.58 mins



Notes

34 Reviewing the Proposed Future State



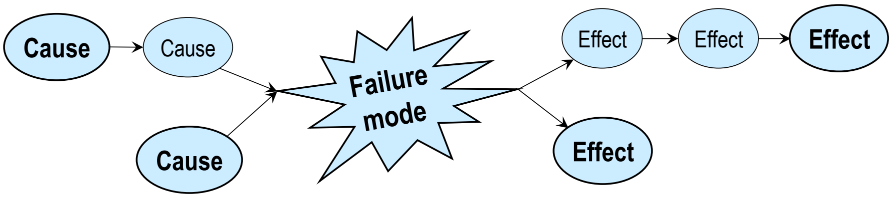
Select project
Charter project
SIPOC
Observe current state
Map current state
Plan data collection
Address measurement systems
Collect data
Quantify current state
Determine root causes
$Y = f(X)$ analysis
Develop future state
Review with stakeholders
Pilot future state
Quantify future state
Develop control plan
Implement future state
Monitor future state
Close out project

Reviewing the future state

- Use *Failure Modes and Effects Analysis* to identify problems (failure modes) that could occur in your new process and their impact (effects)
- Put things in place in the new process, to prevent or mitigate these failure modes, before they happen
- After you develop your proposed future state, the next step is to review it with stakeholders
  - Give them an opportunity to voice concerns or suggest enhancements prior to piloting
  - This can be an informal process of presentation and discussion

Failure Modes & Effects Analysis (FMEA)

1. Identify potential failure modes before deploying a new product, service, or process



3. Identify and prioritize root causes of potential failure modes

2. Identify and evaluate ultimate effects of potential failure modes

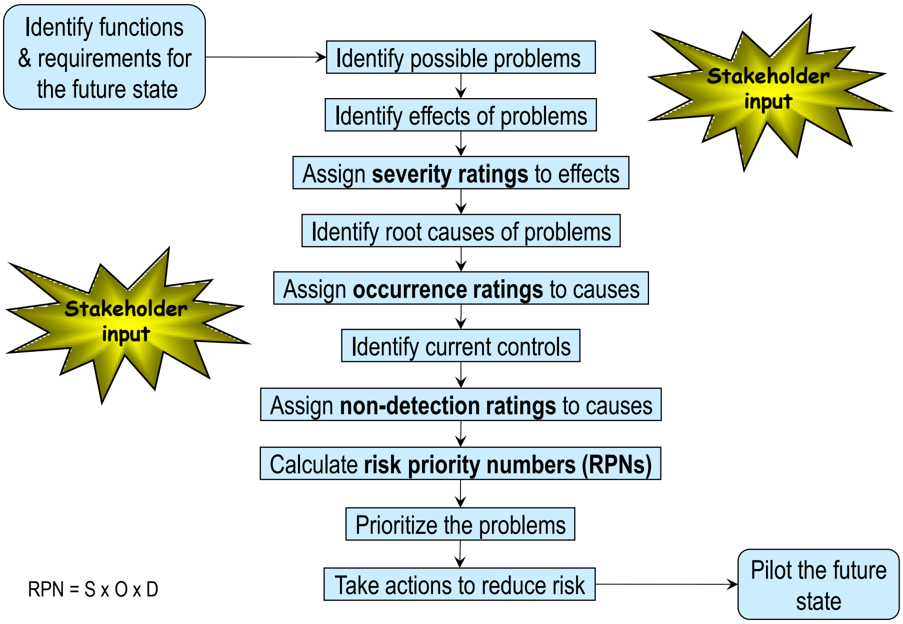
4. Identify and take corrective actions to eliminate or reduce the occurrence of root causes

---

The role of FMEA in a LSS project

- Identify and prioritize stakeholder concerns with the proposed future state
- Take appropriate corrective action prior to piloting the future state
- Use results to strengthen the control plan for the future state

Detailed FMEA process



Identify functions & requirements for the future state

Identify possible problems

Identify effects of problems

Assign **severity ratings** to effects

Identify root causes of problems

Assign **occurrence ratings** to causes

Identify current controls

Assign **non-detection ratings** to causes

Calculate **risk priority numbers (RPNs)**

Prioritize the problems

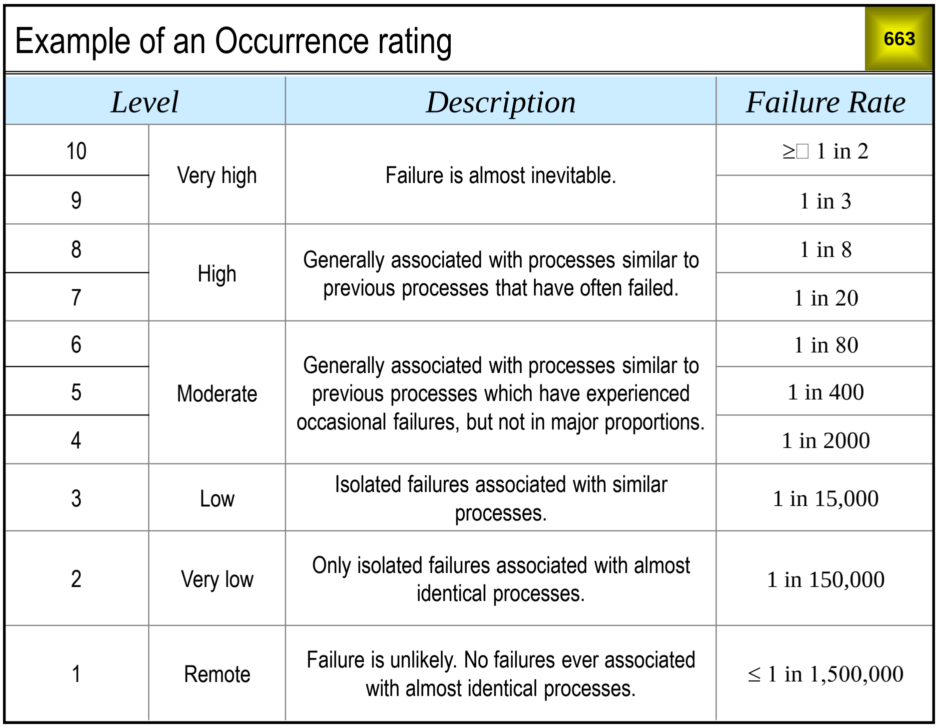
Take actions to reduce risk

Pilot the future state

RPN = S x O x D

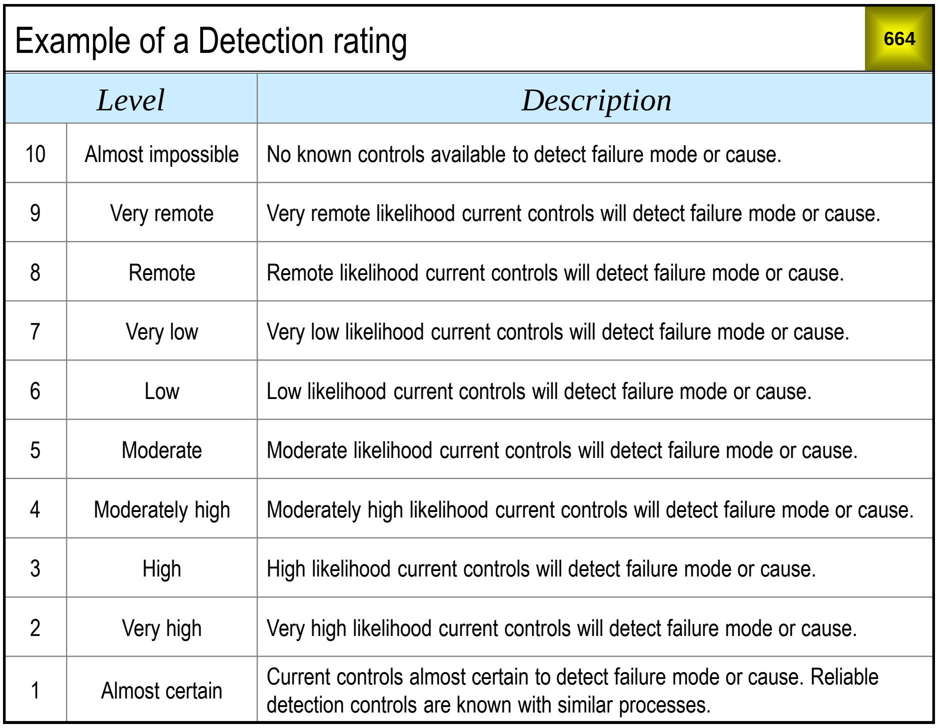
Example of a Severity rating

Level		*Description*
10	Hazardous, no warning	May endanger machine or assembly operator. Failure causes unsafe product operation or noncompliance with government regulation. Failure will occur without warning.
9	Hazardous, warning	May endanger machine or assembly operator. Failure causes unsafe product operation or noncompliance with government regulation. Failure will occur with warning.
8	Very high	Major disruption to production line. 100% of product may have to be scrapped. Product is inoperable with loss of Primary Function.
7	High	Minor disruption to production line. Product may have to be sorted and a portion scrapped. Product is operable but at a reduced level of performance.
6	Moderate	Minor disruption to production line. A portion of the product may have to be scrapped (no sorting). Product is operable but comfort or convenience item(s) are inoperable.
5	Low	Minor disruption to production line. 100% of the product may have to be reworked. Product is operable but comfort or convenience item(s) operate at a reduced level of performance.
4	Very low	Minor disruption to production line. Product may have to be sorted and a portion reworked. Fit/finish or squeak/rattle item does not conform. Most customers notice defect.
3	Minor	Minor disruption to production line. Some product may require rework on-line but out-of-station. Fit/finish or squeak/rattle item does not conform. Average customers notice defect.
2	Very minor	Minor disruption to production line. Some product may require rework on-line but in-station. Fit/finish or squeak/rattle item does not conform. Discriminating customers notice defect.
1	None	No effect.



Example of an Occurrence rating

Level		Description	Failure Rate
10	Very high	Failure is almost inevitable.	≥ 1 in 2
9			1 in 3
8	High	Generally associated with processes similar to previous processes that have often failed.	1 in 8
7			1 in 20
6	Moderate	Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions.	1 in 80
5			1 in 400
4			1 in 2000
3	Low	Isolated failures associated with similar processes.	1 in 15,000
2	Very low	Only isolated failures associated with almost identical processes.	1 in 150,000
1	Remote	Failure is unlikely. No failures ever associated with almost identical processes.	≤ 1 in 1,500,000



Example of a Detection rating

Level		Description
10	Almost impossible	No known controls available to detect failure mode or cause.
9	Very remote	Very remote likelihood current controls will detect failure mode or cause.
8	Remote	Remote likelihood current controls will detect failure mode or cause.
7	Very low	Very low likelihood current controls will detect failure mode or cause.
6	Low	Low likelihood current controls will detect failure mode or cause.
5	Moderate	Moderate likelihood current controls will detect failure mode or cause.
4	Moderately high	Moderately high likelihood current controls will detect failure mode or cause.
3	High	High likelihood current controls will detect failure mode or cause.
2	Very high	Very high likelihood current controls will detect failure mode or cause.
1	Almost certain	Current controls almost certain to detect failure mode or cause. Reliable detection controls are known with similar processes.

FMEA ratings

- The previous three slides give examples of traditional 1–10 ratings for severity, occurrence, and non–detection
- Note the detailed quantitative operational definitions
- Customers or regulatory agencies may require this level of detail
- For the application to LSS projects, qualitative 1–5 ratings are often sufficient:

1. Very low
2. Low
3. Moderate
4. High
5. Very high

Project example

Problem statement

Operations staff within the Gene Expression Lab (GEL) are experiencing frequent material stock outs while performing procedures. They have to stop processing samples until the missing material is delivered. This increases process cycle time and reduces the quality of the data deliverables. Other labs directly affected by this problem are:

- ✓ Tissue Homogenization
- ✓ Experiment Processing
- ✓ Sample Processing

Goal statement

- Reduce frequency of stock outs by 50%.
- Reduce time lost due to stock outs by 50%.

Constraint

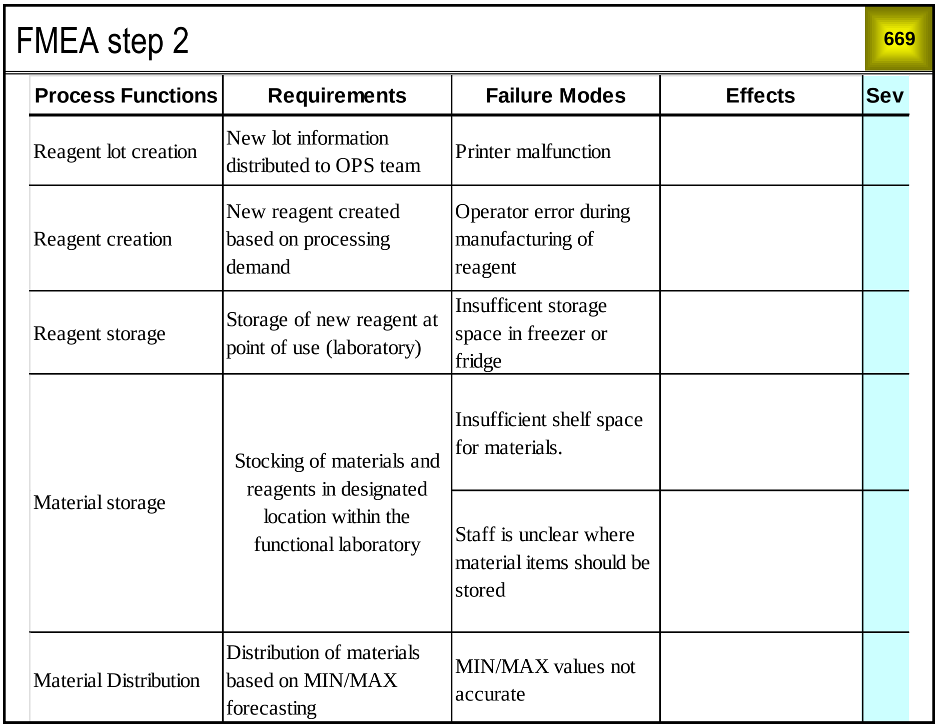
No increase in labor cost.

Current state data

Average daily number of stock outs	2.1
Average time to fill material requests	4 hrs
Annualized direct labor cost	$91,000

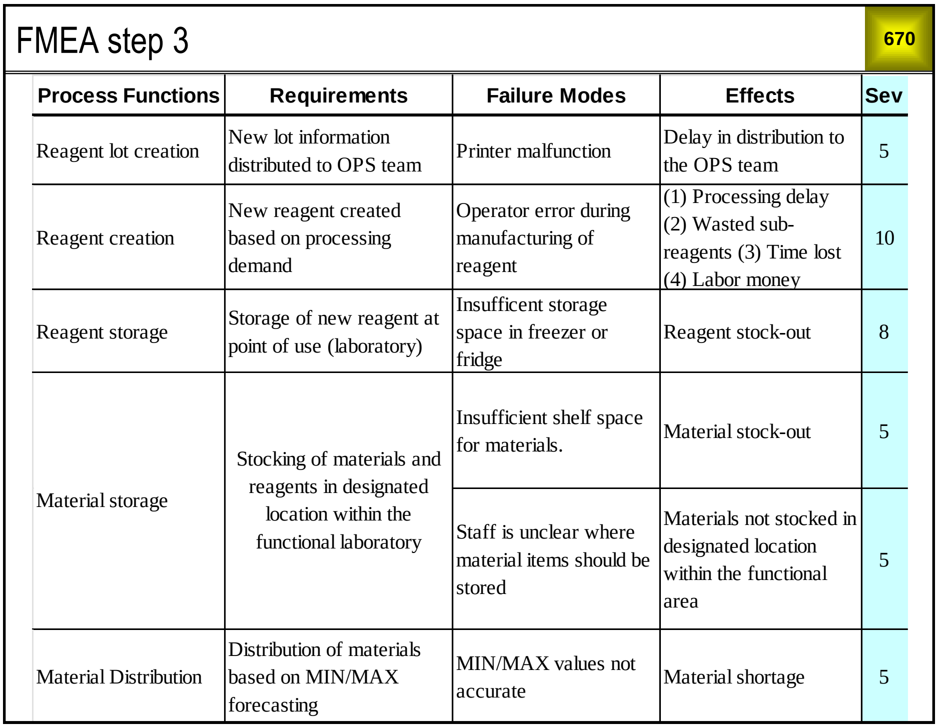
FMEA step 1 for Proposed Future State Process

Process Functions	Requirements	Failure Modes	Effects	Sev
Reagent lot creation	New lot information distributed to OPS team			
Reagent creation	New reagent created based on processing demand			
Reagent storage	Storage of new reagent at point of use (laboratory)			
Material storage	Stocking of materials and reagents in designated location within the functional laboratory			
Material Distribution	Replenishment of materials based on MIN/MAX values			



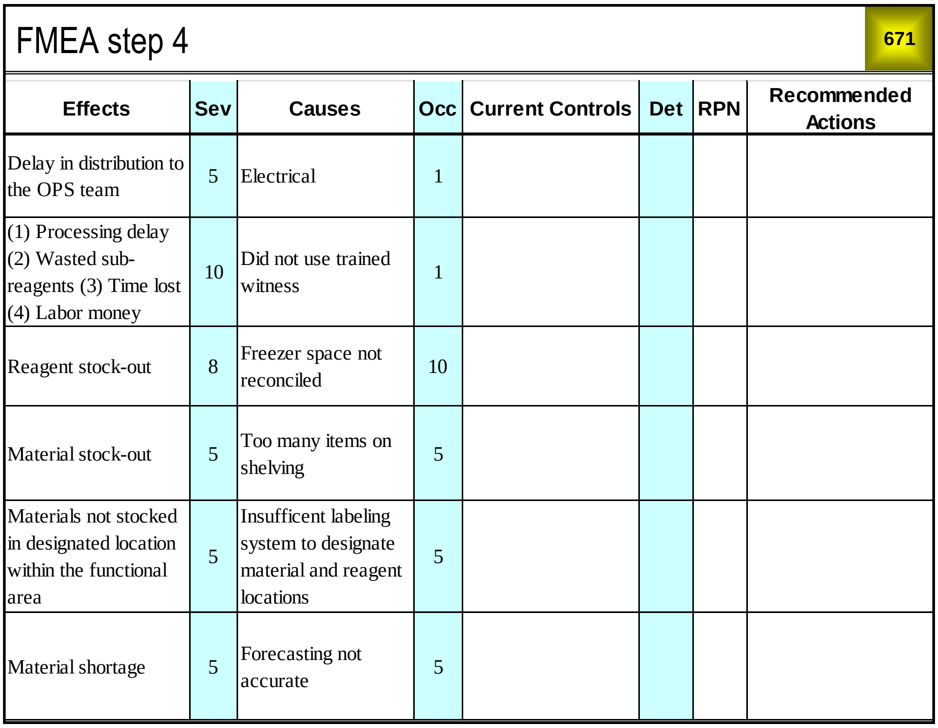
FMEA step 2

Process Functions	Requirements	Failure Modes	Effects	Sev
Reagent lot creation	New lot information distributed to OPS team	Printer malfunction		
Reagent creation	New reagent created based on processing demand	Operator error during manufacturing of reagent		
Reagent storage	Storage of new reagent at point of use (laboratory)	Insufficent storage space in freezer or fridge		
Material storage	Stocking of materials and reagents in designated location within the functional laboratory	Insufficient shelf space for materials.		
		Staff is unclear where material items should be stored		
Material Distribution	Distribution of materials based on MIN/MAX forecasting	MIN/MAX values not accurate		



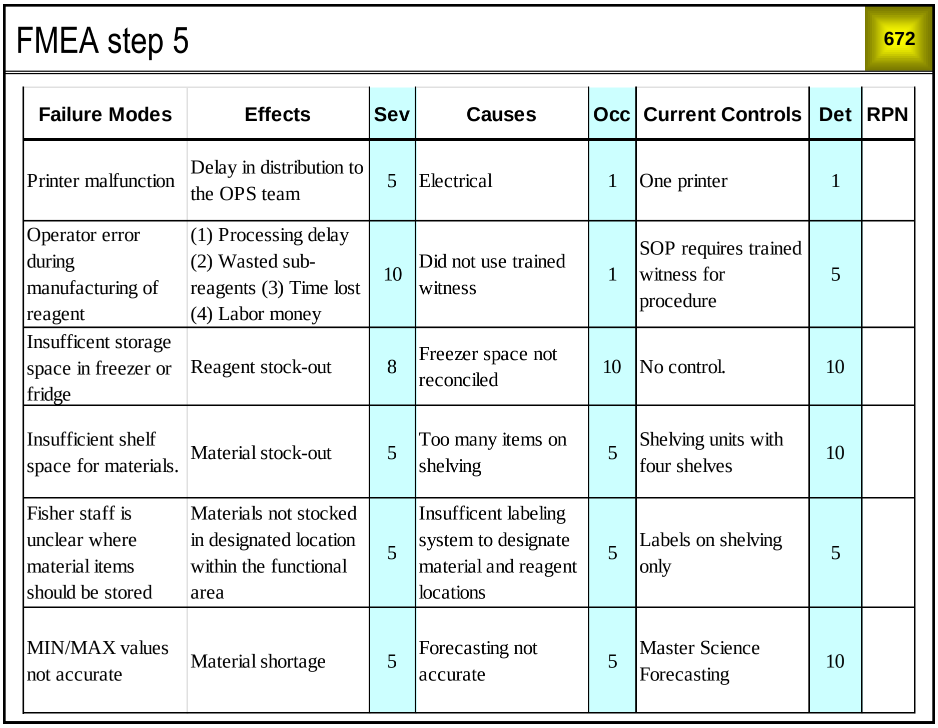
FMEA step 3

Process Functions	Requirements	Failure Modes	Effects	Sev
Reagent lot creation	New lot information distributed to OPS team	Printer malfunction	Delay in distribution to the OPS team	5
Reagent creation	New reagent created based on processing demand	Operator error during manufacturing of reagent	(1) Processing delay (2) Wasted sub-reagents (3) Time lost (4) Labor money	10
Reagent storage	Storage of new reagent at point of use (laboratory)	Insufficent storage space in freezer or fridge	Reagent stock-out	8
Material storage	Stocking of materials and reagents in designated location within the functional laboratory	Insufficient shelf space for materials.	Material stock-out	5
		Staff is unclear where material items should be stored	Materials not stocked in designated location within the functional area	5
Material Distribution	Distribution of materials based on MIN/MAX forecasting	MIN/MAX values not accurate	Material shortage	5



FMEA step 4

Effects	Sev	Causes	Occ	Current Controls	Det	RPN	Recommended Actions
Delay in distribution to the OPS team	5	Electrical	1				
(1) Processing delay (2) Wasted sub-reagents (3) Time lost (4) Labor money	10	Did not use trained witness	1				
Reagent stock-out	8	Freezer space not reconciled	10				
Material stock-out	5	Too many items on shelving	5				
Materials not stocked in designated location within the functional area	5	Insufficent labeling system to designate material and reagent locations	5				
Material shortage	5	Forecasting not accurate	5				



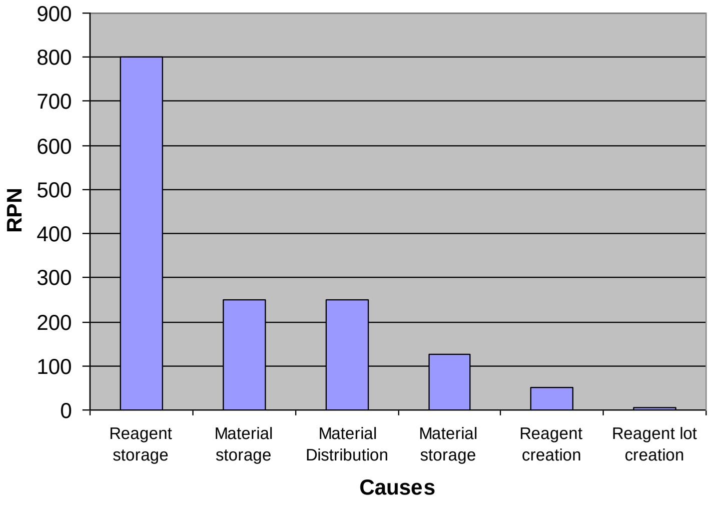
FMEA step 5

Failure Modes	Effects	Sev	Causes	Occ	Current Controls	Det	RPN
Printer malfunction	Delay in distribution to the OPS team	5	Electrical	1	One printer	1	
Operator error during manufacturing of reagent	(1) Processing delay (2) Wasted sub-reagents (3) Time lost (4) Labor money	10	Did not use trained witness	1	SOP requires trained witness for procedure	5	
Insuffiicent storage space in freezer or fridge	Reagent stock-out	8	Freezer space not reconciled	10	No control.	10	
Insufficient shelf space for materials.	Material stock-out	5	Too many items on shelving	5	Shelving units with four shelves	10	
Fisher staff is unclear where material items should be stored	Materials not stocked in designated location within the functional area	5	Insufficent labeling system to designate material and reagent locations	5	Labels on shelving only	5	
MIN/MAX values not accurate	Material shortage	5	Forecasting not accurate	5	Master Science Forecasting	10	

FMEA step 6

Effects	Sev	Causes	Occ	Current Controls	Det	RPN	Recommended Actions
Delay in distribution to the OPS team	5	Electrical	1	One printer	1	5	
(1) Processing delay (2) Wasted sub-reagents (3) Time lost (4) Labor money	10	Did not use trained witness	1	SOP requires trained witness for procedure	5	50	
Reagent stock-out	8	Freezer space not reconciled	10	No control.	10	800	
Material stock-out	5	Too many items on shelving	5	Shelving units with four shelves	10	250	
Materials not stocked in designated location within the functional area	5	Insufficent labeling system to designate material and reagent locations	5	Labels on shelving only	5	125	
Material shortage	5	Forecasting not accurate	5	Master Science Forecasting	10	250	

Pareto of causes by RPN



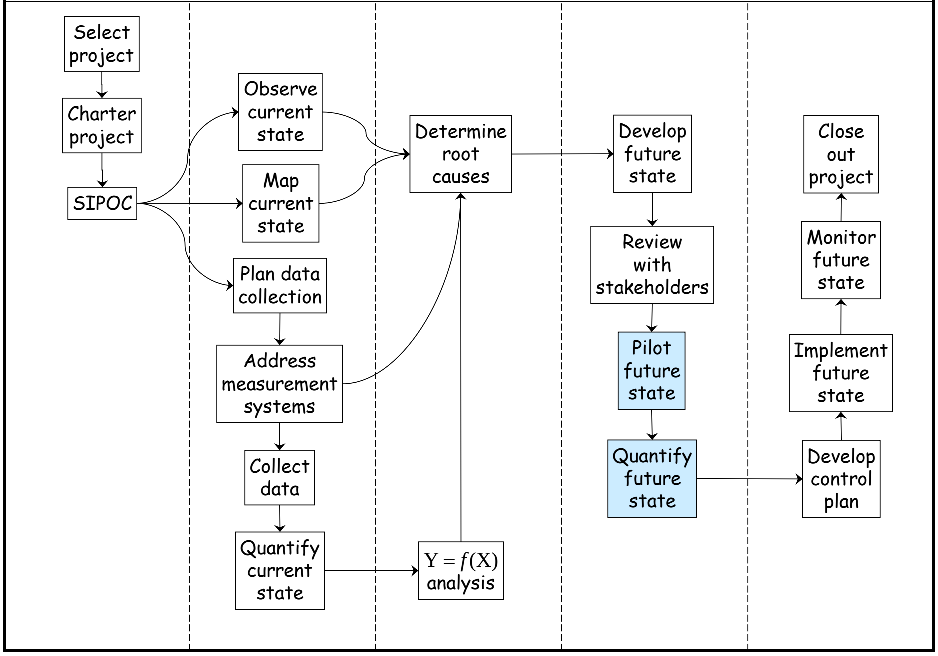
FMEA step 7

Effects	Sev	Causes	Occ	Current Controls	Det	RPN	Recommended Actions
Delay in distribution to the OPS team	5	Electrical	1	One printer	1	5	Install back-up printer
(1) Processing delay (2) Wasted sub-reagents (3) Time lost (4) Labor money	10	Did not use trained witness	1	SOP requires trained witness for procedure	5	50	No further action required
Reagent stock-out	8	Freezer space not reconciled	10	No control.	10	800	Frequent consolidation of freezer inventory
Material stock-out	5	Too many items on shelving	5	Shelving units with four shelves	10	250	Add more shelves to accommodate additional materials
Materials not stocked in designated location within the functional area	5	Insufficent labeling system to designate material and reagent locations	5	Labels on shelving only	5	125	Place labels on freezer canes and fridge shelves to designate locations
Material shortage	5	Forecasting not accurate	5	Master Science Forecasting	10	250	Review MIN/MAX values quarterly for frequently used materials

Results from pilot data

	Current state	Future state	Reduction
Average daily number of stock outs	2.1	0.02	99%
Average time to fill mat’l requests	4 hrs	2.3 hrs	42%
Annualized direct labor cost	$91,000	$1,000	99%

35 Piloting the Future State



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Piloting the future state

- Small scale implementation under close observation
- Scope should be limited*
- Time period should be relatively short

*We try to scope LSS projects into manageable chunks. Because of this, the pilot scope may sometimes be the same as the project scope.

Benefits of piloting

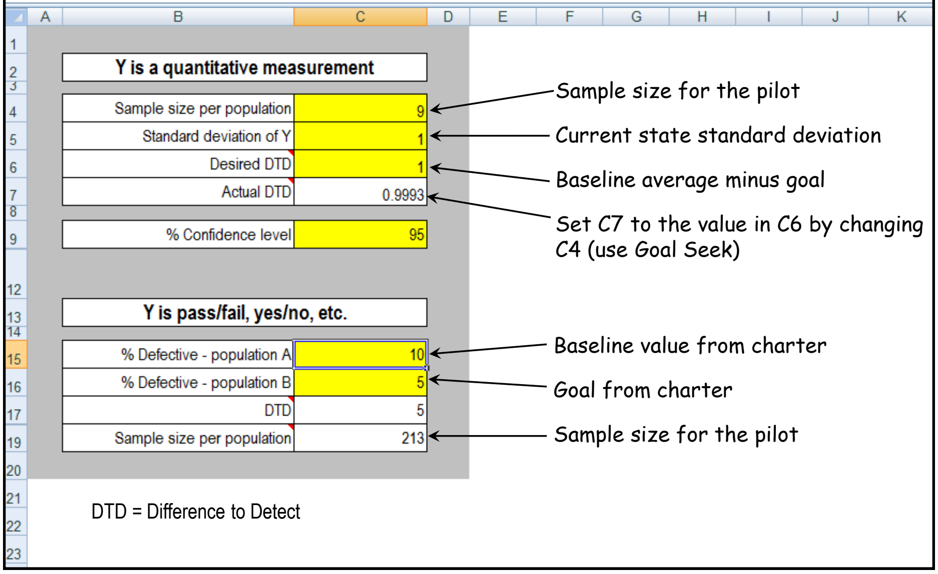
- Identify unanticipated failure modes
- Identify unintended consequences
- Indicates whether or not improvement objectives will be met
- Reduces problems in full scale implementation

Piloting checklist

- ☐ What is the scope? (Location, work area, product, customer, duration, . . .)
- ☐ Who are the participants? (Process owner, process participants, stakeholders, team members, . . .)
- ☐ What data is to be collected? (Y variables and project metrics should be same as in Define and Measure phases.)
- ☐ What measurement systems will be used? (These may have been improved during the project.)
- ☐ What is the sampling plan and sample size necessary to represent typical variation sources?
- ☐ Have we communicated plans to all concerned parties?

Sample size calculation for a pilot study

Student Files → calculator - sample size → Comparisons



Y is a quantitative measurement

Sample size per population	9
Standard deviation of Y	1
Desired DTD	1
Actual DTD	0.9993
% Confidence level	95

Y is pass/fail, yes/no, etc.

% Defective - population A	10
% Defective - population B	5
DTD	5
Sample size per population	213

DTD = Difference to Detect

Sample size for the pilot

Current state standard deviation

Baseline average minus goal

Set C7 to the value in C6 by changing C4 (use Goal Seek)

Baseline value from charter

Goal from charter

Sample size for the pilot

Example: quotation process pilot study

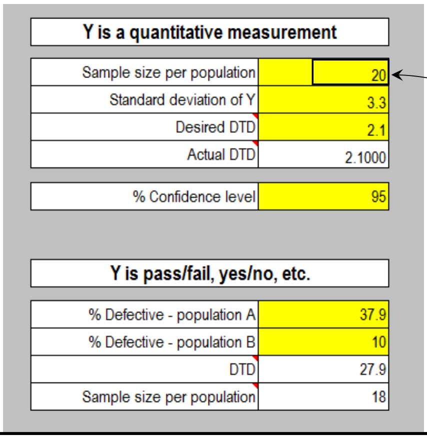
Scope of the pilot: Business Unit 8

Metric	Baseline (BU 8)	Goal
Average TAT	3.6 days	1.5 days
TAT > 3	37.9%	10%

Std Dev = 3.3 days

DTD = 2.1 days

If you have more than one statistical metric, you must use the largest of the calculated sample sizes



Y is a quantitative measurement

Sample size per population	20
Standard deviation of Y	3.3
Desired DTD	2.1
Actual DTD	2.1000
% Confidence level	95

Y is pass/fail, yes/no, etc.

% Defective - population A	37.9
% Defective - population B	10
DTD	27.9
Sample size per population	18

Sample size for the pilot should be at least 20

Exercise 35.1

Use the information given below to calculate the sample size for each metric for the MBDP pilot.

Metric	Baseline	Goal	DTD	Sample Size (n)
Average PO-PD*	29.5 days	50% reduction		
% PO-PD > 30	38.7%	50% reduction		
% MFG not happy	49.4%	50% reduction		

*Std Dev of PO-PD = 19.5 days

Analyzing pilot results

- Collect observations — what worked, what didn't
- Statistical comparison of "before" and "after"
- Evaluate improved project metrics relative to goals
- Establish new statistical baselines
  - They will form the basis for statistical monitoring after implementation

Exercise 35.2

Open *Data Sets* → *MBDP current* & *future pilot*.

a) Test for a significant improvement in average PO–PD. Give the P value and its interpretation in terms of standards of evidence.

b) Did we achieve our goal of 50% reduction for average PO–PD?

c) (Optional) Create a line chart showing the change in PO–PD from the current state to the future state pilot. (Include lines showing the two averages.)

d) Test for a significant improvement in % PO–PD > 30. Give the P value and its interpretation in terms of standards of evidence.

Exercise 35.2 (cont'd)

e) Did we achieve our goal of 50% reduction for % PO–PD > 30?

f) Test for a significant improvement in % MFG not happy. Give the P value and its interpretation in terms of standards of evidence.

g) Did we achieve our goal of 50% reduction for % MFG not happy?

Exercise 35.3

Open *Data Sets* → *quotation process current & future pilot*.

a) Test for a significant improvement in average TAT. Give the P value and its interpretation in terms of standards of evidence.

b) Did we achieve our goal of 1.5 days for average TAT?

c) Optional: Create a line chart showing the change in TAT from the current state to the future state pilot. (Include lines showing the two averages.)

Exercise 35.3 (cont'd)

d) Test for a significant improvement in % TAT > 3. Give the P value and its interpretation in terms of standards of evidence.

e) Did we achieve our goal of reducing % TAT > 3 to 10%?

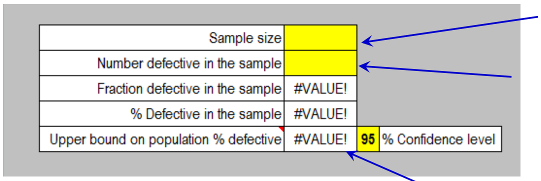
f) Test for a significant improvement in the PO hit rate. Give the P value and its interpretation in terms of standards of evidence.

Margin of Error (MOE) calculation for a pilot study

- In Module 16 Data Collection, we explored the concept of the Margin of Error (MOE) and how to use it to calculate a sample size to estimate Current State population baselines for project metrics.
- We learned that the more precisely we wanted to estimate an overall percent defective or average, the more we had to “spend” in sample size.
- When we are analyzing results from a Future State pilot study, the resulting P value will be affected by the sample size.
  - ➢ If we get a P value of 0.05 or less, we have strong evidence of a difference. In this case, it may be helpful to get a prediction of how high an overall defect rate could go, or an upper and lower bound on the average for the Future State process.
  - ➢ If we get a P value of greater than 0.05, i.e., some or no evidence of a difference, and we suspect we didn’t “spend” enough on our sample size, it could be helpful to get a prediction of whether a larger sample size would have made a difference.
- The *Student Files→ calculator – margin of error* will give us these boundaries.

MOE calculation for a pilot study — Pass/Fail Y

Student Files→ calculator – margin of error → % Defective



Sample size			
Number defective in the sample			
Fraction defective in the sample	#VALUE!		
% Defective in the sample	#VALUE!		
Upper bound on population % defective	#VALUE!	95	% Confidence level

Sample size for the pilot of Future State

Result from the pilot of Future State

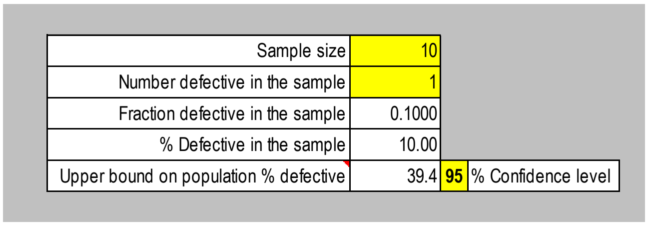
Worst case prediction (with 95% confidence) of the Future State % defective

Example: pilot study MOE calculation — Pass/Fail

Reference Exercise 27.6: Is there a significant reduction in % defective?

Open *Student Files→ calculator – margin of error → % Defective*

	Sample size	No. defective	% Defective
Current state	500	147	29.4%
Future state pilot	10	1	10.0%



Sample size	10		
Number defective in the sample	1		
Fraction defective in the sample	0.1000		
% Defective in the sample	10.00		
Upper bound on population % defective	39.4	95	% Confidence level

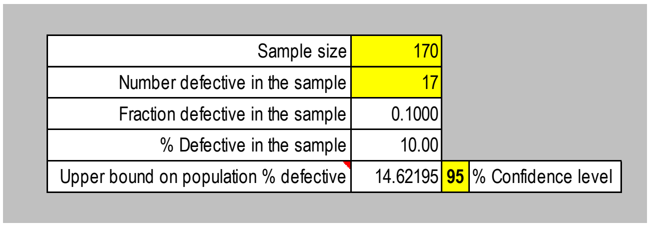
In Exercise 27.7, p = 0.18 — no evidence of difference. A higher upper bound on the future state % defective than the current state baseline is another way of saying there is no evidence of difference. However, we noted the fact of the small sample size for the pilot.

Example: pilot MOE calculation — Pass/Fail (cont'd)

Reference Exercise 27.6: Is there a significant reduction in % defective?

Student Files→ calculator – margin of error → % Defective

- We can use the *calculator – margin of error* to make some predictions of what would happen if a larger sample size with the same defect rate were used.

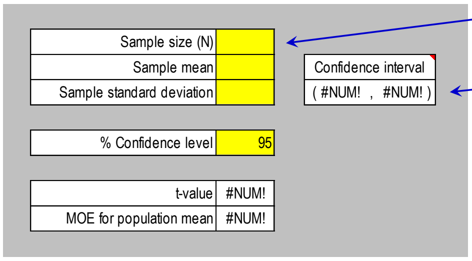


Sample size	170		
Number defective in the sample	17		
Fraction defective in the sample	0.1000		
% Defective in the sample	10.00		
Upper bound on population % defective	14.62195	95	% Confidence level

- An upper bound of 14.6% overall defective sounds a lot better than the current average of 29.4%.
- It may be worth collecting more samples for the Future State process before giving up on the proposed improvements.

MOE calculation for a pilot study — Quantitative Y

Open *Student Files→ calculator – margin of error → Pop. mean of quant.Y*



Sample size (N)	
Sample mean	
Sample standard deviation	
% Confidence level	95
t-value	#NUM!
MOE for population mean	#NUM!

Confidence interval
(#NUM! , #NUM!)

Sample size, mean and std. dev. for the pilot of Future State

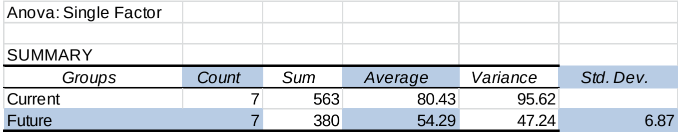
Predicted 95% confidence interval on the population mean (range within which the *center* of the population distribution would fall).

Using the MOE calculator is a way to be a careful consumer of data. In addition to the P value, it helps us evaluate whether the significant difference is worth the cost to implement it by giving us a "confidence interval" on the benefit.

Example: pilot study MOE calculation — Quantitative Y

Reference Exercise 27.8: *Data Sets → lead time*. Is there a significant reduction in lead time?

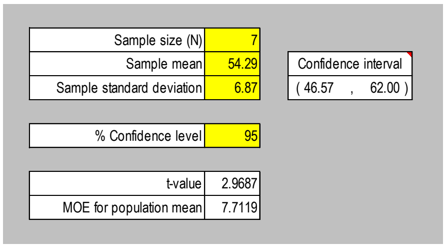
Student Files→ calculator – margin of error → Pop. mean of quant.Y



Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance	Std. Dev.
Current	7	563	80.43	95.62	
Future	7	380	54.29	47.24	6.87

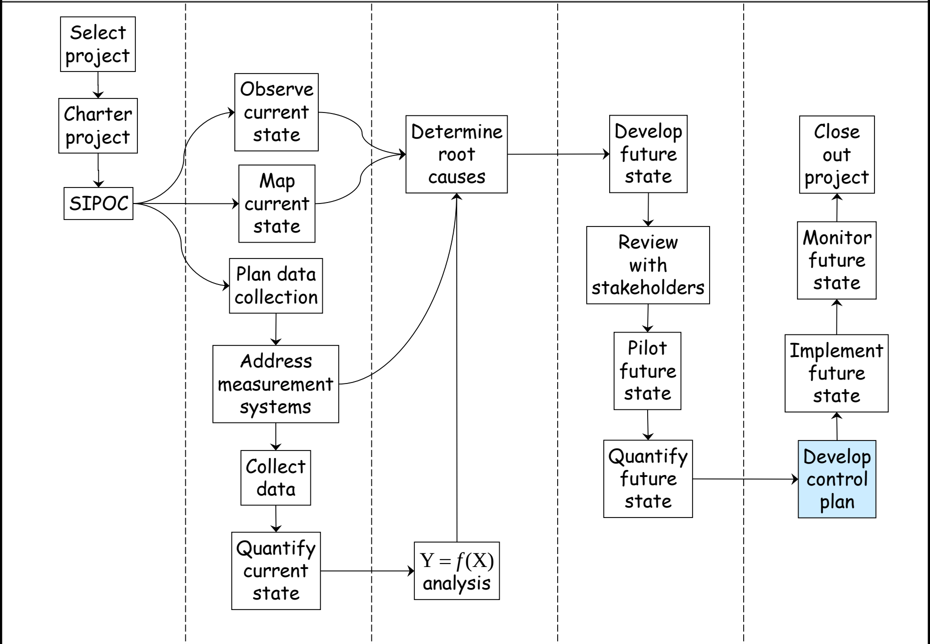


Sample size (N)	7
Sample mean	54.29
Sample standard deviation	6.87
% Confidence level	95
t-value	2.9687
MOE for population mean	7.7119

Confidence interval
(46.57 , 62.00)

In Exercise 27.9, p = 0 — very strong evidence of a difference. The MOE on the average lead time gives us an upper bound of 62 days, much lower than the Current State average of 80.4!

36 Control Plan



What is a control plan?

- A summary of the plan to sustain the gains from a LSS project
- The project team helps the in–scope process owner and participants develop the plan
- Project team advises the in–scope process owner and participants on statistical monitoring issues
- Most common control methods: training, auditing, control chart
- Most common control chart quantities: *individual measurements*, *averages*, and *percentages*

Student Files → blank control plan

Process name:

Process owner:

Revision date:

Process step	Control method	Frequency	Data variable	Meas. system	Metric to monitor	Control limits		Response plan owner	Response plan location
						Lower	Upper		

Student Files → tool development control plan

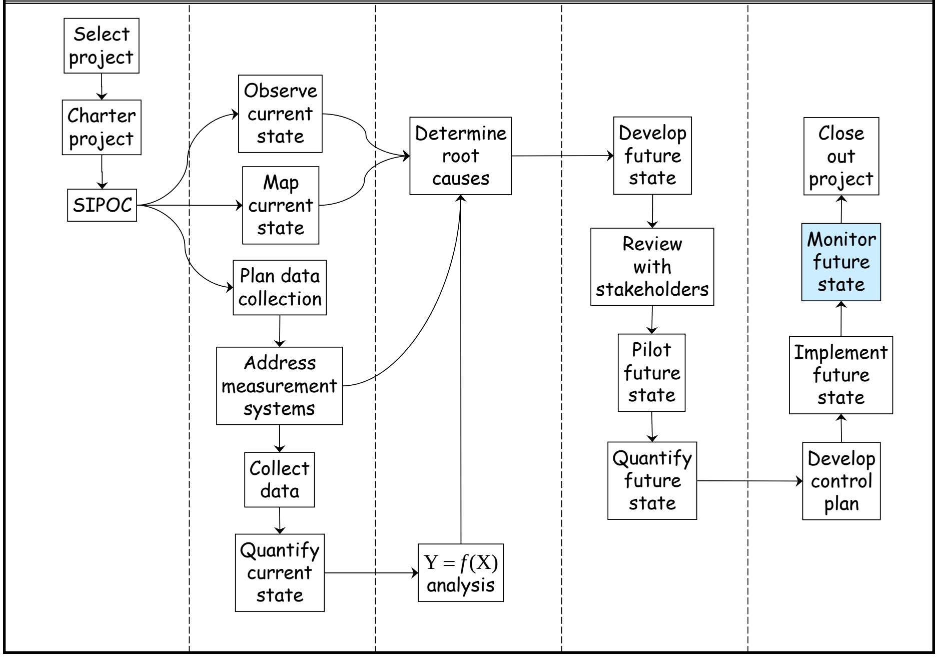
Process name: Tool Testing Process

Process owner: Testing Area Manager

Revision date:

Process step	Control method	Frequency	Data variable	Meas. system	Metric to monitor	Control limits		Response plan owner	Response plan location
						Lower	Upper		
Determine run conditions	Audit compliance with new procedure requiring special approval to change weight or line speed	Monthly, then Quarterly	Run conditions						
Determine run conditions	Disable weight and line speed controls on test line								
Release to manufacturing	Control chart	Weekly	Number of days in testing	Database	Average		TBD	Testing area manager	TBD
Release to manufacturing	Control chart	Weekly	Number of rework cycles	Database	Average		TBD	Testing area manager	TBD
Dimensional inspection	Install DVT gage and train testers to use it								
Dimensional inspection	Periodic gage R&R	TBD	Spec dimensions	DVT	% of Tolerance		TBD	Testing Engineer	TBD

37 Statistical Monitoring



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Statistical monitoring[*]

- Two kinds of variation
- Quantifying common cause variation
- Establishing control limits
- Commonly used control charts
- Interpreting control charts
- Response plans
- Relationship to Process Capability

[*] The more commonly used term is Statistical Process Control (SPC), even though it has nothing to do with "control" in the usual sense.

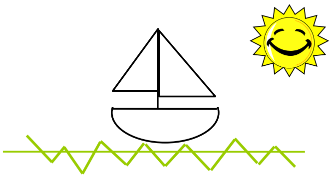
Exercise 37.1

a) Sign your name five times in the space provided below.

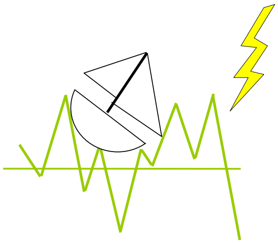
b) Put your pencil or pen into the other hand. Sign your name once in the space provided below.

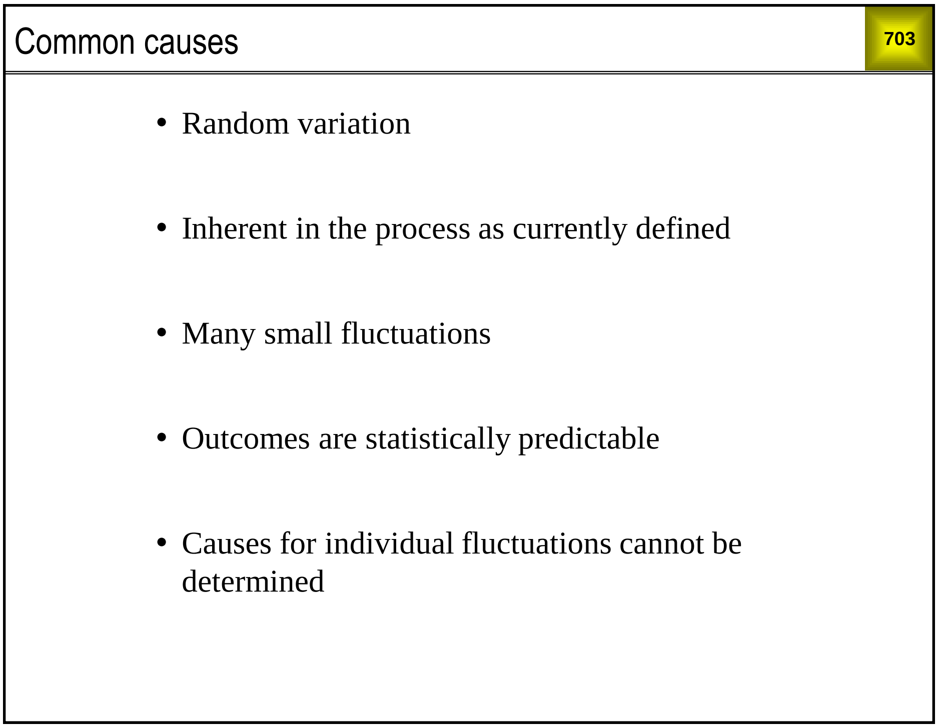
Two kinds of variation

Variation due to *common causes*



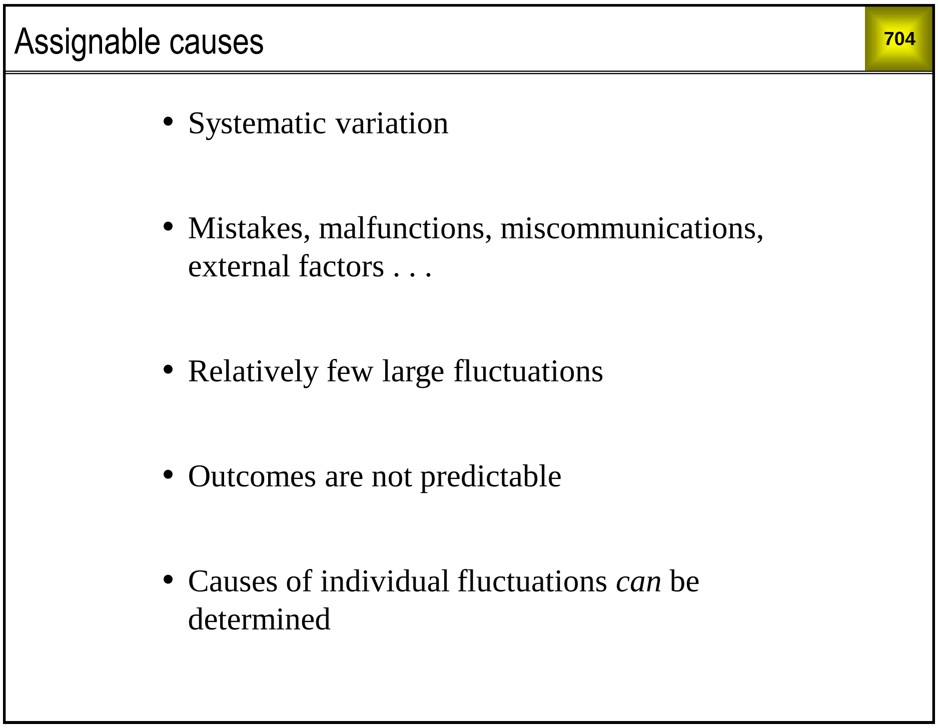
Variation due to *assignable causes*





Common causes

- Random variation
- Inherent in the process as currently defined
- Many small fluctuations
- Outcomes are statistically predictable
- Causes for individual fluctuations cannot be determined



Assignable causes

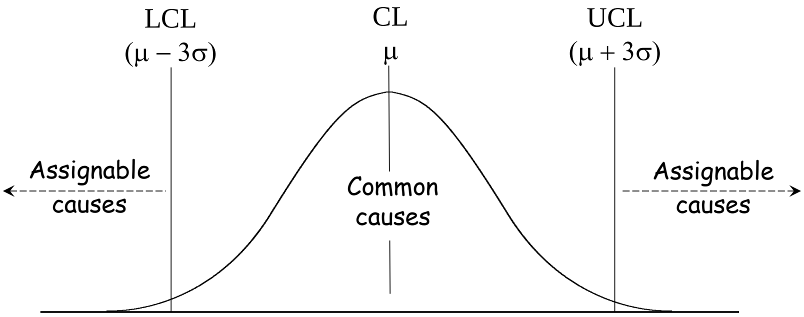
- Systematic variation
- Mistakes, malfunctions, miscommunications, external factors . . .
- Relatively few large fluctuations
- Outcomes are not predictable
- Causes of individual fluctuations *can* be determined

Quantifying common cause variation

- Common cause variation is usually represented by upper and lower *control limits*
- Upper control limit (UCL) = $\mu + 3\sigma$
- Lower control limit (LCL) = $\mu - 3\sigma$
- These are also called *three-sigma limits*
- Center Line (CL) = μ

Common cause variation (cont'd)

Control limits provide an *operational definition*
of common cause variation

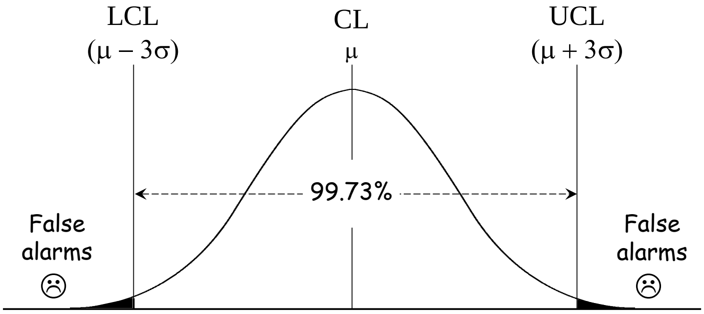


Baseline variation in the quantity to be monitored

μ = average
σ = standard deviation

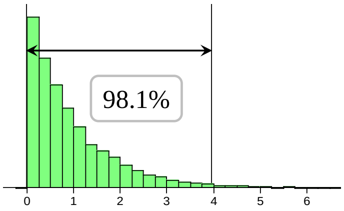
Common cause variation (cont'd)

If the quantity to be monitored follows a Normal distribution, the chance of a *false alarm* is 0.27%

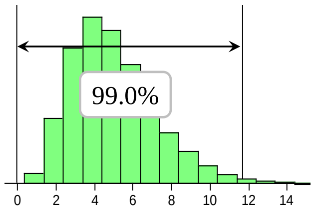


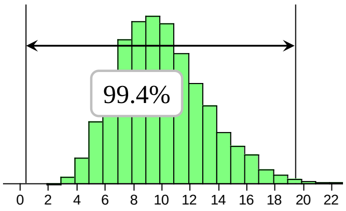
Baseline variation in the quantity to be monitored

Common cause variation (cont'd)



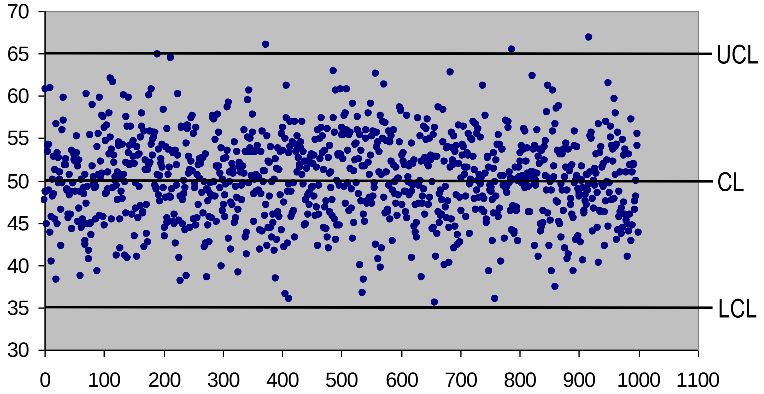
- 3σ limits are shown for three non–Normal distributions
- Data doesn't need to be Normally distributed for most charts
- The *Central Limit Theorem* also greatly reduces the effect of non-Normality when samples are used
- 3σ limits are an economic compromise between *false alarms* and *missed signals*





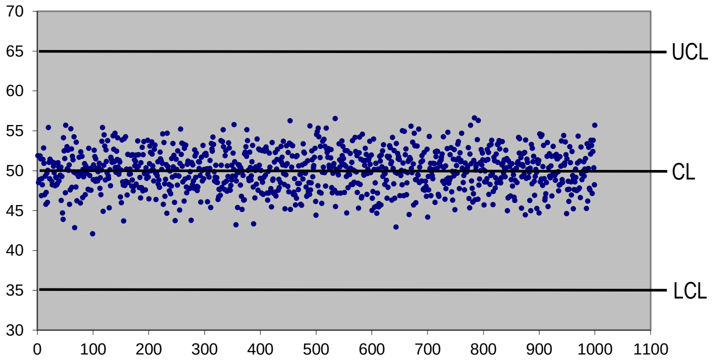
Behavior of Averages: the “Central Limit” effect

Individual data values sampled from a population
with $\mu = 50$ and $\sigma = 5$



Behavior of Averages: the “Central Limit” effect (cont’d)

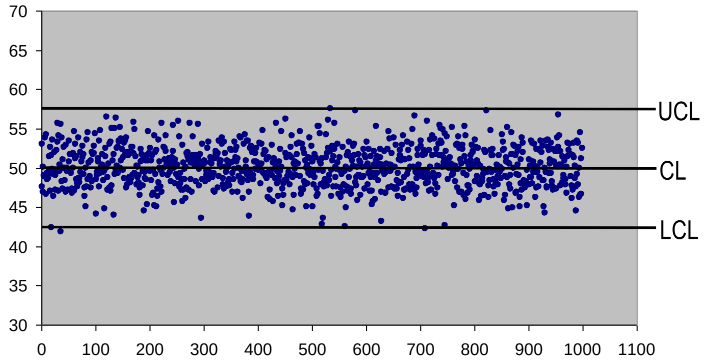
Averages of 4 data values sampled from the same population
with $\mu = 50$ and $\sigma = 5$



- Why would the limits shown above be ineffective for statistical monitoring of the averages?
- Control limits for a distribution of averages must be calculated a different way.

Behavior of Averages: the “Central Limit” effect (cont’d)

Averages of 4 data values sampled from the same population
with $\mu = 50$ and $\sigma = 5$



- These are the true control limits for the averages.
- In addition to the obvious narrowing of the distribution, the Central Limit Theorem (stated simply), concludes that subgroup averages converge to a Normal distribution, even if the underlying distribution is non-Normal.

The Standard Deviation of Averages

If we repeatedly sample sets of N individual data
values from a population with mean μ and
standard deviation σ, and calculate
the average in each case, the
standard deviation of
the averages is:

$$\boxed{\frac{\sigma}{\sqrt{N}}}$$

Control Limits for Averages

If we repeatedly sample sets of N individual data
values from a population with mean μ and
standard deviation σ, and calculate
the average in each case, the
three-sigma limits for
the averages are:

$$\text{UCL} = \mu + 3\frac{\sigma}{\sqrt{\text{N}}}$$

$$\text{LCL} = \mu - 3\frac{\sigma}{\sqrt{\text{N}}}$$

Establishing Control Limits

- Control Limits are calculated using data *representative* of day-to-day process operation
- The exact calculation for three sigma limits depends on the type of control chart being used
- The type of control chart used depends on the type of data and the sampling method
- At least 20 – 25 sample subgroups should be used to set control limits
- Data from a pilot run can be used to set control limits for the “future state” process, if the pilot is representative of the process that will be implemented.
  - If not, run the “future state” process long enough to gather a sufficient sample.

Control limits are *not* the same as specification limits!

Sampling for control charts

To detect process shifts, we need to take a *reasonable* sample of the process.

- Samples should estimate, or try to represent, the population.
- Samples need to be taken in the order of production and as soon as possible in an operation to get an early warning of defects.
- The chance of variation from assignable causes should be *minimized within* an individual sample set (pull parts for a sample close together in time).
- The chance of variation from assignable causes should be *maximized between* samples (time separation between samples).
- Pulling subgroups of parts at a predetermined interval works best.
  - Do not pre-identify which parts will form the SPC sample before they are manufactured (avoid bias).
  - Do not adjust the process during sampling.

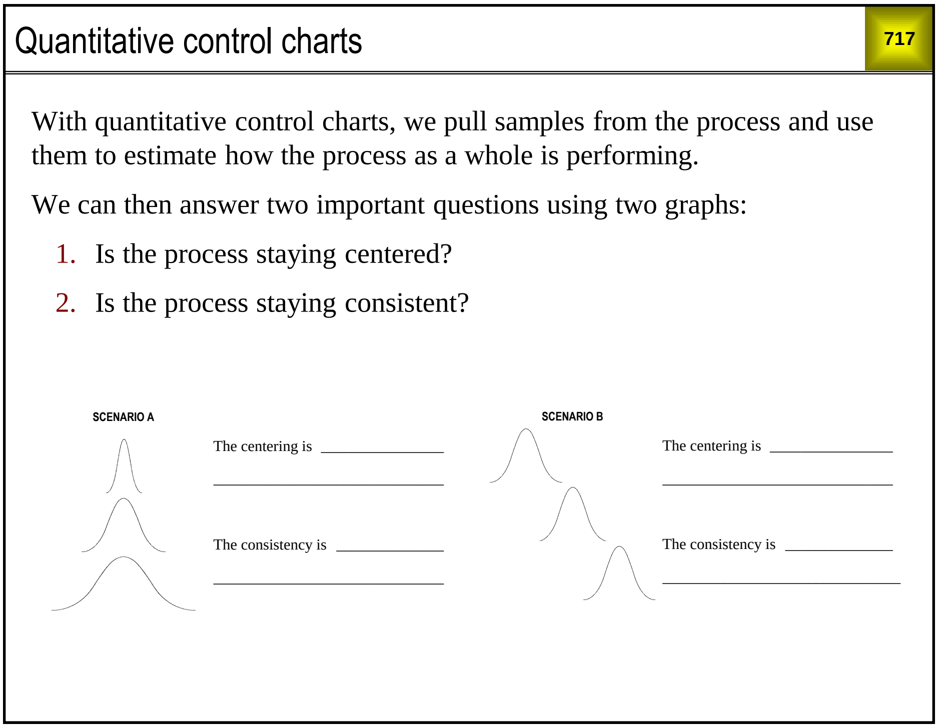
Common Shewhart control charts

Quantitative measurement:

- $\overline{X}$ & s (sample average and standard deviation)
- $\overline{X}$ & R (sample average and range)
- IX and MR (individual values and moving range

Categorical classification:

- p (fraction defective)



Quantitative control charts

With quantitative control charts, we pull samples from the process and use them to estimate how the process as a whole is performing.

We can then answer two important questions using two graphs:

1. Is the process staying centered?
2. Is the process staying consistent?

The centering is ________________

____

The consistency is ______________

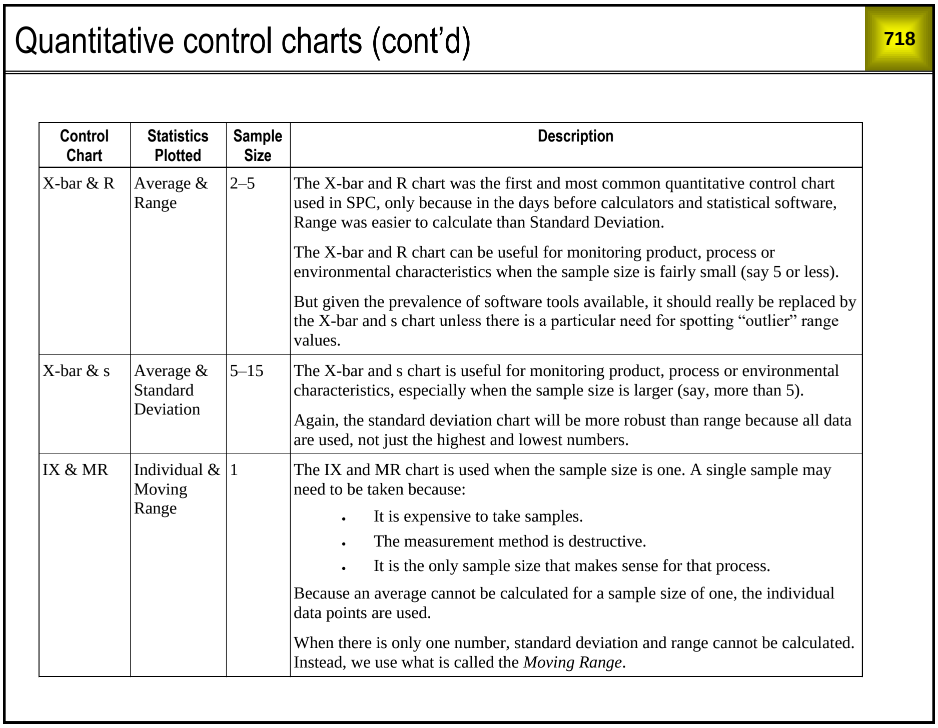
____

The centering is ________________

____

The consistency is ______________

____

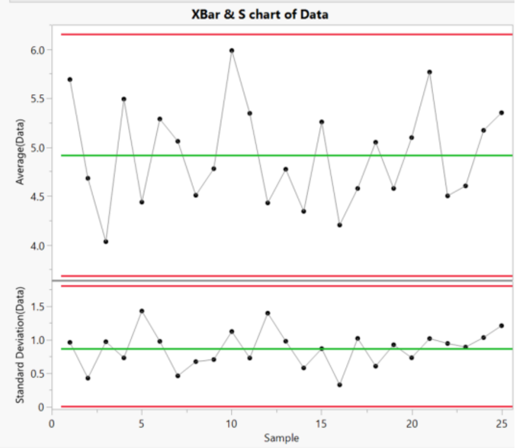


Quantitative control charts (cont'd)

Control Chart	Statistics Plotted	Sample Size	Description
X-bar & R	Average & Range	2–5	The X-bar and R chart was the first and most common quantitative control chart used in SPC, only because in the days before calculators and statistical software, Range was easier to calculate than Standard Deviation. The X-bar and R chart can be useful for monitoring product, process or environmental characteristics when the sample size is fairly small (say 5 or less). But given the prevalence of software tools available, it should really be replaced by the X-bar and s chart unless there is a particular need for spotting "outlier" range values.
X-bar & s	Average & Standard Deviation	5–15	The X-bar and s chart is useful for monitoring product, process or environmental characteristics, especially when the sample size is larger (say, more than 5). Again, the standard deviation chart will be more robust than range because all data are used, not just the highest and lowest numbers.
IX & MR	Individual & Moving Range	1	The IX and MR chart is used when the sample size is one. A single sample may need to be taken because: • It is expensive to take samples. • The measurement method is destructive. • It is the only sample size that makes sense for that process. Because an average cannot be calculated for a sample size of one, the individual data points are used. When there is only one number, standard deviation and range cannot be calculated. Instead, we use what is called the *Moving Range*.

Example: $\overline{X}$ and s chart

For each sample, the average is plotted on the $\overline{X}$ chart (centering) and the standard deviation (consistency) is plotted below on the s chart.



JMP Output of $\overline{X}$s Chart of *control chart diameter*

Control limit calculations for X–bar and s charts

Monitoring frequency	*Metric to monitor*	*Statistic(s) Needed*	*Control limits*
Hourly Daily Weekly Monthly Quarterly etc.	*$\overline{X}$ chart:* Average	Average (μ)	$\text{UCL} = \mu + 3\frac{\sigma}{\sqrt{N}}$ $\text{CL} = \mu$ $\text{LCL} = \mu - 3\frac{\sigma}{\sqrt{N}}$
		Standard deviation (σ)	
	s chart: Standard Deviation	Standard deviation (σ)	$\text{UCL} = \bar{\sigma} + 3\frac{\sigma}{\sqrt{2(N-1)}}$ $\text{CL} = \bar{\sigma}$ $\text{LCL} = \bar{\sigma} - 3\frac{\sigma}{\sqrt{2(N-1)}}$

Exercise 37.2

We want to use $\overline{X}$ and s control charts to monitor a critical dimension, diameter, of the parts we are producing. Open *Data Sets → control chart diameter*. Does the baseline data appear to be adequate to represent process variation?
Use Excel formulas for the following:

a) Calculate the average ($\bar{x}$) and standard deviation (s) for each subgroup of five parts.

b) Calculate the overall average, which will be the center line (CL) of the $\bar{x}$ chart. There are two ways to do so: take the average of all the data points or take the average of the subgroup averages. The name given to the statistic from the second method is $\bar{\bar{X}}$ (X-double bar) or the Grand Average.

c) Calculate the average of the subgroup standard deviations, ($\bar{s}$), which will be the Center Line (CL) for the standard deviation chart.

Exercise 37.2 (cont'd)

d) The estimates of the standard deviation of the distribution of averages and the distribution of standard deviations have been calculated for you. They are used in the "3-sigma" quantities that are added to and subtracted from the Center Lines.

e) Use the numbers found above to calculate the upper and lower control limits for each chart.

$UCL_{\bar{x}} =$

$CL_{\bar{x}} =$

$LCL_{\bar{x}} =$

$UCL_{s} =$

$CL_{s} =$

$LCL_{s} =$

Control limits for X–bar and R charts

$\bar{X}$ Chart Control Limits:

$$UCL = \bar{\bar{x}} + A_2\bar{R}$$

$$CL = \bar{\bar{x}}$$

$$LCL = \bar{\bar{x}} - A_2\bar{R}$$

R Chart Control Limits:

$$UCL = \bar{R}D_4$$

$$CL = \bar{R}$$

$$LCL = \bar{R}D_3$$

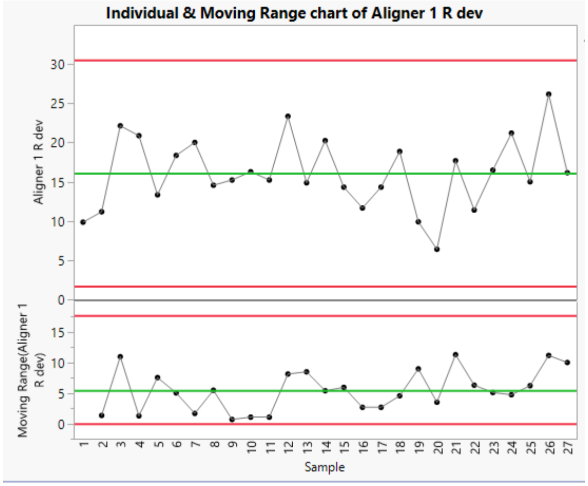
Constants for sample size n

n	A_2	D_3	D_4	d_2
2	1.880	0.000	3.267	1.128
3	1.023	0.000	2.574	1.693
4	0.729	0.000	2.282	2.059
5	0.577	0.000	2.114	2.326
6	0.483	0.000	2.004	2.534
7	0.419	0.076	1.924	2.704
8	0.373	0.136	1.864	2.847
9	0.377	0.184	1.816	2.97
10	0.308	0.223	1.777	3.078

From Introduction to Statistical Quality Control by Douglas C. Montgomery

Example: Individual and Moving Range chart

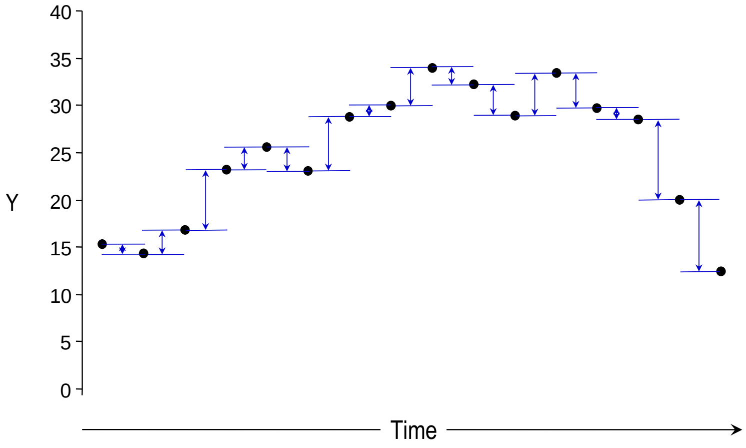
For each unit, the measurement is plotted on the Individual chart and the Moving Range is plotted below.



Why is the first point missing on the MR chart?

Estimating standard deviation using the moving range method

Each moving range is the absolute value of the difference between consecutive data points.



Control limit calculations for Individual and Moving Range chart

Individual Chart Control Limits:

$$\mathrm{UCL} = \bar{x} + 3\frac{\overline{\mathrm{MR}}}{d_2}$$

$$\mathrm{CL} = \bar{x} \qquad\qquad \mathrm{MR} = |x_i - x_{i-1}|$$

$$\mathrm{LCL} = \bar{x} - 3\frac{\overline{\mathrm{MR}}}{d_2}$$

The value of d_2 is 1.128 since the range is between two consecutive points.

Moving Range Chart Control Limits:

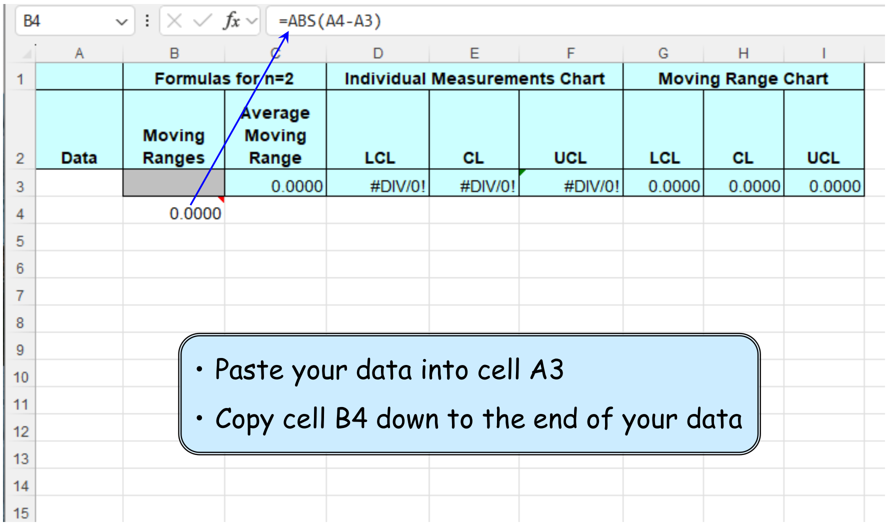
$$\mathrm{UCL} = D_4\overline{\mathrm{MR}} = 3.267\overline{\mathrm{MR}}$$

$$\mathrm{CL} = \overline{\mathrm{MR}}$$

$$\mathrm{LCL} = D_3\overline{\mathrm{MR}} = 0$$

Individual and Moving Range chart calculator

To make it easier to calculate the moving range, open *Student Files → calculator – individual moving range chart*



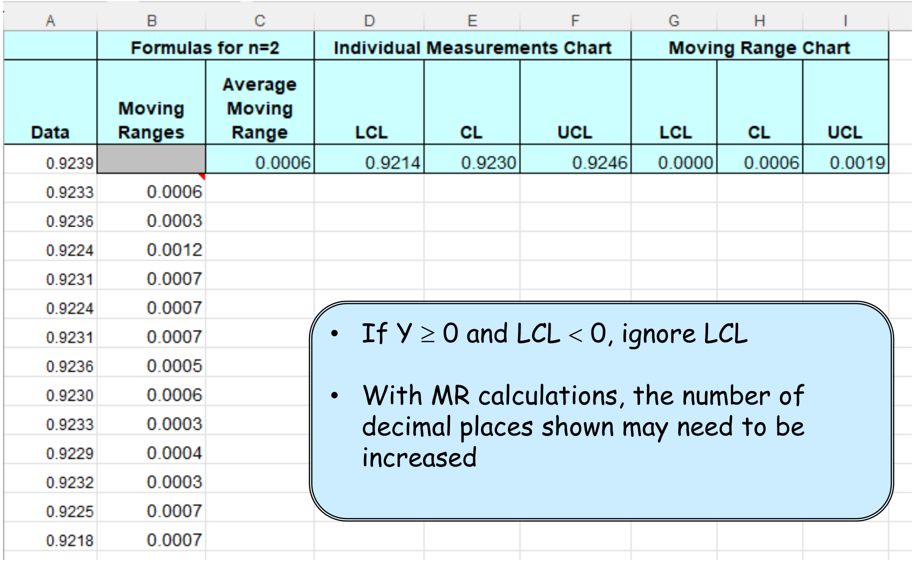
B4 =ABS(A4-A3)

	A	B	C	D	E	F	G	H	I
1		Formulas for n=2		Individual Measurements Chart			Moving Range Chart		
2	Data	Moving Ranges	Average Moving Range	LCL	CL	UCL	LCL	CL	UCL
3			0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.0000	0.0000	0.0000
4		0.0000							
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

- Paste your data into cell A3
- Copy cell B4 down to the end of your data

Example: Individual and Moving Range chart calculator

Excerpted data from *Data Sets→ solution properties*



A	B	C	D	E	F	G	H	I
	Formulas for n=2		Individual Measurements Chart			Moving Range Chart		
Data	Moving Ranges	Average Moving Range	LCL	CL	UCL	LCL	CL	UCL
0.9239		0.0006	0.9214	0.9230	0.9246	0.0000	0.0006	0.0019
0.9233	0.0006							
0.9236	0.0003							
0.9224	0.0012							
0.9231	0.0007							
0.9224	0.0007							
0.9231	0.0007							
0.9236	0.0005							
0.9230	0.0006							
0.9233	0.0003							
0.9229	0.0004							
0.9232	0.0003							
0.9225	0.0007							
0.9218	0.0007							

- If $Y \geq 0$ and $LCL < 0$, ignore LCL
- With MR calculations, the number of decimal places shown may need to be increased

Exercise 37.3

We want to use $\overline{IX}$ and MR control charts to monitor radial deviation. This measurement requires special equipment and is very time-consuming, hence the sample size of one.

Open *Data Sets* → *control chart aligner*

Open *Student Files* → *calculator - individual moving range chart*

a) Copy the R dev data into the calculator (Paste Values).

b) Copy the calculation in cell B4 down Column B, in order to calculate the moving range for R dev. What is the average moving range?

$\overline{MR}$ =

Exercise 37.3 (cont'd)

c) What are the control limits for the Individual Chart?

UCL =

CL =

LCL =

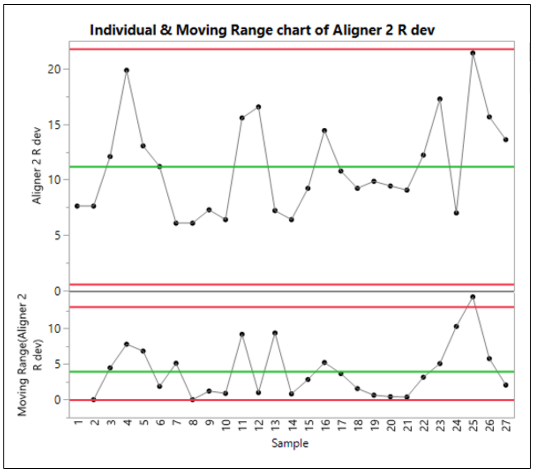
d) What are the control limits for the Moving Range Chart?

UCL =

CL =

LCL =

Individual & Moving Range chart plotted



JMP Output of Individuals & MR Chart of Aligner 2 R dev
Data Sets → control chart aligner

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p Chart

The p Chart is used when:

- Samples are periodically taken and it's determined whether each unit in the sample is good or bad
- The data plotted is fraction or percent defective

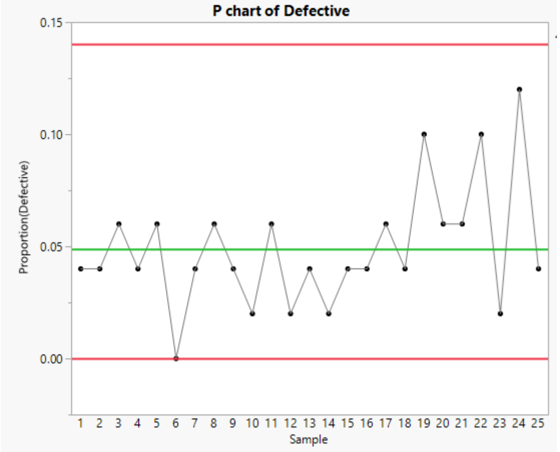
P Chart control limits are based on the Binomial distribution, since pass/fail data is binomial.

- The standard deviation of the Binomial distribution is:

$$\sqrt{\frac{p(1-p)}{n}}$$

p Chart (cont'd)

Example of a p Chart (created in JMP)



In this case, there were 50 units in each sample. Overall percent defective was about 5% for this timeframe.

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p Chart (cont'd)

Control Limits for the p Chart

$$\mathrm{UCL} = \bar{\mathrm{p}} + 3\sqrt{\frac{\bar{\mathrm{p}}(1-\bar{\mathrm{p}})}{\mathrm{n}}}$$

$$\mathrm{CL} = \bar{\mathrm{p}}$$

$$\mathrm{LCL} = \bar{\mathrm{p}} - 3\sqrt{\frac{\bar{\mathrm{p}}(1-\bar{\mathrm{p}})}{\mathrm{n}}}$$

$$\bar{\mathrm{p}} = \frac{\text{Total number of defective units in the samples}}{\text{Total number of units in the samples}}$$

$$\mathrm{n} = \text{number of items in each sample}$$

These control limits are the mean +/- 3 sigma for this distribution.

Exercise 37.4

We want to use a percent defective (p) control chart to monitor the weekly defects per unit occurring during an in-process assembly inspection.

Open *Data Sets → control chart parts inspected & defective*

Use Excel formulas for the following and during calculations, keep the numbers in “fraction defective” form vs percentage:

a) The sample size varies each week, so we’ll use an average sample size for calculating control limits. Calculate the average weekly sample size. What concerns might there be about using this number?

b) Calculate the overall percent defective, $\bar{p}$. Hint: we determined this number in Exercise 23.2 a).

This number will be the center line (CL) for the p chart.

Exercise 37.4 (cont’d)

c) Use the average sample size and $\bar{p}$ found above to calculate the upper and lower control limits for the p chart.

UCL =

CL =

LCL =

d) Optional: Copy the formulas for the control limits down the column for all of the data and use line charts to plot the fraction defective with control chart limits.

Other Shewhart control charts

Categorical classification:

- np chart: number (count) of defective items per sample with a fixed quantity
- u chart: count of defects per unit
- c chart: count of defects) per sample with a fixed quantity

For np, c and u charts, the control limit calculations and chart appearance are similar to the p chart.

Details of these and other specialized control charts are beyond the scope of this course. More information can be found in any basic statistical process control textbook or reference.

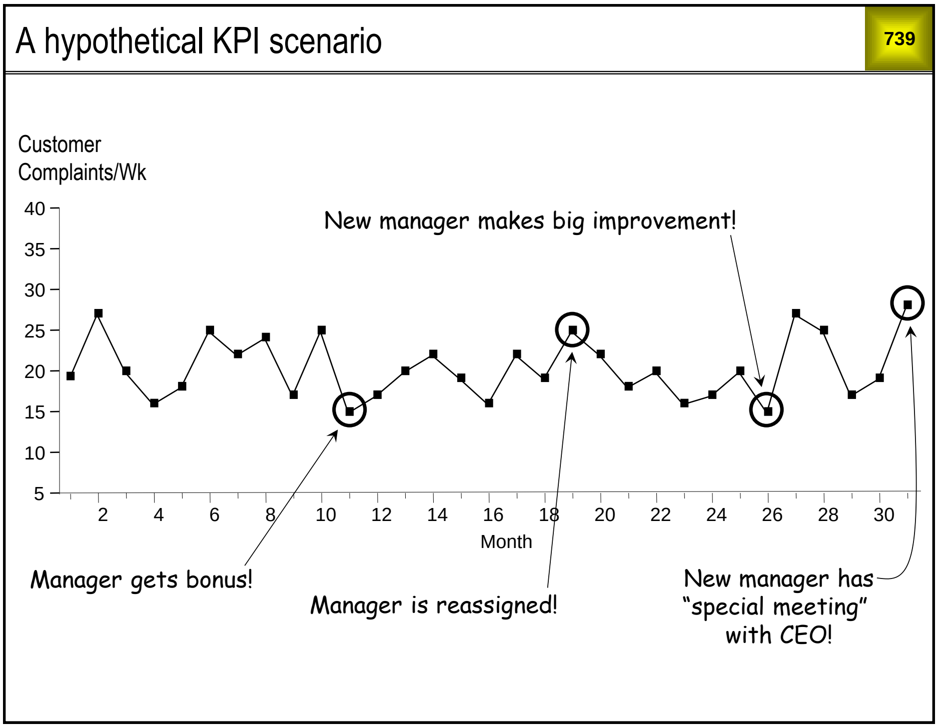
Interpreting control charts

Once the control chart is created, the most valuable work can begin — discerning what the chart is telling us about process variation.

- Is the process “in control” or “out?”
- Are there warning signs that the process may go out of control soon?
- What actions should be take in response to the control chart signals?

The rules we’ll discuss for deciding whether a process is in or out of control work only for control limits — *not* for specification limits.

- Our concern with specification limits is whether an item conforms or not.
- Inspection and testing must be used to screen out bad parts, not control limits.



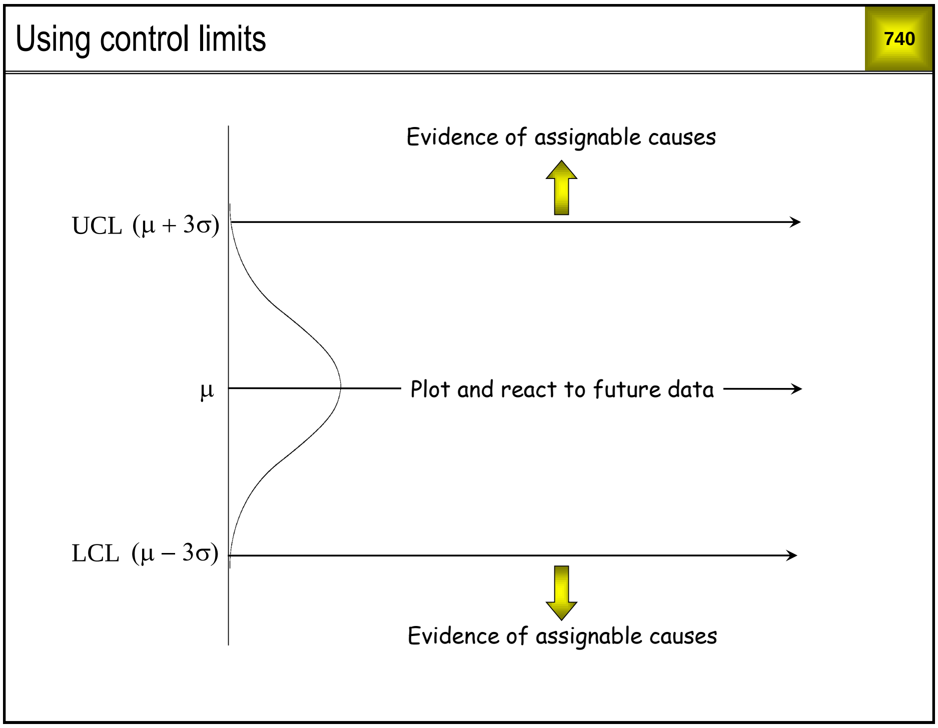
A hypothetical KPI scenario

New manager makes big improvement!

Manager gets bonus!

Manager is reassigned!

New manager has
“special meeting”
with CEO!



Using control limits

Evidence of assignable causes

UCL $(\mu + 3\sigma)$

μ

Plot and react to future data

LCL $(\mu - 3\sigma)$

Evidence of assignable causes

Back to our hypothetical scenario

Control Limits show there are no assignable causes!

Run charts can cause us to overreact.

Using control limits (cont'd)

- Control limits provide an operational definition of assignable cause variation
- Simplest rule: points inside the limits are common cause variation, points outside the limits have assignable causes
- 27 in 10,000 common cause data points are expected to fall outside the control limits* — this is the nominal *false alarm* rate
- Assignable causes may occur without producing points outside the limits — these are *missed signals*
- To reduce missed signals, additional rules are sometimes applied

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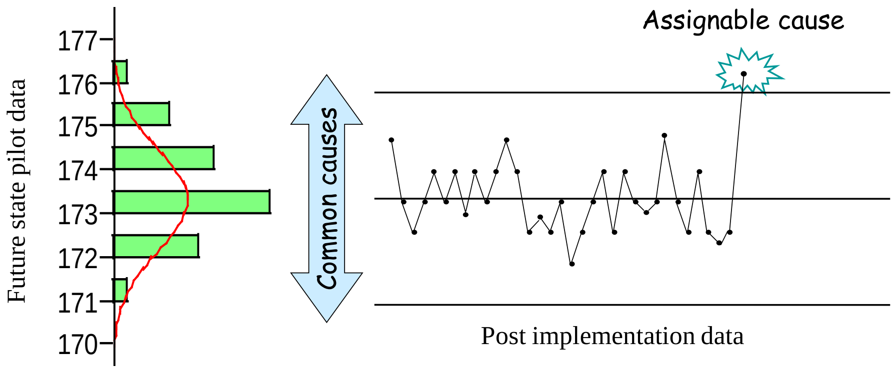
*Assuming a Normal distribution

Using control limits (cont’d)

When monitoring a straightforward KPI, such as number of customer complaints/week or monthly on-time delivery, Management may only want to see a chart of the KPI metric itself.

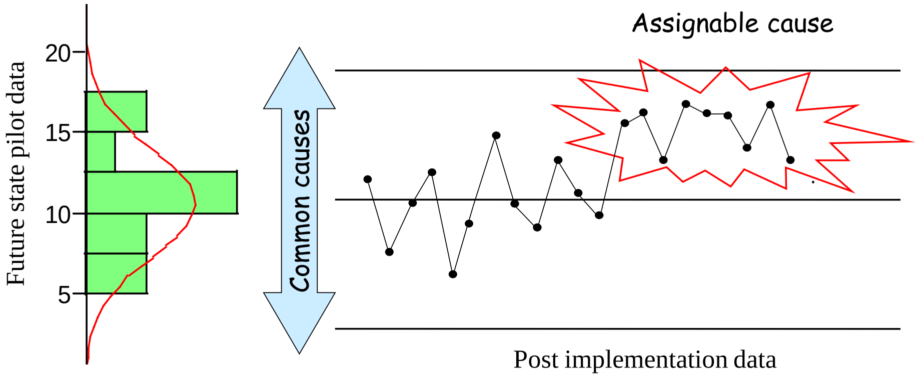
- In this case, it may be sufficient to use an X-bar or IX chart without the associated standard deviation or range chart.
- Adding control limits to the resulting X-bar or IX chart will provide a statistical basis for action.
- It may also be helpful to add a target or goal line to the chart (aligned with the KPI calculation method).
- An associated variation chart could be created for deeper root cause analysis if necessary. For example:
  - ➢ Are late deliveries “normal” for the organization?
  - ➢ Are there inconsistencies between divisions for global KPI charts?

Using control limits (cont’d)



1. This event has probability 0.00135 (0.0027 ÷ 2)
2. Investigate to determine the cause
3. Take corrective action to eliminate the cause

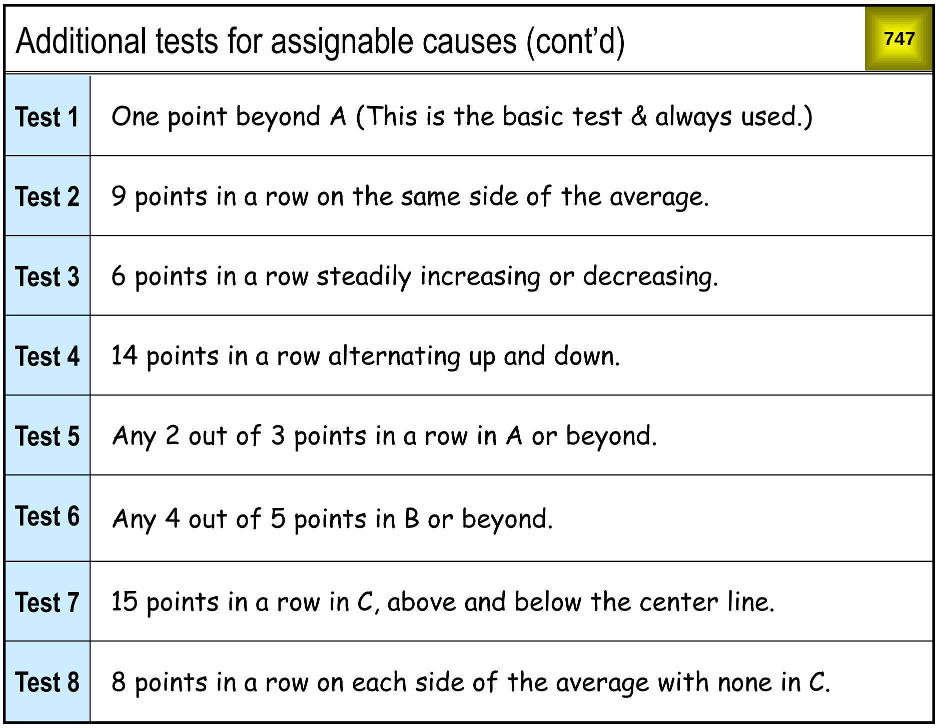
Using control limits (cont'd)



1. This event has probability 0.00195 [$(0.5)^9$]
2. Investigate to determine the cause
3. Take corrective action to eliminate the cause

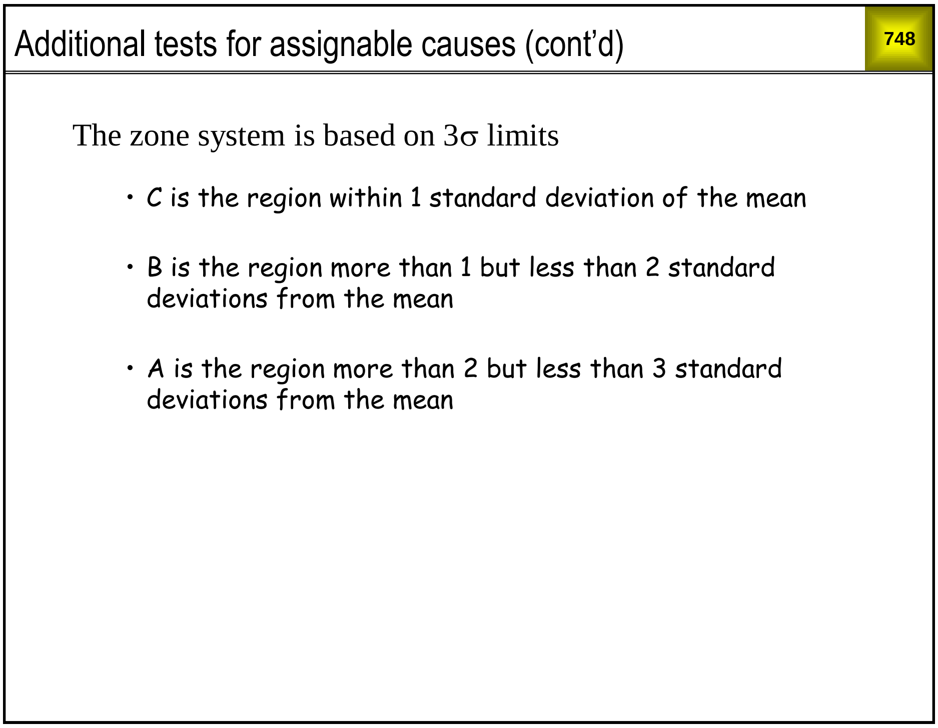
Additional tests for assignable causes

Control chart zones: A, B, and C



Additional tests for assignable causes (cont’d)

Test 1	One point beyond A (This is the basic test & always used.)
Test 2	9 points in a row on the same side of the average.
Test 3	6 points in a row steadily increasing or decreasing.
Test 4	14 points in a row alternating up and down.
Test 5	Any 2 out of 3 points in a row in A or beyond.
Test 6	Any 4 out of 5 points in B or beyond.
Test 7	15 points in a row in C, above and below the center line.
Test 8	8 points in a row on each side of the average with none in C.



Additional tests for assignable causes (cont’d)

The zone system is based on 3σ limits

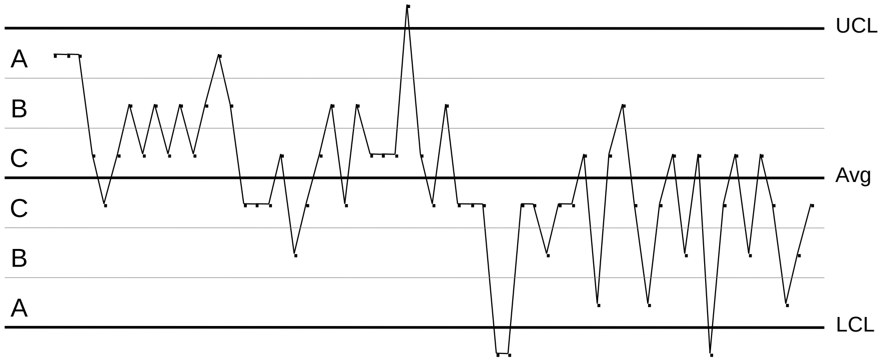
- C is the region within 1 standard deviation of the mean
- B is the region more than 1 but less than 2 standard deviations from the mean
- A is the region more than 2 but less than 3 standard deviations from the mean

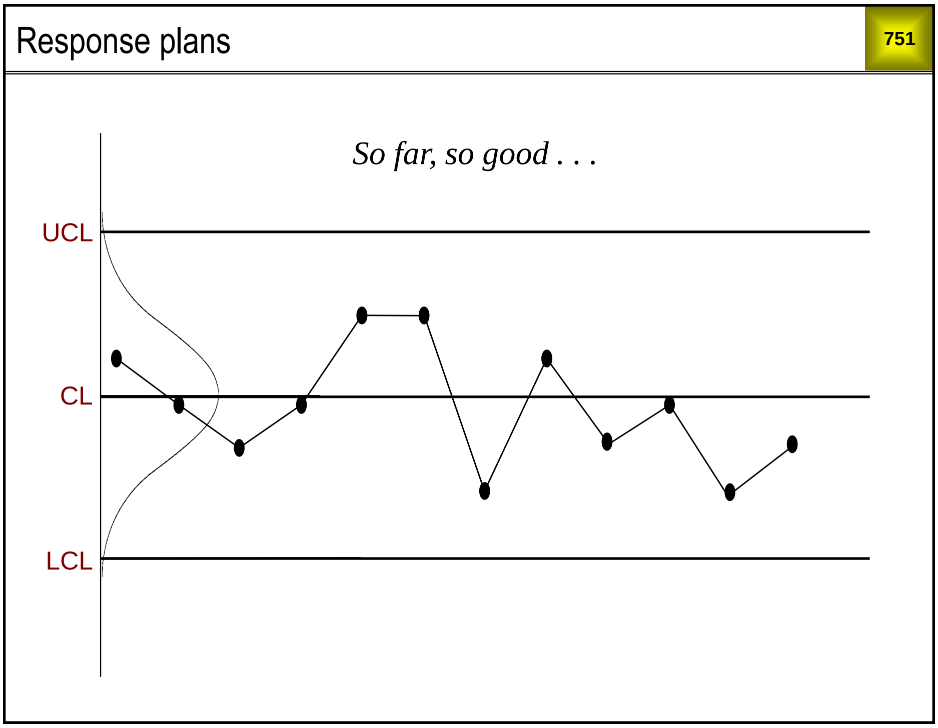
Tests most commonly used (and most useful)

Test #1	One or more points outside the control limits.
Test #2	Nine or more points in a row on one side of the average.

Exercise 37.5

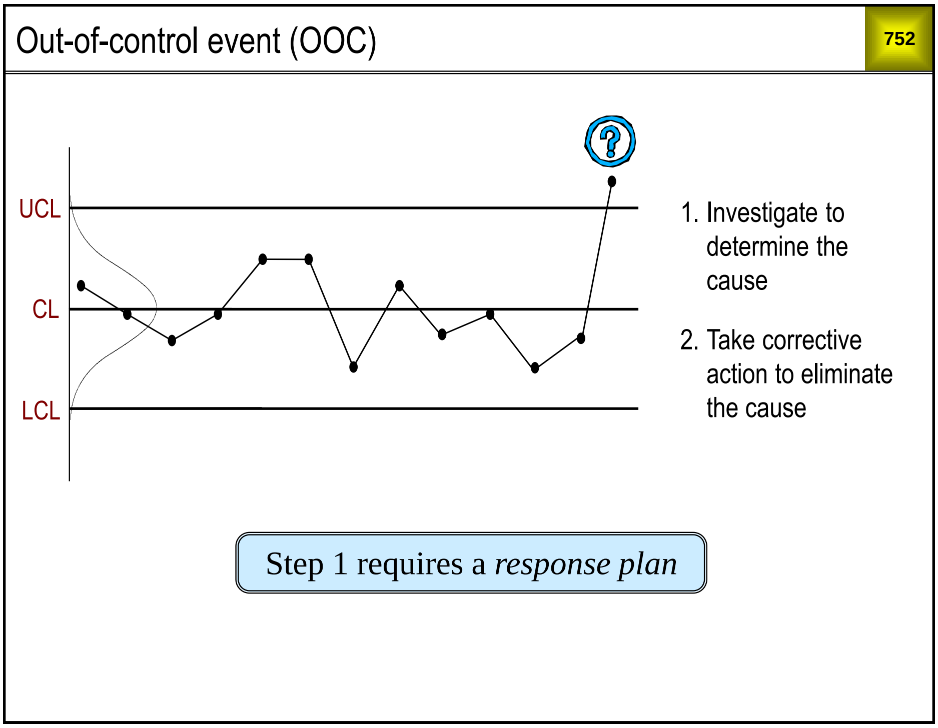
Circle occurrences of Tests 1 and 2 on the control chart shown below. Indicate which is which.





Response plans

So far, so good . . .

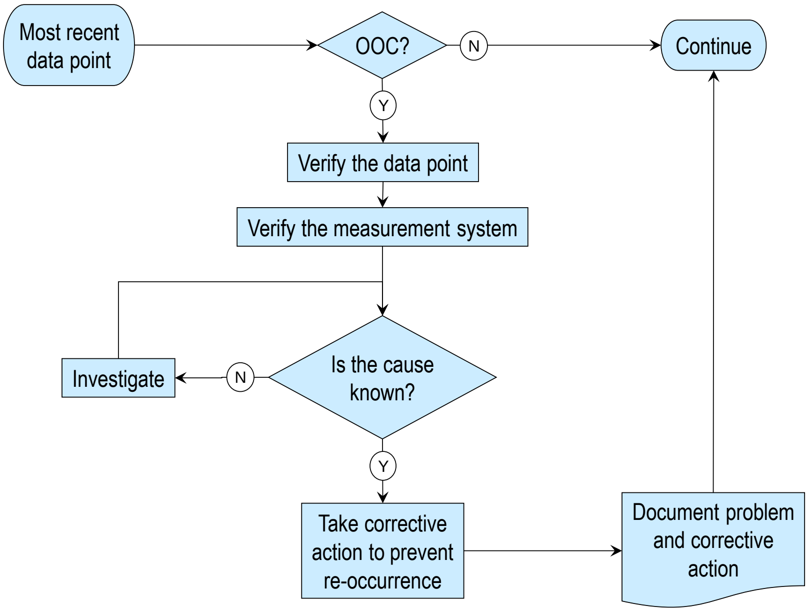


Out-of-control event (OOC)

1. Investigate to determine the cause
2. Take corrective action to eliminate the cause

Step 1 requires a *response plan*

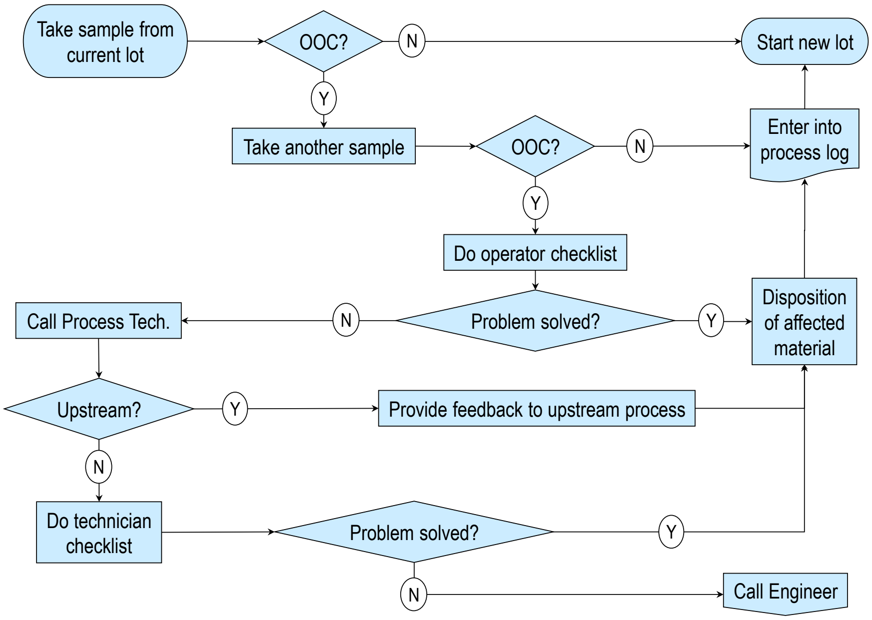
Response plan "skeleton"



Response plan (cont'd)

- OOC stands for *out of control*
- This means the control chart indicates an assignable cause according to one or more selected tests
- The success of statistical monitoring depends on having a documented plan for responding to OOCs
- The most effective form of documentation is a process map like the one shown above
- It should posted in a place clearly visible to process participants

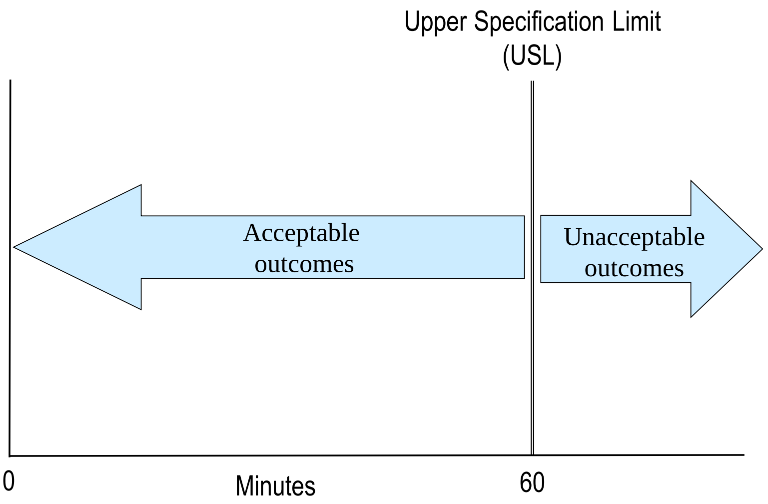
Response plan example



Response plan (cont'd)

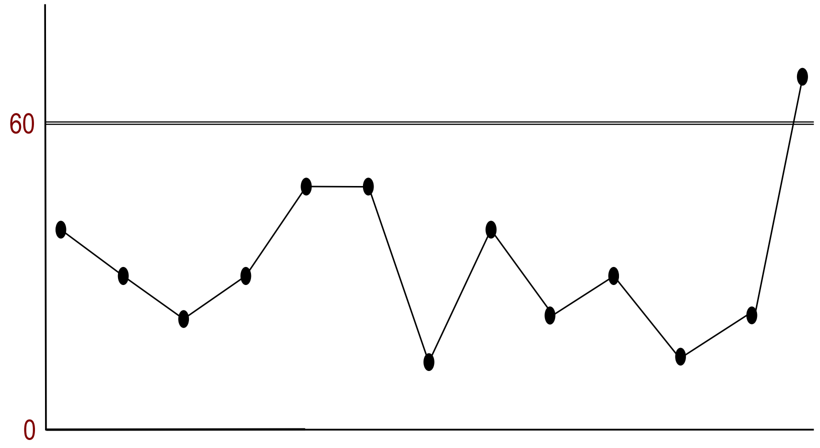
- Example from a high-volume automated assembly process (“sanitized”)
- Development team: operators, technicians, engineers, area manager
- Based on experience, they wanted to verify an OOC with a second sample from the same lot
- Note the escalation from Operator to Technician to Engineer.
- When an OOC was confirmed, production was halted
- Within a few months:
    - *Chronic equipment and process problems were solved*
    - *Unplanned downtime and need for Engineering support plummeted*
    - *Engineers able to focus more on process improvement*
    - *Productivity increased dramatically*

What about performance requirements?

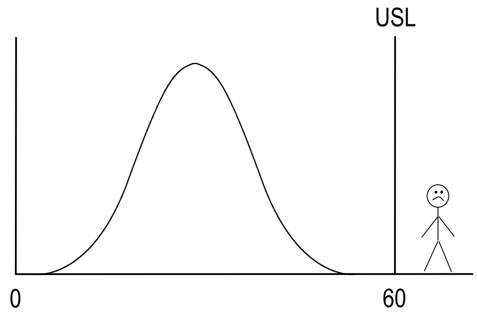


Out-of-specification event (OOS)

What do we do now?

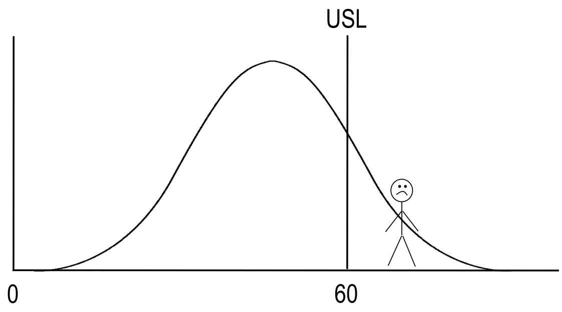


Scenario 1: process capability is good



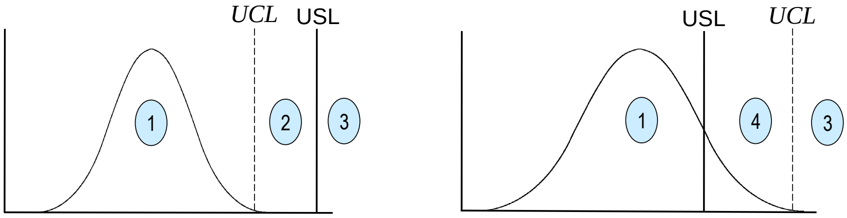
- If the process has good capability, it will virtually never produce a defective outcome, unless there is an assignable cause
- Any OOS point is also OOC
- Any OOS point should trigger the response plan

Scenario 2: process capability is poor



- If the process has poor capability, there will be OOS outcomes that are not OOC
- These outcomes do not indicate assignable causes
- They should *not* trigger the response plan

Exercise 37.6



Check the appropriate actions for outcomes in each of the 4 zones shown above.

Zone	Initiate OOC response plan	Scrap, rework, do over, etc.	Do nothing
1			
2			
3			
4			