Systemic Lack of Water: Droughts
Part I: Initial Assessment

The Beginning of a Quality Engineering Project

MFE634: Quality and Productivity

Jorge L. Romeu; Course Instructor
Spring 2025

Problem Statement

This project analyzes Subtropical Systemic Water problems: floods & droughts. Jake Jock analyzes the floods part, and this Instructor analyzes the drought part.

Scope: analysis of a specific Region's Systemic (annual tropical and subtropical problems) such as dealing with the distribution of water among its stake holders, (human population, cattle, agriculture, etc.). For more background see:
https://en.wikipedia.org/wiki/Tropics
https://en.wikipedia.org/wiki/Subtropics#Definition

Not included in this study scope are:

Ocasional problems, political issues and other regions.

Project Topic

This project is about applying Quality Engineering to mitigating Drought and Flood Cycles in Tropical Savannahs (more information about climate in https://en.wikipedia.org/wiki/Tropics and https://en.wikipedia.org/wiki/Subtropics#Definition).

Tropical savannahs are common in Caribbean countries such as Cuba, the Gulf coast of Mexico, Central and South America, and in India, Indonesia and some coastal African countries. They share a yearly cycle of two seasons: rain and drought. In the first, copious rains inundate the countryside; in the second, scant rain occurs and cattle and agriculture suffer of lack of water.

Input/output model shows rain water either moves out, or it moves up, flooding the surrounding areas. The issue is to find a way for water to leave at the same speed rain falls into the ground. A series of issues prevent this. One, that there may not be enough means (rivers, canals, etc.). The other, that there may not be a gradient to quickly push water out into the sea. Finally, there may exist marshes, close to the sea, that accumulate water and block their exit out of the area, forcing the remaining water to go up and inundate the surrounding areas. Finally, some rain water must be stored for its use during the dry season, to avoid drought. Thence, several lakes, reservoirs, etc. must be built to store the rain water that falls during the rainy season.

The design and construction of a system that fulfills these requirements is our project objective. The First Part deals with the Rainy Season; the Second Part deals with the Dry Season. This is the Second Part.

System Pseudocode Description:

<u>Start</u>

Are there active reservoirs? If not, create them.

Are there distribution Canals? If not, create them.
Is human usage distribution known? If not, find it.
Is animal usage distribution known? If not, find it.
Is agricultural usage distribution known? If not, find it.
If they are not, then create/find said information
Implement a Brainstorming session: analyze results
Implement a distribution analysis for key variables.
Assess whether said variables fulfill system needs.

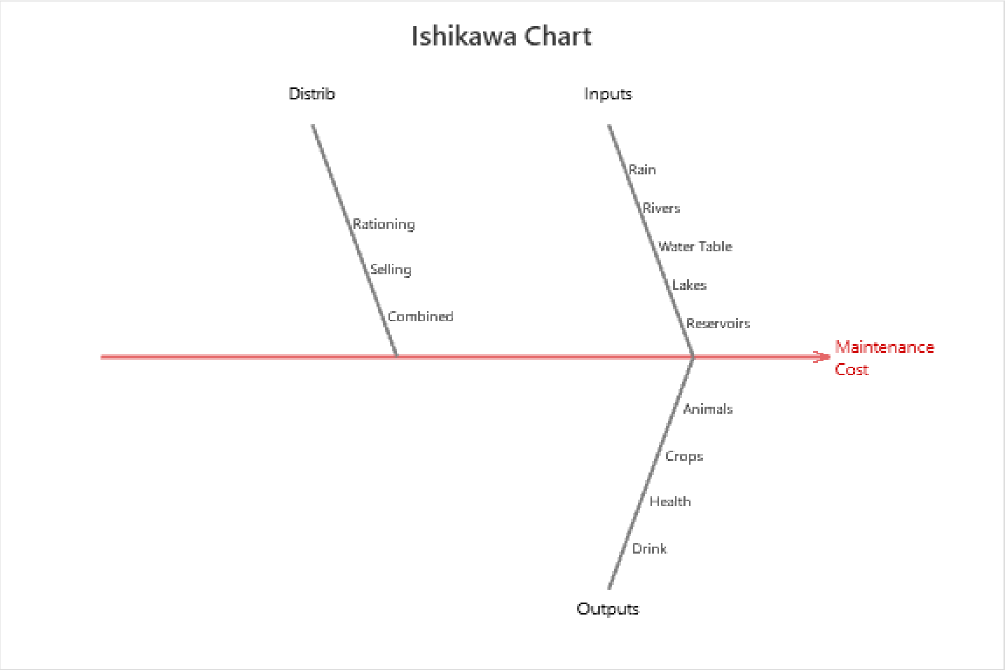
<u>End</u>.

Brainstorming and Ishikawa Chart:

<u>Affinity Diagram</u>:

Inputs	**Outputs**	**Distribution**
Rain	Drink	Free
Rivers	Health	Rationing
Water Table	Crops	Selling
Lakes	Animals	Combined
Reservoirs		

<u>Ichikawa or Fishbone Charts </u>provide a diagrammatic description of how problem factors affect a response or performance measure. Later, said qualitative diagram can become a quantitative regression model.



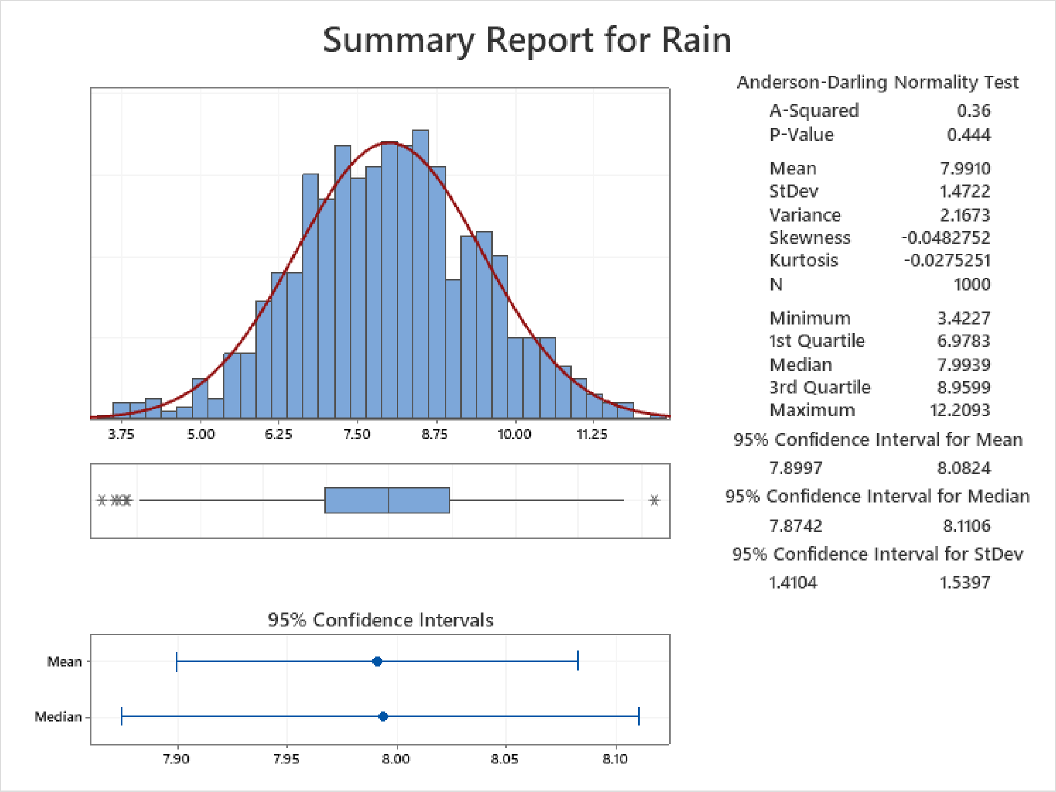
Cost of Poor Quality for Drought:

COPQ	Drought			
Process	Internal Failures	External Fail	Appraisals	Prevention
Evacuation Canals	Small capacity	Can’t Cope	Weekly Measure	Periodic Cleaning
Reservoirs	Small capacity	Cattle suffers	Weekly Measure	Maintenance Training
Crop Fields	Dry or lacking Water	Agriculture suffers	Weekly Measure	Periodic Cleaning

Imperative to Determine whether input (water availability) > output (user needs)

If this condition is not met, then the improvement project consists in creating it.

Weekly Consumption Distribution (cm^3)



We need to know the Consumption Distribution in order to plan how to meet it with the available resources, or how to create the additional necessary resources. Process Capability quantifies the input/ /output relationship.

Overview of Improvement Work

- Determine the daily, system users, water consumption
- Determine whether the current availability fulfills the needs
- Determine the reservoir capacity required to fulfill needs
- Determine whether capacity exists or needs to be created
- Determine how the water will be distributed among users
- Determine how water distribution system will be managed
- Determine the costs of Drought and Improvement Project

Conclusions

- Insufficient Water problem needs to be solved
- Cost of Drought is larger than Improvement Project
- We need to start by finding the key information.
- Continue, by defining the CTQ (critical) issues.
- Then, rank the critical issues by importance ($)
- Convince the Leadership of Project Need.
- Such is the Initial Assessment phase.
- Afterward, comes the Six Sigma Analysis

Systemic Lack of Water: Droughts
Part II: Six Sigma DMAIC

System Exists, but is Inefficient and Needs Improvement

MFE634: Quality and Productivity

Jorge L. Romeu; Course Instructor
Spring 2025

Six Sigma DMAIC Phases

Define: Project is justified, scoped, organized, chartered and started;

Measure: MSA, data Id, collection, capability, FMEAs and root-cause;

Analyze: theories tested, more data collection, diagnostic of causes;

Improve: solutions proposed, ranked, DOEs and implemented, effectiveness;

Control: final MSA/capability, improvement assessment, resistance controls;

Discuss and Deliver the Final Report.

Define Phase

Select Champion: provincial civil/military chief

Select Tech Team: Black belt, agricultural, civil and Industrial engineers, accountant, public health specialists

Brainstorming with community leaders/stake holders

COPQ and tech interviews with leaders/stake holders

Determine key CTQ elements

Propose projects with their characteristics

Evaluation of projects/selection of the “best”

Project Charter and Operational Plan

Gann chart with personnel load

Initial COPQ

After developing Brainstorming sessions with the stakeholders, and after interviewing system users and technicians, these costs are found

COPQ from Drought

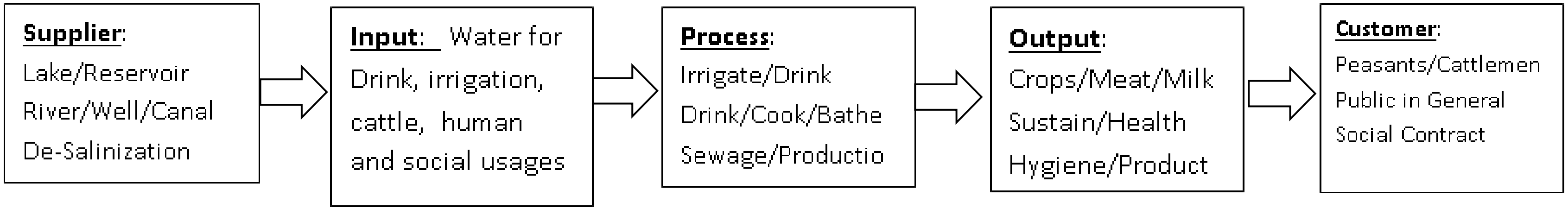
Process	Internal Failures	External Fail	Appraisals	Prevention
Evacuation Canals	Few Distribution Canals	Can’t Cope with need.	Weekly Measure	Periodic Cleaning
Reservoirs	Small reservoir capacity	The Cattle suffers	Weekly Measure	Maintenance Worker Training
Marshes	Are Dry, and the water is scarce	Agriculture suffers	Weekly Measure	Periodic Cleaning

Long-term material losses are much higher than improvement costs. Such situation justifies the implementation of an improvement effort.

System Operation:

SIPOC = Supply-Input-Process-Output-Customer Model

Water is obtained, distributed, and consumed by system users.



A Balance, between water coming into, and leaving the system (the Input and Output Model) is pursued. Such a balance is obtained from building a more efficient canal system, more and deeper reservoirs and wells, etc.

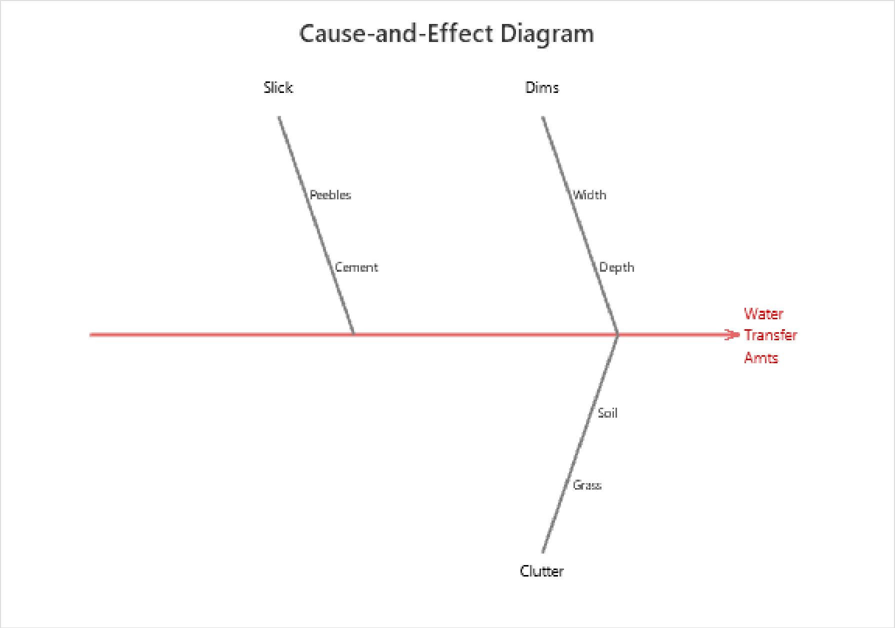
Project Selection

Pareto Priority Index Calcs

Project	Savings	Probs	Cost	Time	PPI
A	10	0.7	0.5	8	1.75
B	9	0.8	0.4	9	2.00
C	12	0.9	0.6	7	2.57

A	Deepen/widen existing water reservoir/canal nets
B	Create new water reservoir/canal networks
C	Combination of A and B options above

Comparison of Alternative Canal Projects and Selection of the best: Project C (combination) is Selected as its PPI = 2.57 was the highest.



Some Factors affecting Canal Water Transfer Velocity: dimensions (depth/width) and clutter. (stones/mud).

Measure Phase

Plan data collection: items and places

Collection of rain and consumption data at
Different Sites; from Different Users

Establishment/discussion of LSL/USL values

Initial Water Consumption Capability Analysis

Water Distribution Network Analysis (canals)

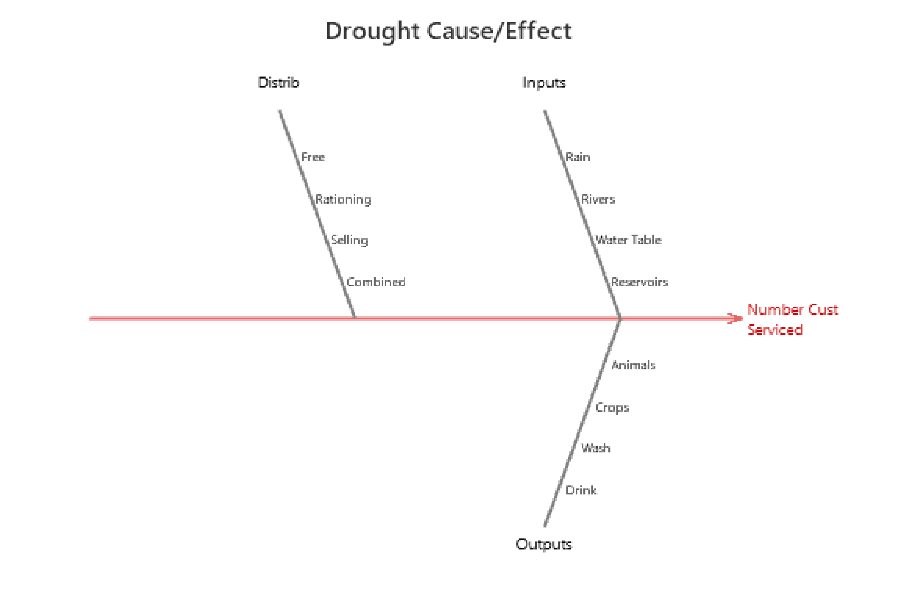
Establishment of water distribution rules

COPQ of weak water distribution network

FMEAs of the water distribution network

Factors that affect water consumption

Inputs	**Outputs**	**Distribution**
Rain	Drink	Free
Rivers	Wash	Rationing
Water Table	Crops	Selling
Reservoirs	Animals	Combined



Water Distribution Methods:

(1) Sell; (2) Ration; (3) Same amount; (4) Other

Water Distribution Schedule:

(1) Daily; (2) Weekly; (3) Other

Water Distribution Delivery:

(1) Individually; (2) Groups; (3) Other

Water distribution methods (free/rationing/selling), water sources (reservoirs, wells, lakes) and its uses (human/agriculture/cattle) affect Number of Customers Served.

Measurement Systems Analysis

Gage R&R

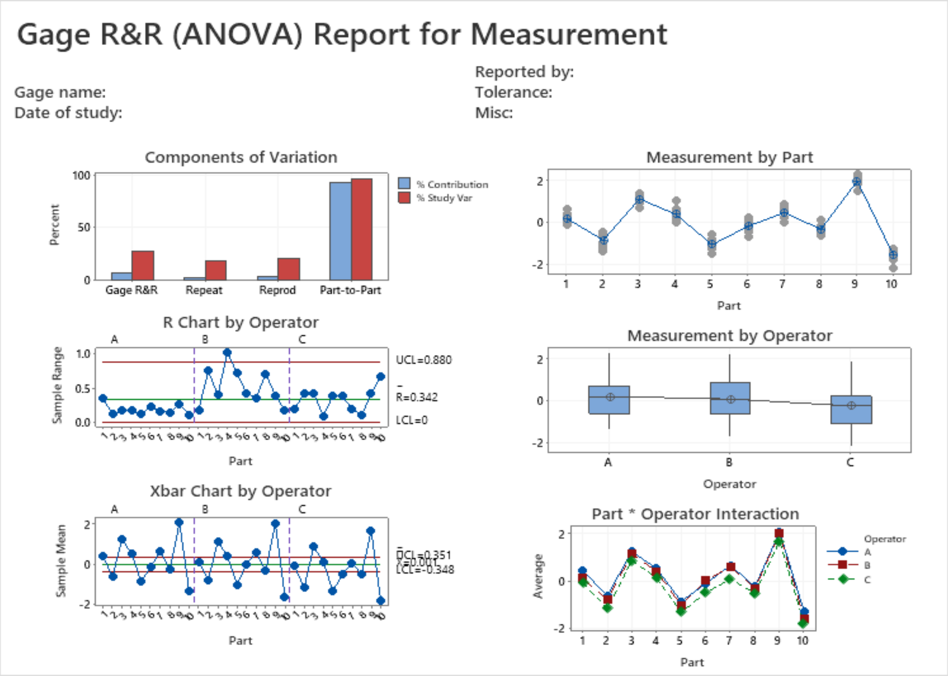
Variance Components

Source	VarComp	%Contribution
(of VarComp)		
Total Gage R&R	0.09143	7.76
Repeatability	0.03997	3.39
Reproducibility	0.05146	4.37
Operator	0.05146	4.37
Part-To-Part	1.08645	92.24
Total Variation	1.17788	100.00

Gage Evaluation

Source	StdDev (SD)	Study Var	
(6 × SD)	%Study Var		
(%SV)			
Total Gage R&R	0.30237	1.81423	27.86
Repeatability	0.19993	1.19960	18.42
Reproducibility	0.22684	1.36103	20.90
Operator	0.22684	1.36103	20.90
Part-To-Part	1.04233	6.25396	96.04
Total Variation	1.08530	6.51180	100.00

Number of Distinct Categories = 4



<u>Result</u>: Measurement System is <u>weak (92.2)</u> both in gages (3.39) and operators (4.37). Train the operators and recalibrate/replace gauges. Then, perform another Gage R&R.

COPQ Distribution Of Water (Cont.)

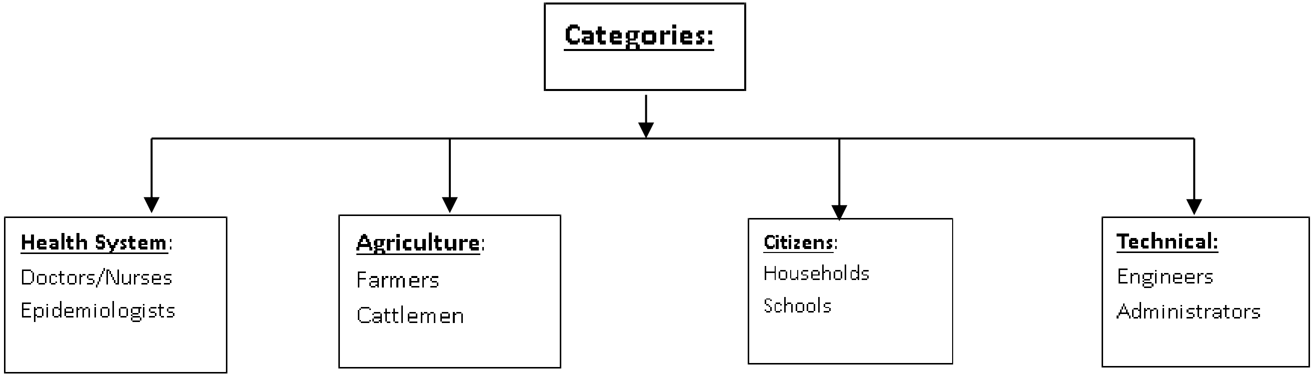
Process	Internal Failures	External Fails	Appraisals	Prevention
Canals	small capacity	Infighting	Control Charts	Surveillance
Canals	Water Leaks	Infighting	Control Charts	Surveillance
Canals	Water Thefts	Infighting	Measuring	Policing

Additional Concerns and Questions about Water Allocation

- Rain schedule cannot be altered/modified
- Minimal Consumption cannot be altered
- Water Distribution can be optimized
- Theft/leaks can be minimized
- Distribution System can work efficiently

Investigate these concerns further via interviews with system stakeholders.
Find out the root-causes of said problems and propose some solutions.

Organization Tree for Data and Information Gathering:

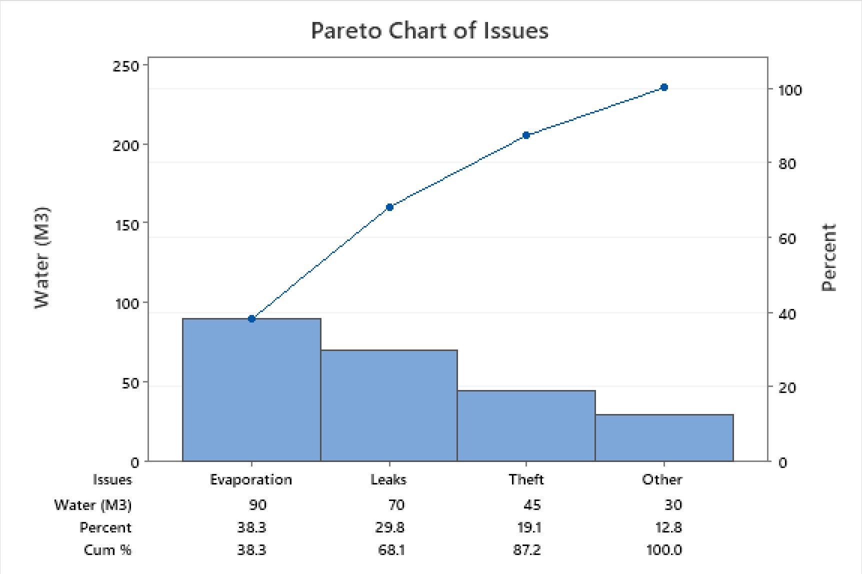


Interview individuals from each category; send them a questionnaire, set date/time.

From these interviews, obtain the information about possible problems, hypothesize causes and effects, and propose some solutions.

From said information implement Pareto Charts and FMEAs, and rank possible projects to attack and select those with higher impact and probability of success.

Pareto Chart of Principal Problems



FMEA Analysis of Initial System

Function	FailMode	Effects	Causes	Detection	Actions
Canal	Leak	LostWater	Breach	Ctr Chart	Repair
Canal	Theft	LostWater	Crime	Police	Punish
Reservoir	Evaporate	LostWater	Surface	Ctr Chart	Reshape

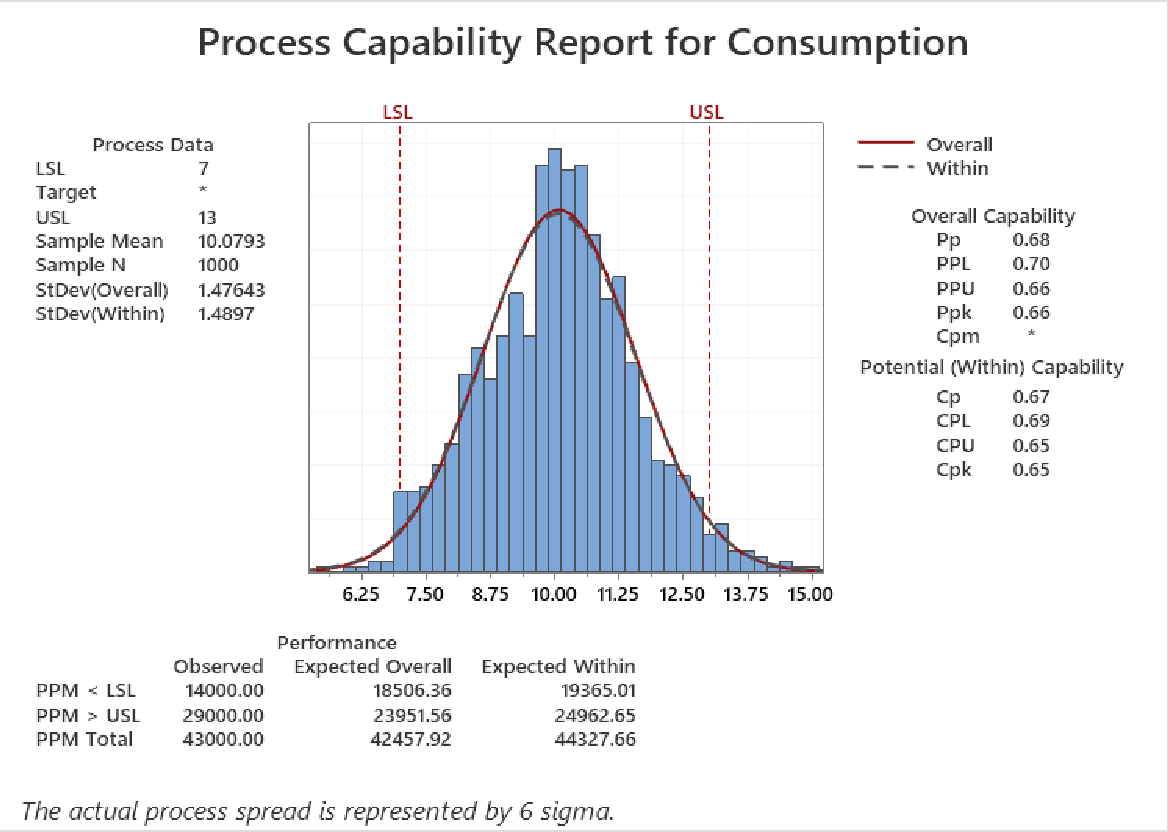
Control Charts measure canal water levels and can help detect occurring water losses.

Said losses can occur from evaporation, leaks, theft, and other causes. Control Chart does not specify water loss causes, but flags occurrence.

Detailed root-cause analyses help determine root causes and provide solutions for avoidance.

Pareto Chart shows Evaporation is a critical cause of water loss; FMEAs shows that size of reservoir surface is a key factor. Deeper reservoirs yielding same capacity but less surface, may be a solution.

Consumption of Daily total water (in Liters)



Water Specification Limits (storage):

LSL: less is unrealistic
USL: more endangers cattle health, life, etc. Their needs are unmet. Initial Capability Ratio is 0.68 is very low. We cannot control water needs; but we can change the USL (storage capacity) by building larger reservoirs that can store more rain water during the rainy season. USL is the water capacity limit.

Analyze Phase

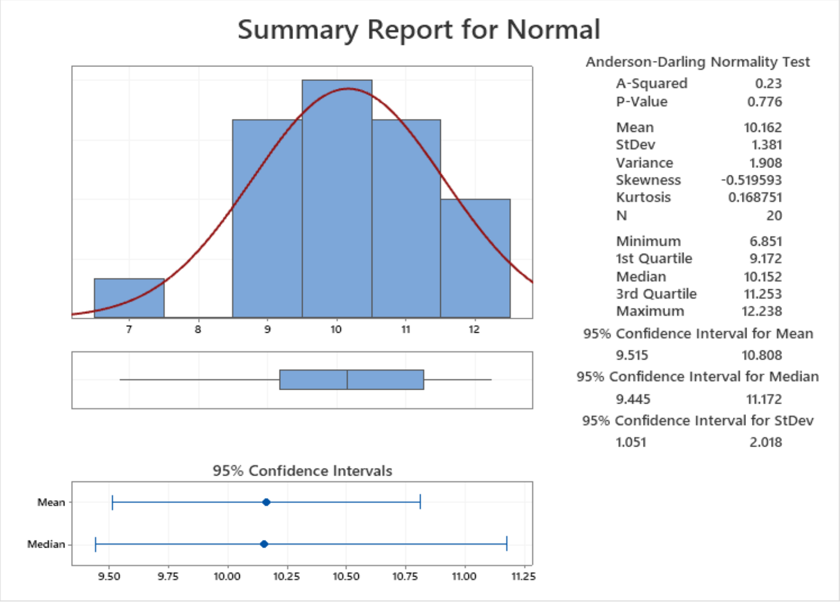
Collect remaining necessary data
Prepare a list of theories to test
Perform required statistical tests:
    Parametric and Non Parametric
Analyze/interpret test results
Establish theories/useful relationships
Develop the Process/Value Stream Map
Diagnose causes of the problems
Hypothesize possible solutions
Assess and Rank said solutions

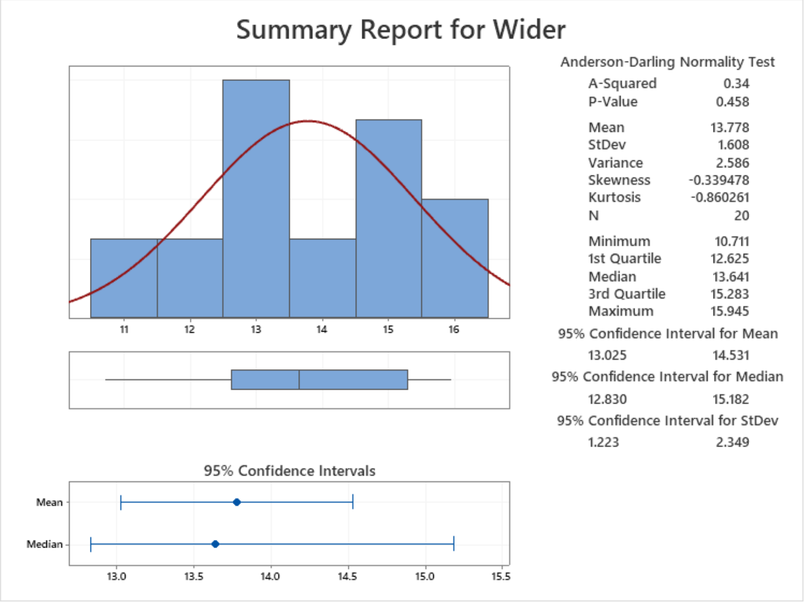
Examples

List of Theories:

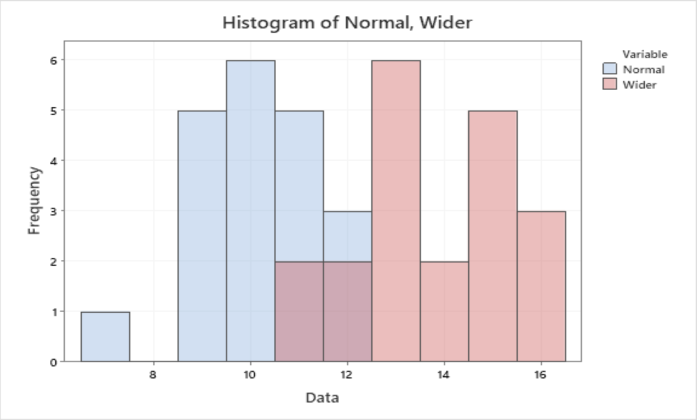
- Wider canals perform better
- Deeper canals perform better
- Gravel bottom canals perform better
- Deeper reservoirs suffer less evaporation
- Interconnected reservoirs perform better

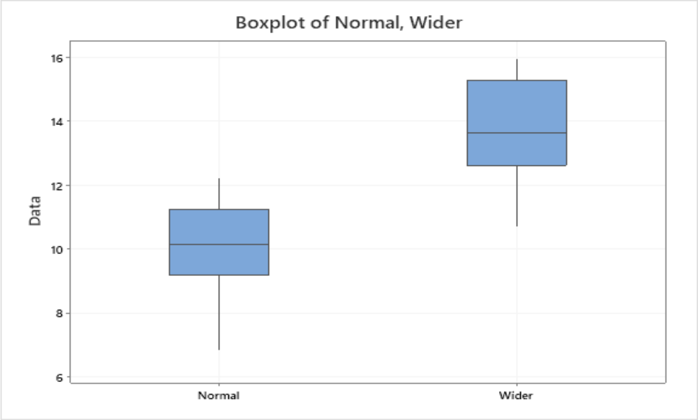
Descriptive statistics for the canal water flows, in normal and wider canals, suggest *Wider canals perform better. We need to implement a physical experiment, and perform a statistical test on collected data to demonstrate the Theory*





Example of Statistical Analysis: *wider canal provides more water*





Test

Null hypothesis: $H_0: \mu_1 = \mu_2$

Alternative hypothesis: $H_1: \mu_1 \neq \mu_2$

T-Value	DF	P-Value
-7.63	38	0.000

Descriptive Statistics

Sample	N	Mean	StDev
Normal	20	10.16	1.38
Wider	20	13.78	1.61

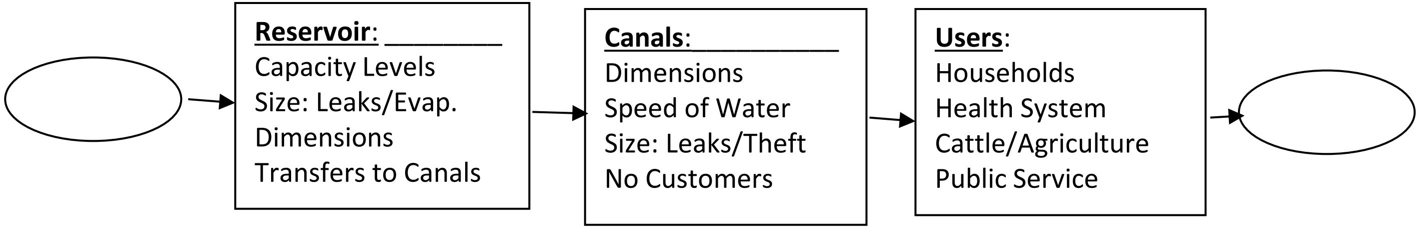
Estimation for Difference

Difference	Pool StDev.	95% CI
-3.616	1.499	(-4.57, -2.65)

We implement a **hypothesis test** for assessing the theory that the flows differ.

Results show that wider canal water flows *are significantly larger: (2.6 to 4.5)*

Value Stream Map (current state)



VSM describes quantitatively the operation of the water distribution system so it can be optimized. Here, the current factors capacity and dimensions of the Reservoir, the dimensions and number of customers served by Canals, and the number and types of Users, determine the efficiency of the water distribution system, at this time.

We develop Two Value Stream Maps (VSM): one before the improvement process (current state); then, another at the end of the process (final state). VSM quantifies the system improvements obtained with the changes implemented in its operation.

Improve Phase

- Propose improvement solutions
- Evaluate/Select the proposed solution
- Develop the improvement solution
- DOE to optimize improvement solution
- Analyze and verify the DOE results
- Update the FMEAs and Process Map
- Implement Solution in Pilot program
- Upgrade the solution to the entire system
- Address resistance to change issues

Selection of the most cost/efficient solution (improvement strategy).

Solution	Savings	Probs	Cost	Time	PPI
A	10	0.7	0.5	8	1.75
B	9	0.8	0.4	9	2.00
C	12	0.9	0.6	7	2.57

A	Deepen and widen existing/new water network
B	Create new water reservoirs and canals
C	Implement Combination of A & B

A combination of wider/deeper old canals, plus new canals, and connected reservoirs, is selected. Using the PPI index results, this solution comes out to be the most cost efficient, as it has the best combination of time and probability to completion, of water damage savings, and of strategy development costs.

DOE/Design of Experiments Description

There is a need to experiment with the factors that have been identified as improving the system water distribution and storage. From the Brainstorming, interviews and FMEA analyses, among other improvement activities, we have been able to determine that the flow of water is affected by both, the dimensions of the canal, and by providing a bottom to it, in the form of pebbles or other hard material that facilitates the water flow.

Implement a Two Factor Design of Experiment (DOE) by using a sample of canals, with the desired dimensions, some canals with pebble bottom, and others without it. Then measure the water flow in them, under similar conditions (e.g. same temperature, weather, etc.).

Factor A is dimensional (width: narrow/wide). Factor B is canal bottom (pebbles or not). We have four possible combinations (experimental treatments). Implement three replications from each treatment in a random order, to avoid correlation or effect of extraneous factors.

Results are shown in the next slide. Notice how Width is statistically significant (it impacts flow), while neither Pebble Bottom nor Interaction are. A 95% confidence interval (CI) for the Main Effect of Width is obtained by adding and subtracting the Effect Half Width (2.83) to said Main Effect (6.76). *Width Main Effect 95% CI,* for water flow increase, is: -3.96 to -9.56 units.

DOE/Design of Experiments (Excel)

		Factor A	
		Low	High
		26.36	15.48
	Low	19.13	16.48
		28.28	22.48
Factor B			
		22.89	27.28
	High	29.38	15.15
		26.89	15.50

Data Definition:

Fact. A: Depth 4/8 FT

Fact B: Peebles/None

AB: Interaction

Replications: 3/treat.

Definition of the DOE Experiment: Analyze the effects of the Canal Dimension (Depth) and the Canal Bottom (pebbles) on the Response “amount of water lost” (in m^3 per unit time). Statistical Results indicate that the Canal Dimensions (Factor A: Canal Depth) significantly decreases the canal water loss (in -6.76 m^3/unit time, on the average). Its Std-Dev = 2.83). Neither Factor B (Pebbles Bottom), nor the Interaction of Factors AxB, are statistically significant (i.e. they do not have any effect on the Canal water loss).

Factorial Experiments: Two Factors at Two Levels (2^2):

DOE Full Factorial 2^2

Run	**A**	**B**	**AB**
-1	-1	-1	1
a	1	-1	-1
b	-1	1	-1
ab	1	1	1

Calculations:

TotSum			
SumY+	37.45	45.70	43.90
SumY-	50.97	42.73	44.53
AvgY+	18.73	22.85	21.95
AvgY-	25.49	21.37	22.27
Effect	**-6.76**	**1.48**	**-0.32**

Regression: **bo + b1*A + b2*B + b3*AB**

Regression Estimations

RegCoef	**b1**	**b2**	**b3**
Estimat.	**3.380**	0.741	-0.160

Var. of Model		**23.99**	**StdDv**	**4.90**
Var. of Effect		8.00	**StdDv**	2.83
Deg. Freedom=	**n*(r-1) =**	8		
Student T (0.05;DF) =			**2.31**	
C.I. Half Width =			**6.52**	

Factor	**A**	**B**	**AB**
Significant?	**Yes**	**No**	**No**

Criteria: **Absolute value of Effect > C.I. Half Width**

DOE/Design of Experiments (Minitab)

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Val
Constant	---	22.11	1.41	15.64	0.000
Width	-6.76	-3.38	1.41	-2.39	0.044
Pebbles	1.48	0.74	1.41	0.52	0.614
Width*Pebbles	-0.32	-0.16	1.41	-0.11	0.913

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Val
Model	3	143.956	47.985	2.00	0.193
Linear	2	143.651	71.825	2.99	0.107
Width	1	137.064	137.064	5.71	0.044
Pebbles	1	6.587	6.587	0.27	0.614
2-Way Interact	1	0.305	0.305	0.01	0.913
Width*Pebb	1	0.305	0.305	0.01	0.913
Error	8	191.916	23.990		
Total	11	335.872			

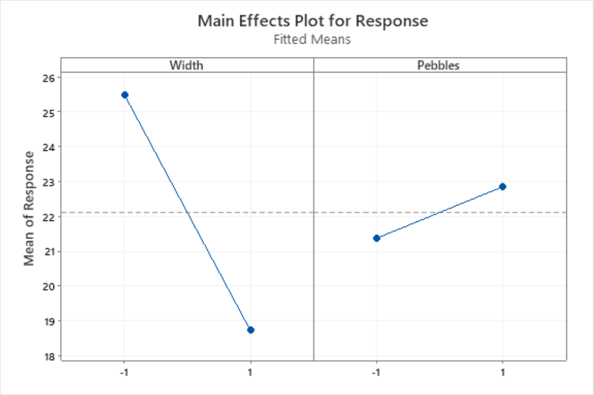
Model Summary

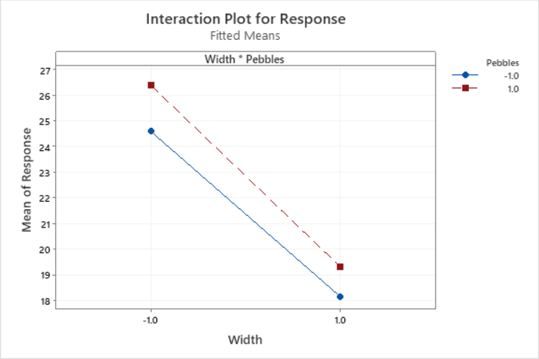
S	R-sq	R-sq(adj)	R-sq(pred)
4.89791	42.86%	21.43%	0.00%

Regression Equation in Uncoded Units

Response = 22.11 - 3.38 Width + 0.74 Pebbles - 0.16 Width*Pebbles

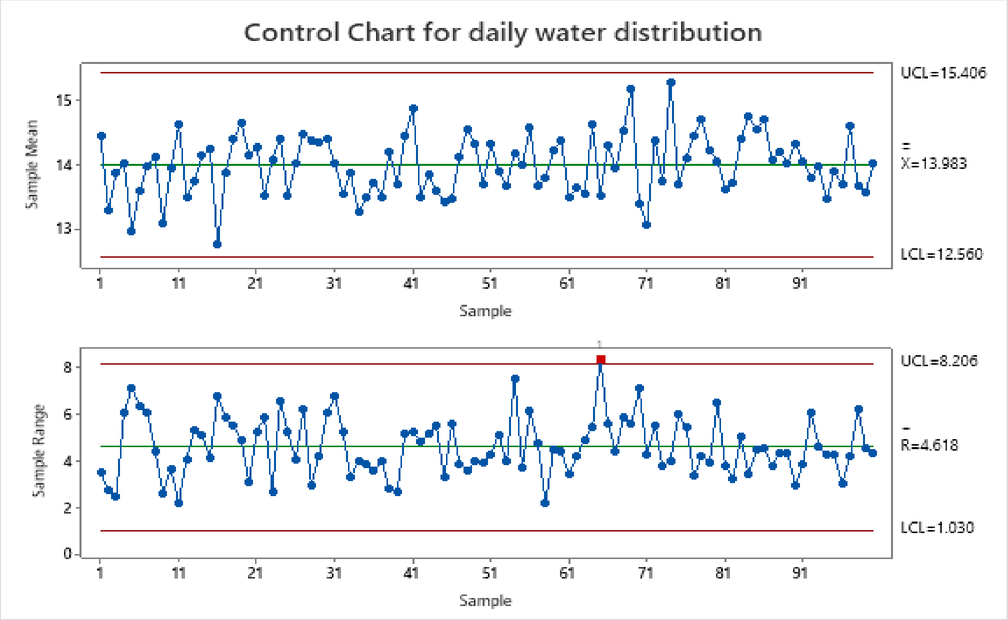
Minitab Graphs: Response v. Factor Value





FMECA Analysis and Control Charts for the Improved System

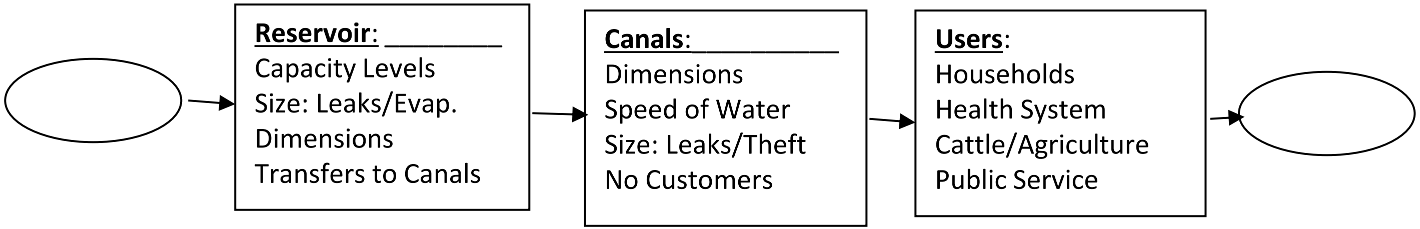
Function	FailMode	Effects	Sev.	Causes	Occur	Detection	Ease	Risk	Actions
Canal	Leak	LostWater	7	Clogged	4	CtrChrt	8	224	Clean
Canal	Theft	LostWater	8	Crime	6	Police	5	240	Punish
Reservoir	Evaporate	LostWater	5	Surface	9	CtrChrt	7	315	Deeper



New FMEA shows how, by digging deeper reservoirs with the same capacity but less surface the amount of water evaporation decreases. Root-cause analyses helped determine causes and provide solutions.

Control Charts of canal water flow can help detect when a shortage may occur, or when there is a plug or leak in the canal. Water should flow at the specified levels, within the specified variations. If some change occurs, there is a reason for it. Control Chart flags such situation, that can be investigated. Once it is detected it can be fixed.

Value Stream Map (VSM) of Improved System



VSM describes quantitatively the operation of the water distribution for the new and improved system, now optimized. Here, the updated (improved) factors capacity and dimensions of the Reservoir, the dimensions and number of customers served by Canals, and the number and types of Users, show the greater efficiency of the water distribution system, once it has been improved.

The new Value Stream Maps (VSM), done at the end of the improvement process (final state), quantifies the improvements obtained with the changes implemented (deepening/widening canals, adding pebbles to bottom, new pumps/gates, etc.)

Control Phase

- Validate the Measurement System
- Assess the Capability of the Solution
- Establish the Process Controls (SPC)
- Establish the Process Operating Procedures
- Write/Establish the Training Manuals
- Perform Statistical Analyses to Prove Results
- Prepare the Final Report and Analyses
- Review the Results with Management

New Measurement Systems Analysis

Gage R&R

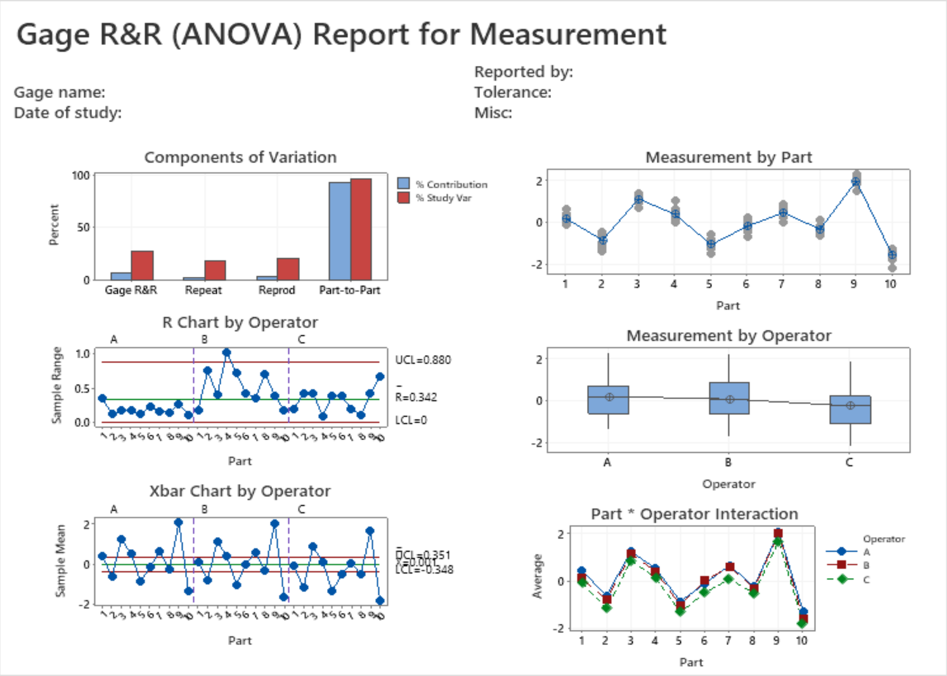
Variance Components

Source	**VarComp**	**%Contribution**
(of VarComp)		
Total Gage R&R	0.09143	2.76
Repeatability	**0.03997**	**1.39**
Reproducibil.	**0.051**	**1.37**
Operator	0.05146	1.37
Part-To-Part	**1.08645**	**97.24**
Total Variation	1.17788	100.00

Gage Evaluation

Source	**StdDev (SD)**	**Study Var**	
(6 × SD)	**%Study Var**		
(%SV)			
Total Gage R&R	0.30237	1.81423	27.86
Repeatability	0.19993	1.19960	18.42
Reproducibility	0.22684	1.36103	20.90
Operator	0.22684	1.36103	20.90
Part-To-Part	1.04233	6.25396	96.04
Total Variation	1.08530	6.51180	100.00

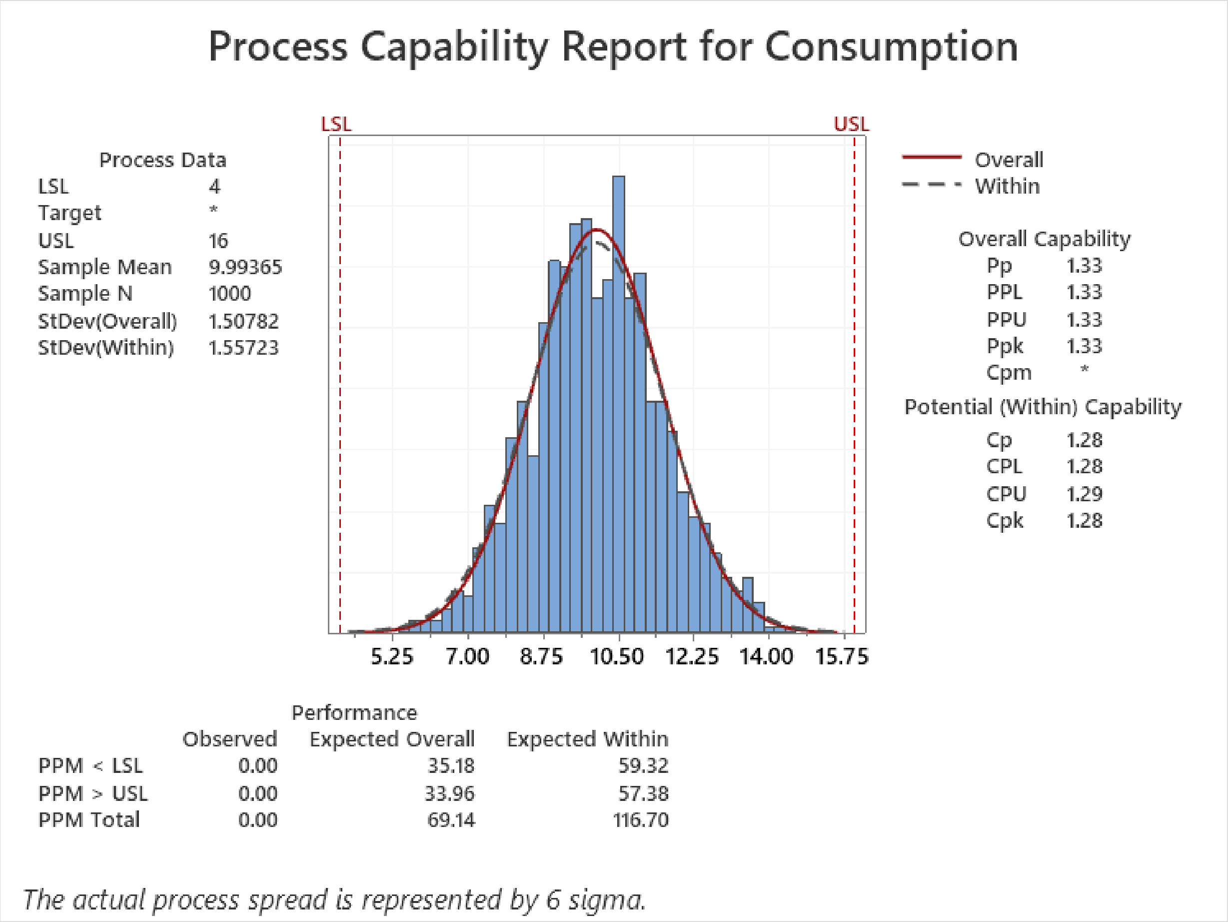
Number of Distinct Categories = 4



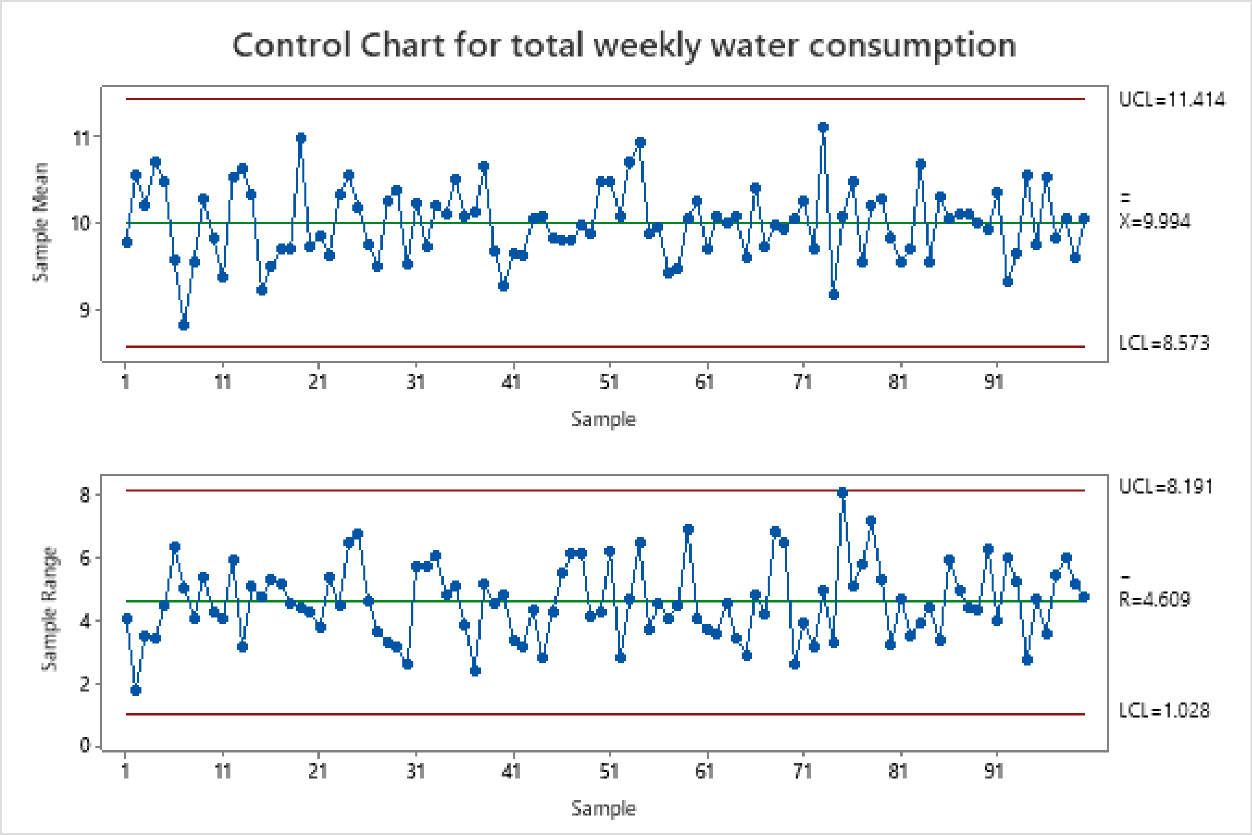
<u>Result</u>: Measurement System is now <u>acceptable</u>: it provides 97.2% of item measure. Errors percentages, by gages (1.39) and operators (1.37), have been reduced with better operator training, and recalibration and/or replacement of the deficient gauges.

Updated Process Capability

We do not have the option of modifying actual water consumption distributions. We can find, implementing a Capability Analysis, the LSL and USL required to obtain a Capability Index Cp of 1.3 or better. We found that an LSL= 4 and USL=16, yield satisfactory Cp = 1.33. Improvement effort then develops water reservoirs of sizes that can deliver such LSL/USL.

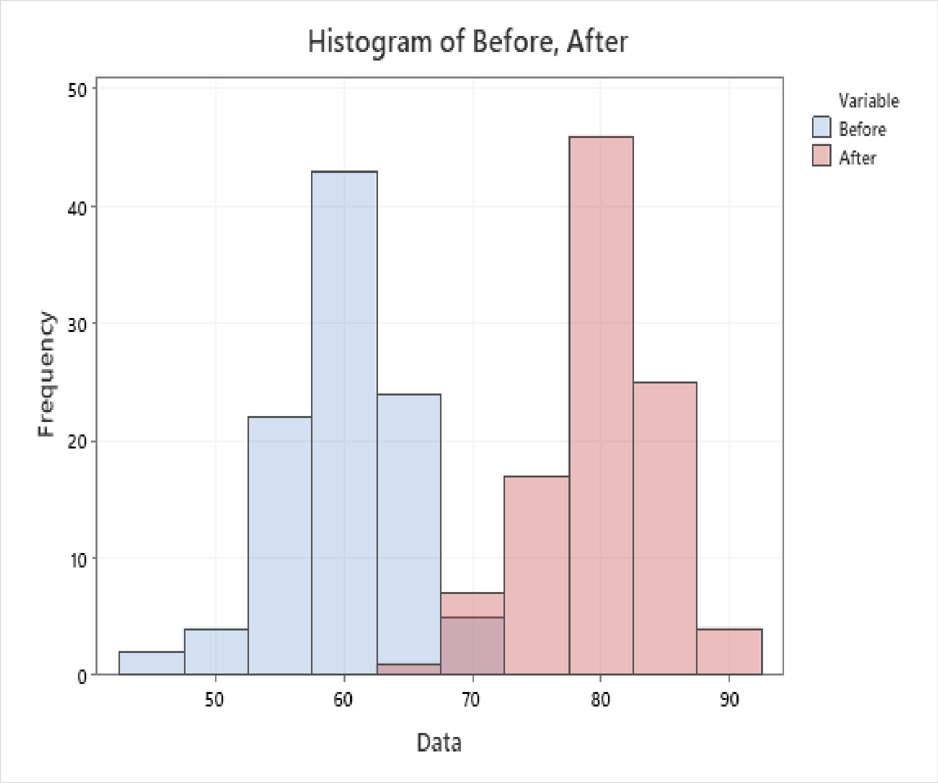


Control Charts (SPC)



After system improvement, the water supply is stable and fulfills customer needs. No data point in the Control Chart falls outside the UCL/LCL Limits, either for the mean nor for the variance.

Statistical Analyses to Prove Results: Customers Served (000s)



Method

μ_1: population mean Before Improve
μ_2: population mean After Improve
Difference: $\mu_1 - \mu_2$
Equal variances are assumed for analysis.

Test

Null hypothesis		$H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis		$H_1: \mu_1 - \mu_2 \neq$
T-Value	**DF**	**P-Value**
-31.06	198	0.000

Estimation for Difference

Difference	**Pooled StDev**	**95% CI for Diff**
-20.100	4.576	(-21.376, -18.824)

After improvement, the system is serving between 18.8 and 21 000s more water customers..

Conclusion

Water problems have been greatly improved:

- Population now uses more water (drinking, washing etc.)
- Cattle can now drink sufficient water to keep healthy
- Grazing grounds can now be irrigated and well kept
- Agriculture can flourish, as there is sufficient irrigation water
- Theft and infighting decreased; with enough water for all
- Need for Rationing water use, has been avoided

Systemic Lack of Water: Droughts

Part III: Designing with Six Sigma

System Doesn’t Exist and Must be Designed.

MFE634: Quality and Productivity

Jorge L. Romeu; Course Instructor
Spring 2025

Phases of Six Sigma for Design (DMAIC)

<u>Define</u>: Project justified, scoped, organized, chartered and Team;
  Water needs v. availability; COPQ, analyze source alternatives, pseudocode;
<u>Measure</u>: Brainstorming, data collection, CTQ, Proc Capability, FMEAs;
  Collect consumption, reservoir capacity, canals, cost/rank alternatives;
<u>Analyze</u>: QFD, design alternatives/assessments, simulation, prototype;
  High level/detailed network design, cost/efficiency, matrices, comparisons;
<u>Design</u>: implement working design/prototype, test them, assess risks;
  Select/implement best design, build/test/simulate canal/reservoir network;
<u>Verify</u>: plan full deployment, Project Capability, documentation;
  Assess building requirements (include De-salinization), Gannt, MSA Analysis;
<u>Write/Deliver</u> Final Report including costs, risks, time frames, etc.
  Develop statistical proof of project savings in human life and resources.

Define Phase

Main Uses of New Water Canals: water distribution from sources to the different users

- To link with the water utility plant, and provide population with:
  - Drinking/potable water; clean washing/bathing water, General Purpose household needs;
- To link with the agricultural needs:
  - Irrigation canals, PG cleaning and support farm purposes;
- To link with the cattle raising needs:
  - Cattle drinking and support water, pasture support water;
- To link with the key public services needs:
  - Fire department, street cleaning, hospitals, schools, etc.

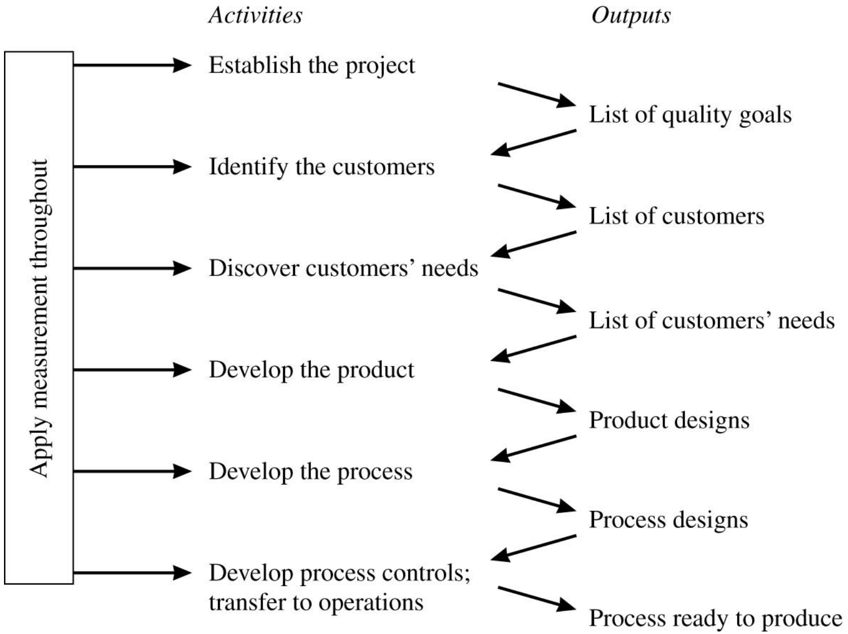
Main Sources of Water Comparisons: some sources are easier to build and more economical to operate;

- Reservoirs, lakes, rivers, wells, desalinization plant; assess each option cost/efficiency

Project Team: civil/agricultural engineers, accountant, health services, sociologist, administrators;

COPQ: lack of water creates serious health issues in humans and cattle and diminishes agricultural output;

Quality Planning Steps:



- Define the Project: distribution of water during drought period
- Quality Goals: sufficient and usable (quality) water by consumers
- Identify/list Customers: citizens, cattle, agriculture, public services
- Needs: drink, bathe, agriculture, cattle, health and public services
- Product development consists of reservoirs, canals, distribution rules
- Development process consists in building the canals, reservoirs, etc.
- Process controls are Charts and Procedures to monitor/operate system

Measure Phase

Similar to DMAIC Phase (but system is not built yet)

- Evaluate needs v. availability relationship through system Process Capability (Poor: 0.55)
- Determine Number/size of reservoirs/canals required to meet system water needs
- Determine design alternatives for the system and their respective cost/efficiency values
- Rank and select the different designs based on their feasibility, costs, efficiency, etc.

Process Capability (PC) Description (next slide):

Six Pack Components:

X-Bar and R Charts help establish that the process under analysis is stable (a PC assumption)

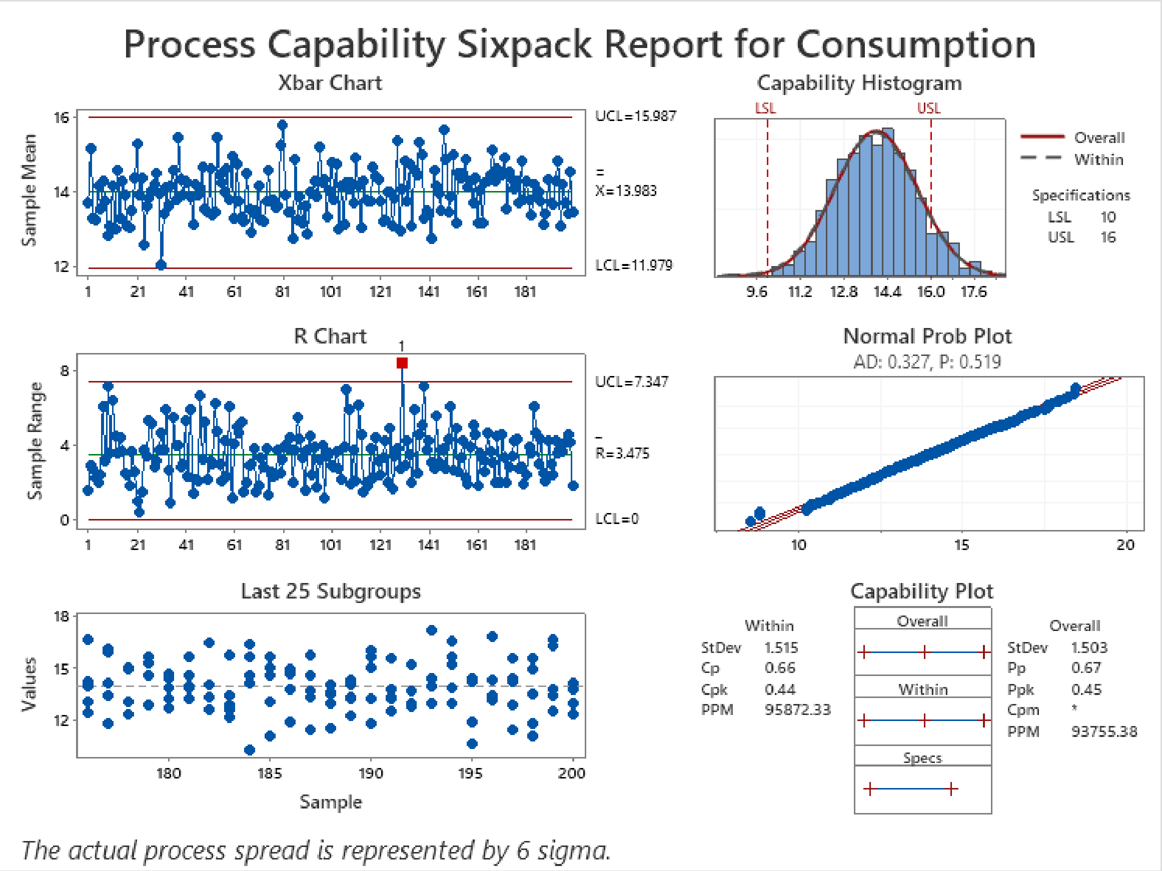
Normal Plot helps establish Normality of process collected data (another PC assumption)

Last 25 subgroups chart helps establish process collected data randomness (another PC assumption)

Capability Calculations:

Capability Ratio Cp = 0.66 (very low)

The Capability of the Process is unacceptable and needs to improve.



Process Capability Sixpack Report for Consumption
Xbar Chart
Sample Mean
UCL=15.987
X=13.983
LCL=11.979
Capability Histogram
LSL
USL
Overall
Within
Specifications
LSL 10
USL 16
R Chart
Sample Range
UCL=7.347
R=3.475
LCL=0
Normal Prob Plot
AD: 0.327, P: 0.519
Last 25 Subgroups
Values
Sample
Capability Plot
Within
StDev 1.515
Cp 0.66
Cpk 0.44
PPM 95872.33
Overall
Within
Specs
Overall
StDev 1.503
Pp 0.67
Ppk 0.45
Cpm *
PPM 93755.38
The actual process spread is represented by 6 sigma.

Measurement Systems Analysis (MSA):

Draw random sample of measurements/operators

Draw a random sample of gauges used

Draw a random sample of sites and measure

Apply Gage R&R procedure to selected variable.

Gage R&R implementation

Calculate and interpret the analysis results

If MSA is acceptable, proceed to measure

If MSA evaluation is not acceptable, then

If issues are due to operator problems, then

Train the operators, or hire better ones.

If issues are due to gauge problems, then

Calibrate or fix the gauges, or buy new ones.

Then, repeat MSA analysis until results are OK

FMEA for Canal Water Transfers from Reservoirs:

Failure Modes and Causes:

Dimensions: not large enough to supply users with their water needs. Needs to increase their size/number.

Evaporation: are due to large reservoir surfaces or slow transfers in canals. Needs to deepen reservoirs.

Leaks: by obstruction of channel or break of canal wall. Loss of water with grave damage to stakeholders.

Theft: of water by users infringing established quotas. Place police and provide enough water to make theft unnecessary

Obstructions: by rocks, mud, earth, tall grass, that slows or impedes water flow. Clean/protect canal environments.

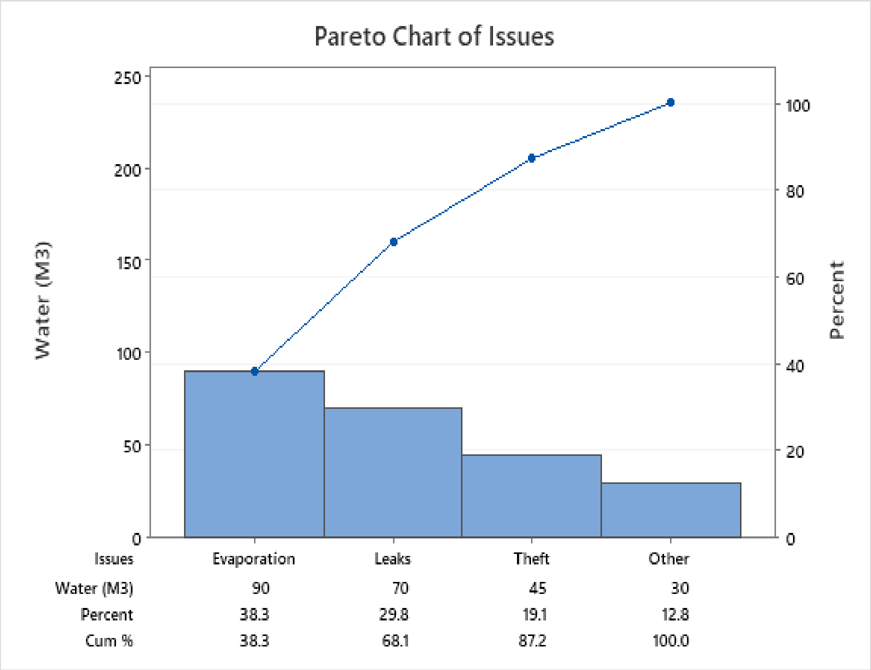
Effects: prevents water transfer schedules; reduces flow.

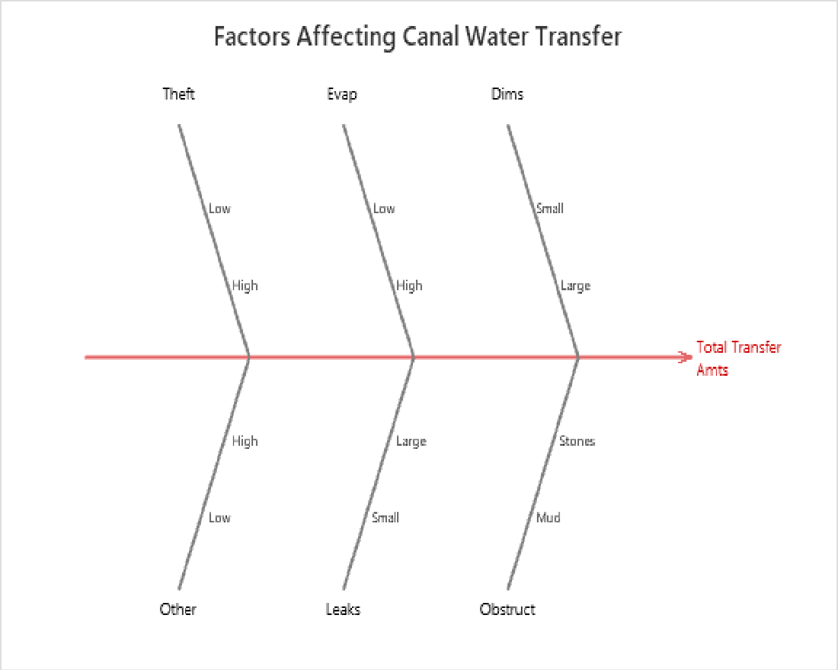
Problem Solutions:

Develop proper maintenance and repair procedures

Develop flow monitoring and SPC control procedures

Pareto and Ichikawa Charts help identify factors that affect water loss and transfer





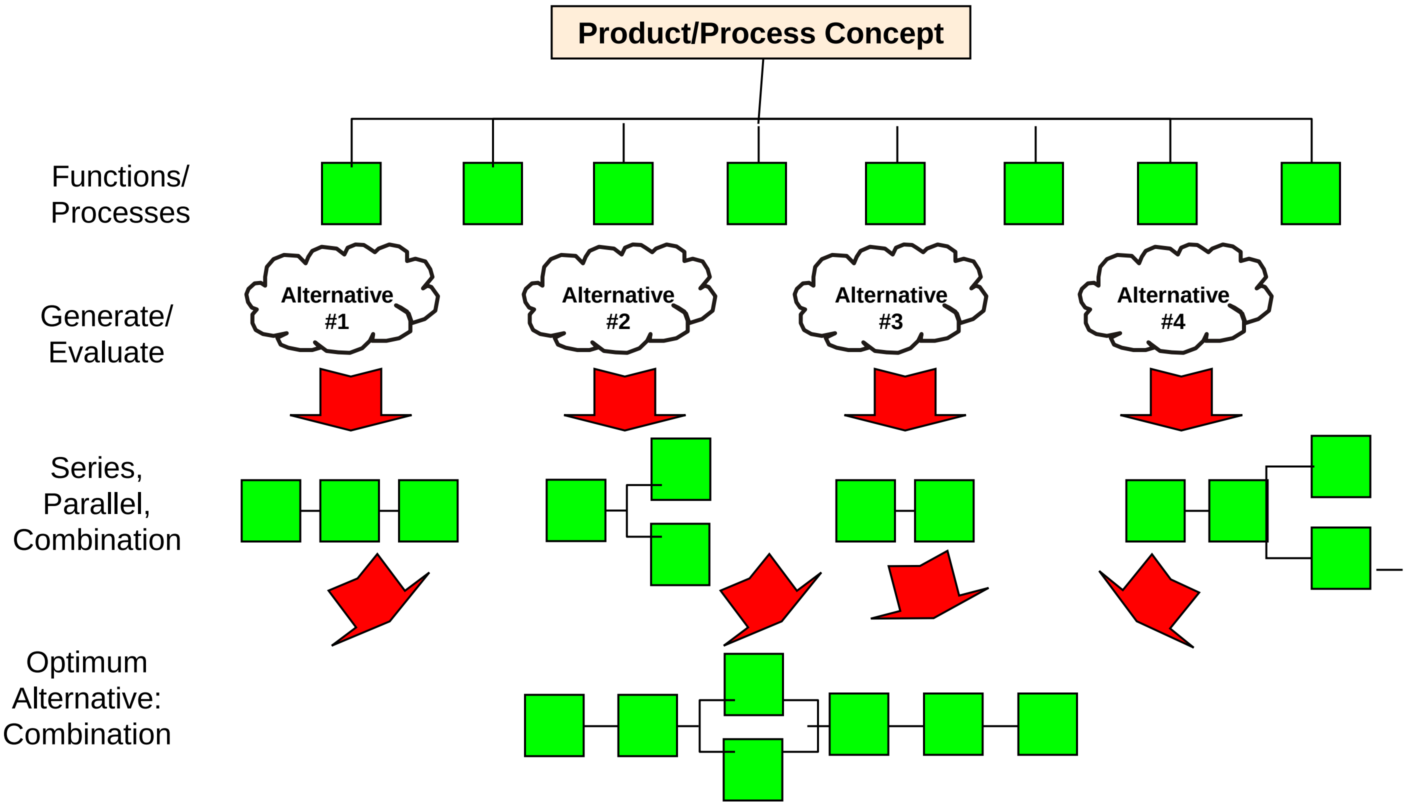
Analyze Phase

Establishing/Analyzing Competing Designs

- Obtain estimates of stockholders' daily water consumption and total reservoir capacity needs
- Obtain estimates of canal network capacity and its regional reach, sufficient to serve the system
- Reservoir availability and canal network must be able to distribute water to all system stockholders
- If not able to provide service, then feasible water alternatives must be sought to achieve it.
- More, or larger reservoirs must be built and wells must be dug, with the canals to support them
- Still unable to provide service, then consider the expensive/complex Desalinization plant solution
- Consider alternative distribution methods to canals, such as pipes, hoses and mechanical pumps
- Consider combination of distribution means and methods, if these are feasible and efficient
- Simulate, using computer languages (e.g. GPSS) the water distribution system operation
- Alternatively, build a physical prototype of the water distribution system to experiment with
- Compare (see next slide) different network topologies, with regard to efficiency and cost
- Perform a system FMEA analysis to determine the risks of system operation
- Evaluate results and select the optimal design from the systems analyses

Develop/Analyze Canal Network Designs

Series/Parallel/Combined Designs



FMECAs help identify problems in the new designs, and improve them.

Function	FailMode	Effects	Severity	Causes	Occur	Detection	Ease	Risks	Actions
Canals	Leak	LostWater	7	Clogged	4	CtrlChrt	8	224	Clean
Pipes	Break	LostWater	8	Rust	6	CtrlChrt	5	240	Replace
Reservoir	Evaporate	LostWater	5	Surface	9	CtrlChrt	7	315	Deeper

We then need to select the best/most cost/efficient design

Solution	Savings	Probs	Cost	Time	PPI
A	8	0.6	0.7	5	1.37
B	7	0.8	0.5	11	1.02
C	12	0.9	0.6	9	2.00

A Design a Series system of the water network

B Design a Parallel system of reservoirs/canals

C Implement a Combination of A & B

Design Phase

- Develop a Detail Phased QFD Matrix Cascade:
  - Perform a water distribution design analysis
- Perform an Efficiency Systems Analysis
- Perform an FMEA of each QFD Phase Matrices
- Perform a risk analysis of the distribution system
- Perform a Design Comparison analysis
- Prepare the final House of Quality Matrix
- Prepare full deployment to build the system
  - Including a Detailed Gannt chart

Example of a QFD (House of Quality) Matrix

<u>QFD Matrix to Help Design</u> a Security System to Prevent Terrorist Attacks in Public Spaces. QFD correlates different Deterrence Options w/different Types of Public Activities.

Event Ratings

0 Little/no impact

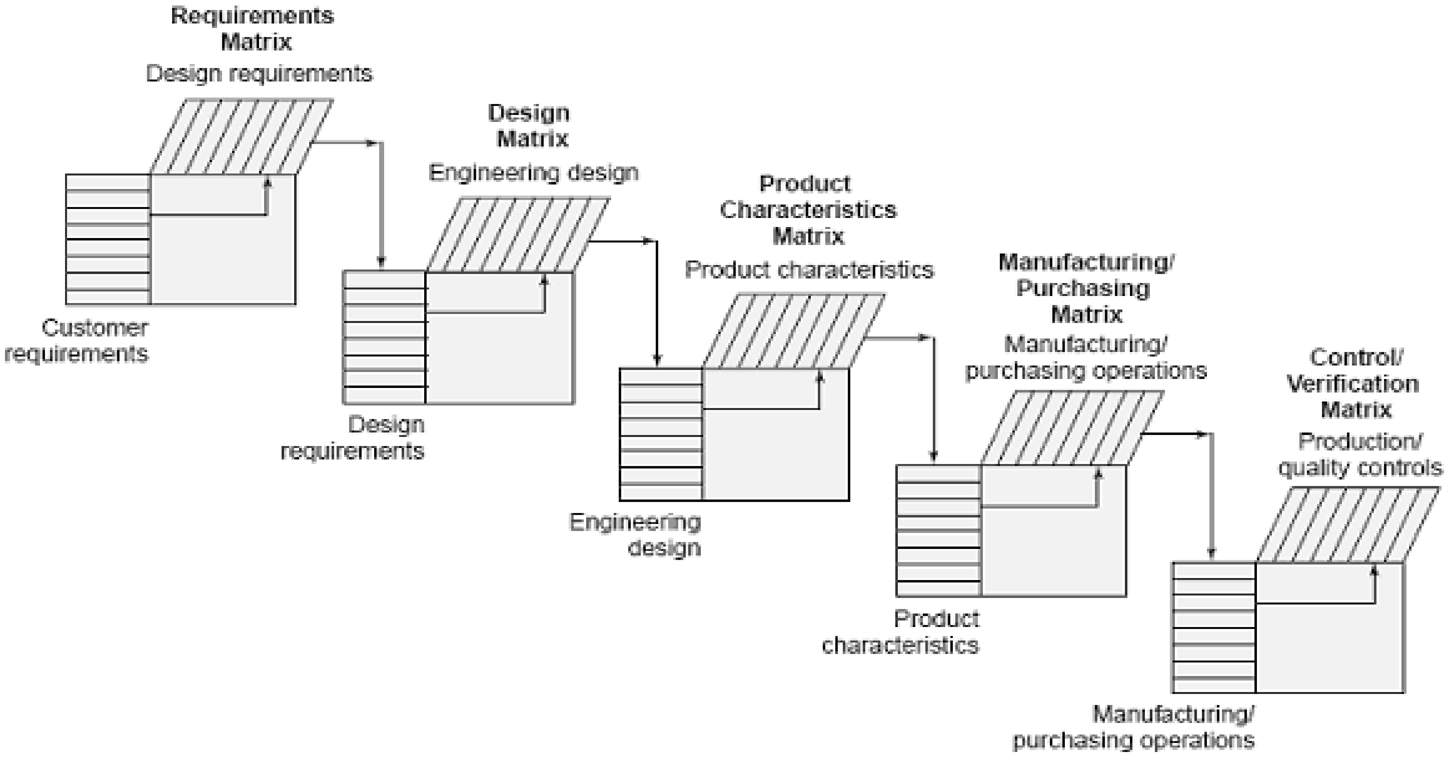
3 Low impact

6 Medium impact

9 Critical Event

VOC/VOE	Police	Covered	Military	FBI/ATF	Chemic	CpSW	Engineer	Medical	Citizens		Fitness	UK	France
Shop. Mall	6	9	3	6	3	0	3	6	9		3	2	2
Stadium/Park	6	9	6	6	6	0	3	6	9		3		
Water Sources	3	3	3	6	9	6	9	9	3		4		
Water Network											3		
Electric Network											3		
Phone/Fax											3		
Internet											3		
Heating Sys.											4		
Fuel Supply											4		
Subways											3		
Airports											3		
Road/Railway											4		
Tot. Ratings	15	21	12	18	18	6	15	21	21				
. Importance	10.2	14.2	8.16	12.24	12.24	4.08	10.20	14.29	14.29				

Figure 2 — Waterfall relationship of QFD matrices

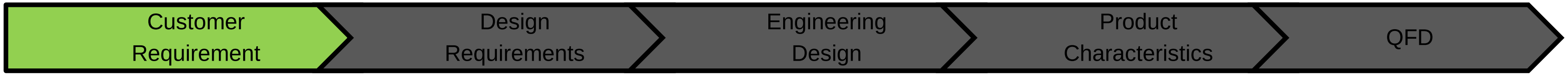


QFD Cascade Matrix: Customer Requirements

Customer needs are satisfied via different solutions: Population needs to drink, bathe, and clean house; Farmers need to irrigate their crops. Cattlemen need ordinary water for cattle purposes; all use different water.

The WHATs and the HOWs

	Customer Needs				
Customers	Drink	Hygiene	Support	Health	Services
Population	9	6	6	6	3
Cattle	9	3	6	3	3
Agriculture		3	9		3
Services	3	6	9	6	3



QFD Cascade Matrix: Design Requirements

To Drink, population needs potable water; if unavailable, clean or running water that can be boiled or filtered. Values 9, 6, 3, provide the levels of need. Services (schools, fire department etc.) can use running water or water from reservoirs.

Needs are satisfied via different engineering solutions

	Design Requirements			
Needs	Potable	Clean	Running	Reservoir
Drink	9	6	3	
Hygiene		9	3	3
Health		9	6	3
Support			9	6
Services			6	3

Customer Requirement → Design Requirements → Engineering Design → Product Characteristics → QFD

QFD Cascade Matrix: Engineering Design

Potable water may be obtained by filtering from storage pools, wells, or from rivers. If potable water needs become very strong, we then get it from a contractor. Clean water, for bathing, cooking, cleaning, etc., is obtained from all other sources except from the filtering plant, which is only for drinking.

Water types are provided from different sources

		Sources			
Rqmts	FilterPlant	StorePool	River	Wells	Contract
Potable	9	3			6
Clean		9	3	6	3
Running			9	3	
Reservoir			3	9	

Customer Requirement → Design Requirements → Engineering Design → Product Characteristics → QFD

QFD Cascade Matrix: Transportation Means

Filtered water should not be transferred via irrigation canals, but through water pipes, to maintain its purity. River and well water for cleaning and irrigation purposes, may also be transferred via canals. Contract water comes in bottles, and is transported via trucks or other vehicles.

Water types are transferred in different ways

		Transportation Means		
Sources	Canals	Pipes	Trucks	Bottled
FilterPlant		9		
StorePool	3	9		
River	9	3		
Wells	3	9		
Contract			6	3

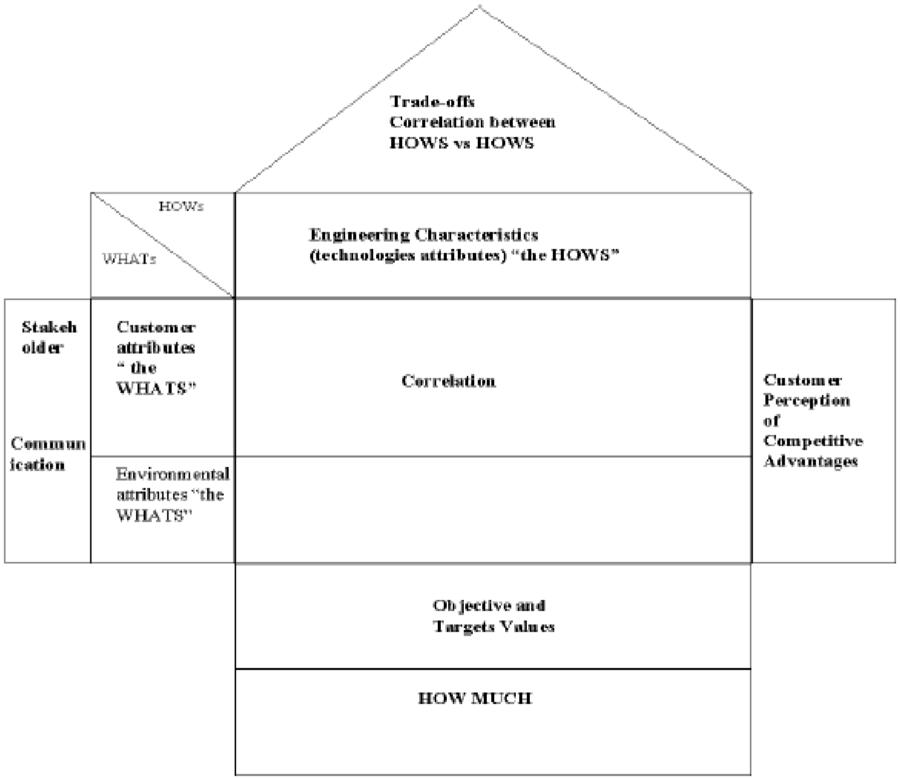
Customer Requirement → Design Requirements → Engineering Design → Transportation Means → QFD

Skeleton of a House of Quality (QFD)

QFD Matrix Description:

Whats are the customer needs

Hows are engineering solutions
Correlation strengths between them are expressed in numbers (3 is low, 9 is strong)
The "roof" provides an association between the different engineering solutions (3,6,9)
Comparison, assess different organizations that have worked on this problem in the past
Technical characteristics of the engineering solutions (mean, variance, upper and lower specifications, max, min, etc.)



Customer Requirement → Design Requirements → Engineering Design → Product Characteristics → QFD

Bottled Water Distribution System

When potable *water is insufficient to satisfy population needs*, contract delivery of bottled water from a supplier. This creates two additional activities. First, to set up *an acceptance sampling scheme*, for analyzing the water quality being delivered by the supplier. Second, to *avoid problems*, at the time of distributing water among the population, use an approach similar to *Talk-Time*, to calculate how *to distribute the water, and staff required* to do so.

Example: assume there are *500 households in the region*, each receiving the same number of bottles of water. And that the *distribution is done in a single day, from 6 am to 8 pm* (14 hours or 14*60=840 min). Then: *Pace = 840/500=1.68 (~2 minutes) is the* time allotted to resolve each instance. Assume that it *takes five minutes to process a customer* (verify user and register water delivery) *and provide the water*. Then we need: 5/1.68=2.97 (~3 employees) to process simultaneously said delivery, to be able to provide water to the 500 town households, in the available 14 hours, from 6 am to 8 pm. We then make an alphabetical list of all household heads, divide these in 14 equal periods of one hour each, and have them come at the stated hour, to pick up their bottled water. *Wait time* is maxed to one hour and *agglomeration*, to a max of 500/14=35.7 (~36 persons).

Verify Phase

Using the physical prototype or the simulation model:

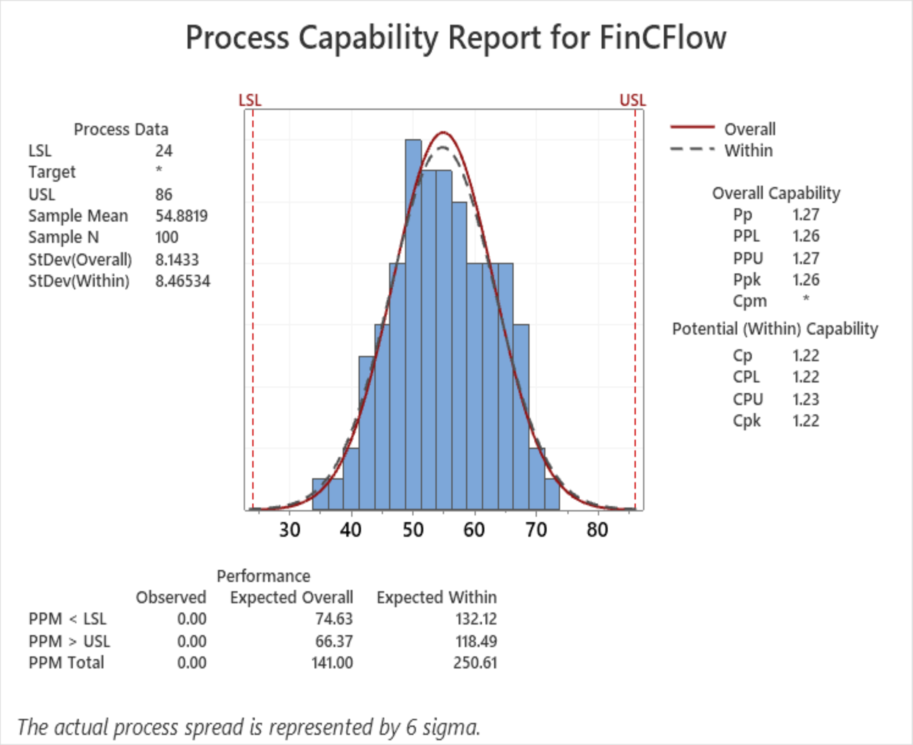
- Perform a final Measurement Systems Analysis
- Perform an FMEA of the final version of the system
- Perform a final Risk Analysis of the distribution system
- Perform a final systems Process Capability analysis
- Prepare the final project documentation
- Plan full deployment to build the system
  - Assess building requirements
  - Detailed Gannt chart

FMECAs help assess and correct problems in the improved designs.

Function	FailureMode	Effects	Severity	Causes	Occur	Detection	Ease	Risks	Actions
Canals	Leak	LostWater	7	Clogged	4	CtrlChrt	8	224	Clean
Pipes	Break	LostWater	8	Rust	6	CtrlChrt	5	240	Replace
Reservoir	Evaporate	LostWater	5	Surface	9	CtrlChrt	7	315	Deeper

The Improved System's design has now different failure modes and risks. We can see that Canals can fail by leaking and pipes, by breaking, both with water loss results. The causes differ: canals are clogged and pipes rust. Reservoirs lose water by evaporation, which a bad design problem (too large a surface). These failures are detected by systematic measurement of the control charts. The greatest risk (315) is posed by the Water Evaporation in Reservoirs, which is thence the first and most important failure to resolve.

The Improved System's Process Capability and Measurement System results are both within acceptable limits.



Gage R&R Variance Components

Source	VarComp	%Contrib.
TotGage R&R	0.09143	2.76
Repeatability	0.03997	1.39
Reproducib.	0.05146	1.37
Operator	0.05146	4.37
Part-To-Part	1.08645	97.3
Total Variation	1.17788	100.00

A Capability of 1.27 is close to acceptable values of 1.3; The MSA loss, due to errors in operator and gauges, is less than 3% . Both problems can still be improved, but measurement system may start working.

Conclusions

Water problems have been greatly improved:

- Population now uses more (drinking, washing etc.) water
- Farmers can now irrigate their crops more often
- Cattle can now have more drinking water
- Grazing grounds are now watered more often
- Services, especially fire department, has more water
- Health levels improve as cleaning can be done more often.
- Cost of system is less than the cost of loss/replacement

Systemic Lack of Water: Droughts
Part IV: Lean and Kaizen Projects

Improving Systems by Eliminating Non-Value-Added Steps
And Streamlining the Flow

MFE634: Quality and Productivity

Jorge L. Romeu; Course Instructor
Spring 2025

Eight Wastes Lean Fights:

1. **Overproduction**: too much or too early
2. **Waiting**: for information, people, materials
3. **Transportation**: moving things around
4. **Process Design**: too many or too few steps
5. **Inventory**: work in progress, electronic files
6. **Motion**: poor layout and ergonomics
7. **Defects**: errors, scrap, rework, etc.
8. **Underutilization**: of personnel or resources

Application Examples of these Wastes

Waste	Example	Implication
Defects	Floodgate door fails to open	Delay in water distribution
Over Production	Too much water is transferred	Water is wasted
Excessive Inventories	Reservoir is too large	Waste of valuable resources
Excessive Motion	Many transfers to same place	Waste of time and resources
Excessive Processing	Multiple Functional moves	More staff needed
Transportation	Unnecessary Moves	Time and Materials lost
Waiting	Waiting for water transfer orders	Cattle/crops fail to use water

Examine all wastes, constraints and customer needs to optimize the system

Kaizen Principles

- Kaisen: continuous improvement

  * Achieved by reducing **the three Evil M’s**
  - **Muda**: waste/non-value-added activities
    - Moving Water from Canal to Canal
  - **Mura**: inconsistent use of people/processes
    - Manual instead of mechanized operations
  - **Muri**: excessive demands on people/processes
    - More water flow than canals can accommodate

Five S System

Sort: keep only necessary things

Maintenance crews keep only key tools

Set in order: arrange efficiently

Use an organized metal toolbox

Shine: maintain cleanliness/avoid clutter

Keep toolbox stored under lock and key

Standardize: proceed consistently

Have all maintenance crews keep same tools

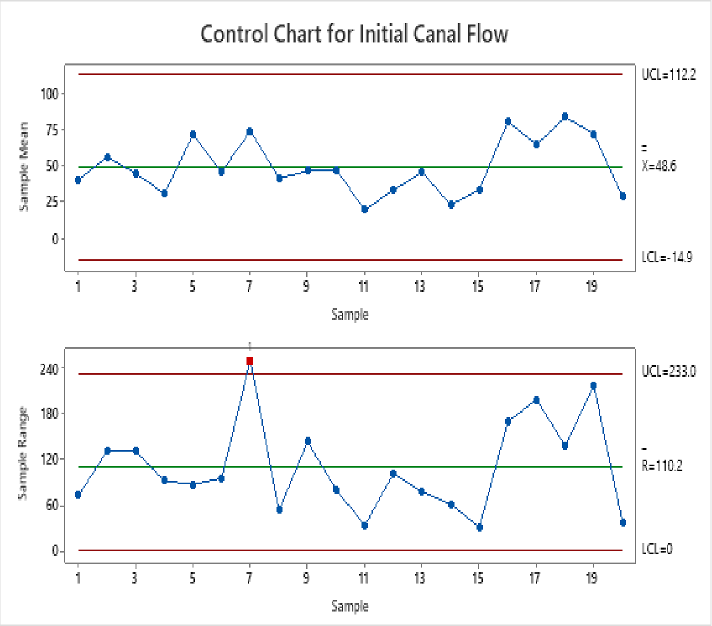
Sustain: a cooperative working environment

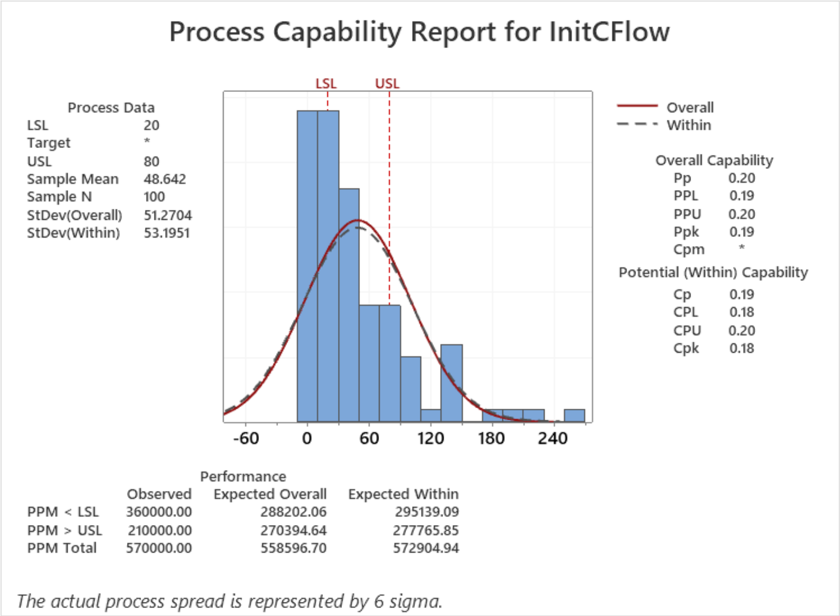
Maintenance crews good working relationships

Five Why's System

- **Why-1**: why is the cattle thinning and dying?
  - Because there is not enough water to drink or grow pasture
- **Why-2**: Why is there not enough water?
  - Because water canals are too small and/or obstructed.
- **Why-3**: Why are canals too small and/or obstructed?
  - Because canals were poorly designed/built, or are clogged.
- **Why-4**: Why were canals poorly built and are clogged?
  - Because canal Planning and Design was poorly conceived.
- **Why-5**: Why was Design poorly conceived?
  - Because the Canal Design team did not follow DFSS procedures

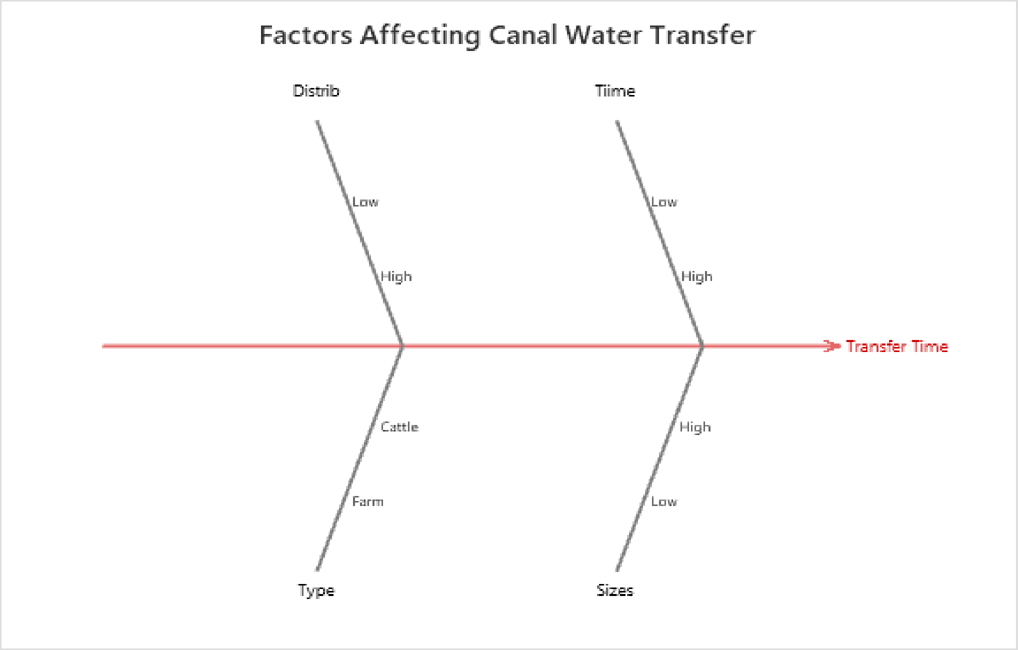
Initial Analysis of Canal Water Flow





Initial Data on the Main Canal Water Flow (cubic feet/unit time) was collected to establish the Baseline: Mean = 48.6 cu-ft; Std-Dev = 51.3. Mean/Range SPC charts shows a large variability. Water Needs defined a Specification Range: LSL=20; USL=80. Process Capability = 0.19 terrible!

Analysis of Canal Water Delivery Times and Potential Factors



Time	Size	Distance
40.616	50	100
37.559	120	220
78.995	30	60
9.309	80	160
83.244	45	90
23.626	70	140
4.709	60	120
59.035	100	200
13.459	35	70
168.026	40	80
120.084	25	50
6.639	50	100

Water is distributed according to number of farm animals (cattle) or irrigated acres (farm size). Test if water delivery times depend on distance, farm size, or animals.

Canal Average Water Delivery Time = 53.8 units; Standard Deviation = 51.0

What is VSM?

- A Value Stream consists of all activities (both value added and non-value added) to bring a product from conception through delivery to the customer

- Value stream mapping is a lean manufacturing technique used to analyze and design the flow of materials and information required to bring a product or service to a consumer

Regression Equation

Time = 107.4 + 3.80 **Size** - 2.39 **Distance**

Coefficients

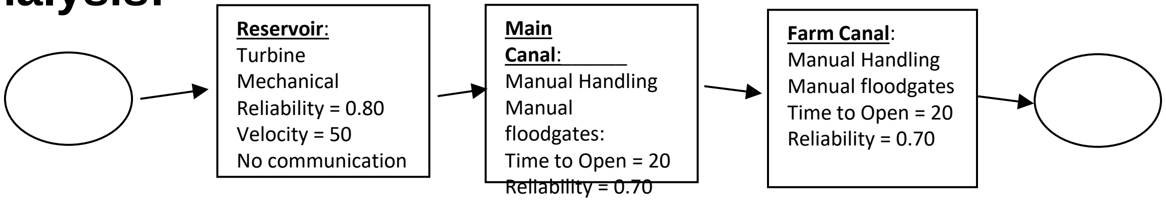
Term	Coef	SE Coef	T-Value	P-Value
Const.	107.4	40.7	2.64	0.027
Size	3.80	6.67	0.57	**0.582**
Dist.	-2.39	3.56	-0.67	**0.518**

Model Summary

S	R-sq	R-sq(adj)
50.88	**18.39%**	0.25%

Factors are non significant (p-values > alpha = 0.05). **Total Time to water Delivery doesn't depend on Factors.**

VSM Analysis:



Current State VSM

Time to Canal Water Delivery is independent from farm distance and size and distributed Exponential (see stat test). Current State Water Delivery Operation Value Stream Map, using existing Canal Network System, shows a need for developing an Improvement Project

Reliability: Quality in Time

We use the previous 12 data points to estimate Mean Water Delivery Time confidence interval (CI) Let T be Total Delivery Time of said 12 data points: T = 645.3. The distribution of 2T/μ, where μ is the Exponential mean, is distributed Chi Square (χ2), with 2n = 2*12 = 24 Degrees of Freedom (ϒ). A 1- α = 95% CI for the unknown Exponential Mean (μ) is obtained using the formula:

$$[2T/ \chi 2(\alpha/2, \Upsilon), 2T/ \chi 2(\alpha/2, \Upsilon)] = [2*645.3/39.4; 2*645.3/12.4 /] = [32.75, 104.08]$$

(where $\chi 2(\alpha/2, \Upsilon)=12.4$; $\chi 2(1-\alpha/2, \Upsilon)=39.4$, are the χ2 percentiles)

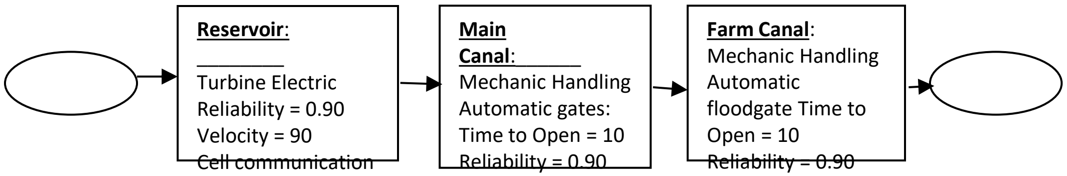
Then, using the Lower and Upper CI limits, and the Average (32.75, 104.08, 53.8) as Optimist, Pessimist and Regular Exponential Mean estimations, we obtain the corresponding Reliability Estimations R(To), of the Probability that a Canal Total Water Delivery takes over 60-time units (i.e., for a Mission Time of To =60):

Optimist Reliability for Mission Time To(60) = Exp(-60/32.75) = **0.160**

Regular Reliability for Mission Time To(60) = Exp(-60/53.8) = **0.327**

Pessimist Reliability for Mission Time To(60) = Exp(-60/104.085) = **0.561**

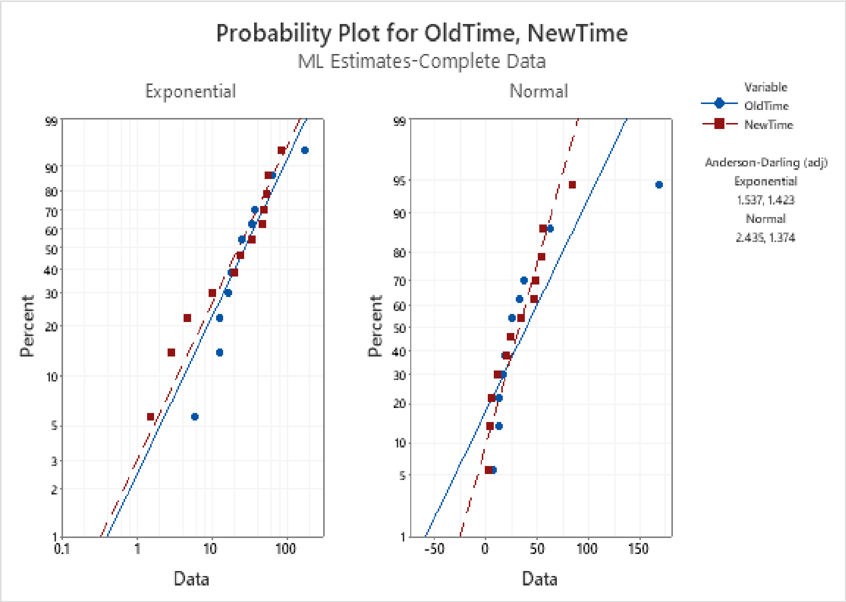
Future State VSM



The Above *Future State* Value Stream Map (VSM), includes improvements made to the System: Canal Water Distribution System was improved by providing gravel bottoms, cell communications between floodgate operators, changing reservoir turbine service from mechanical to electrical and floodgates from manual to mechanical. Improvements reduced delivery times by making faster transfers from Reservoir to Canal and from these to farm reservoirs. This also reduces non-value-added steps. The percent of successful water transfers (Reliability), and Velocity, have also improved significantly.

Times for Improved Canal Water Delivery System are significantly smaller
Average Water Delivery Time = 31.71 and Standard Deviation = 25.9

Comparison of Water Delivery Times Before/After System Improvement



We Test Old v. New Water Delivery Times, using the Wilcoxon Non-Parametric test, for data that is not normally (exponentially) distributed (see plots). Wilcoxon test shows how New Water Delivery Times are faster. Difference between speeds Before/After Improvement, and the Mean Water Delivery Times, are about two time-units faster/better.

Test

Null hypothesis	H_0: $\eta_1 - \eta_2 = 0$
Alternative hypothesis	H_1: $\eta_1 - \eta_2 > 0$

Wilc.-Value	P-Value
168.00	0.156

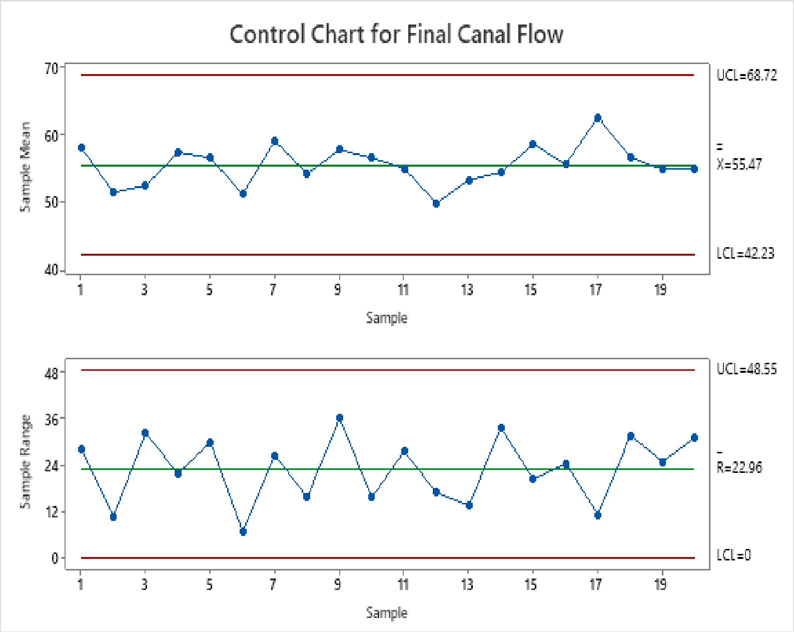
Descriptive Statistics

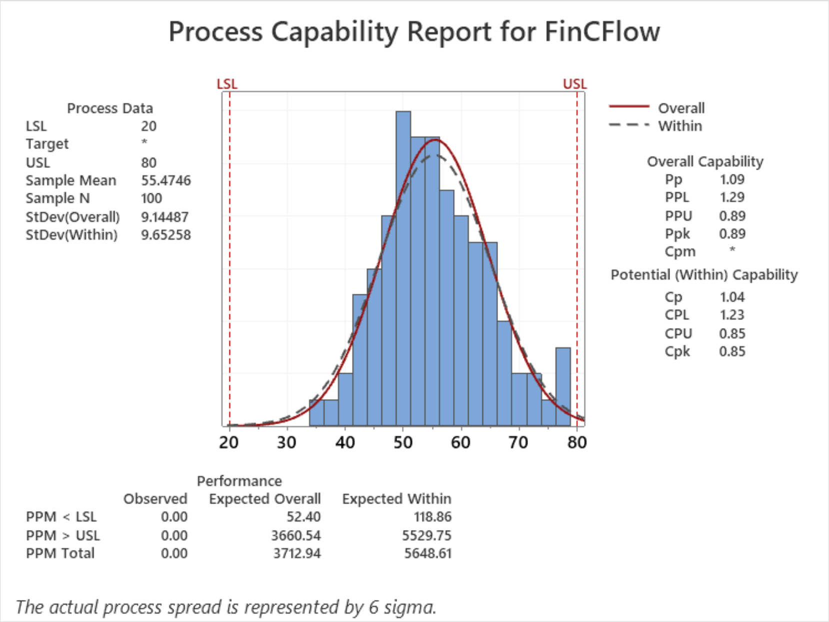
Sample	N	Median
OldTime	12	39.09
NewTime	12	28.55

Estimation for Difference

Difference in Medians	Lower Bound for Median Diffs	Achieved Confidence
10.7439	1.9711	81.46

Analysis of Canal Water Flows After System Improvement





Final Canal Network Water Flow Analysis yields: Mean = 55.5; Std-Dev = 9.2. Comparing with the Initial Flow, Mean Increased by 10%; Variability Decreased five-fold. Water Flow Stability provides steady water input, increasing crop yields, cattle weight and a regular water flow for the population

Advantages of Lean-Six Sigma Combination

Lean/Six Sigma can be conveniently combined:

Lean: reduces waste and improves flow

It Streamlines the system operation to new level

Six Sigma: reduces process variation

It Optimizes the current system operation

Lean alone: only cuts process “extra fat”

Six Sigma alone: improves “as is” system

Their Combination Provides:

A New and Improved System!

Conclusions

Lean Continuous Improvement

* Was able to reduce **the three Evil M's**

- **Muda**: waste/non-value-added activities
  - Easing Water Transfer between Canals
- **Mura**: inconsistent use of people/processes
  - Mechanizing all possible activities
- **Muri**: excessive demands on people/processes
  - Moving to more stable canal water flows.