Systemic Excess of Water: Floods
Part I: Initial Assessment

MFE 634
Quality and Productivity
Spring 2025

Team Members
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Problem Statement

This project analyzes Subtropical Systemic Water Problems: floods & droughts. Jake Jock will analyze flooding, and Dr. Jorge L. Romeu will analyze droughts.

- Scope:
  - Analysis of a specific region with systemic (annual tropical & subtropical problems), such as diversion of flood waters to avoid damages to stakeholders: loss of life (human & animals), housing, property
  - More background can be found here:

  https://en.wikipedia.org/wiki/Tropics
  https://en.wikipedia.org/wiki/Subtropics#Definition

- Not in our scope of study?
  - Occasional problems (transient)
  - Political issues
  - Other regions

Project Topic

- This project aims to apply quality engineering techniques to mitigate drought and flood cycles in tropical savannahs (more information on regional climate here, https://en.wikipedia.org/wiki/Tropics and https://en.wikipedia.org/wiki/Subtropics#Definition).
- Tropical savannahs are common in areas such as Cuba, Gulf of Mexico, Central and South America, India, Indonesia, and several coastal countries in Africa. These region share similar annual seasons, rain and drought. During the rain season, copious amounts of rain inundate the countryside. During the drought season, limited rain burdens residents, cattle, and agriculture from lack of water.
- Input/output models show rain either is evacuated, or water levels rise, causing flooding in surrounding areas. The task is to find a way to evacuated the water at the same rate the rain falls on the ground. Several issues can prevent this. There may not be enough means (rivers, canals, etc.), areas with limited gradient, i.e. flatlands may not allow water to flow quickly enough to the sea, and wetlands close to the sea may cause water to accumulate and block flow into the sea. These issues may cause water levels to rise inundating surrounding areas.
- Furthermore, rainwater from the flood season must be stored for use in the drought season to avoid lack of water. To avoid this, lakes, reservoirs, distribution canals, etc. must be built to store rainwater during the flood season.
- Our project objective is a design and construction of a system that fulfills these discussed requirements. The first part is the flood season, this will be address in this assessment.

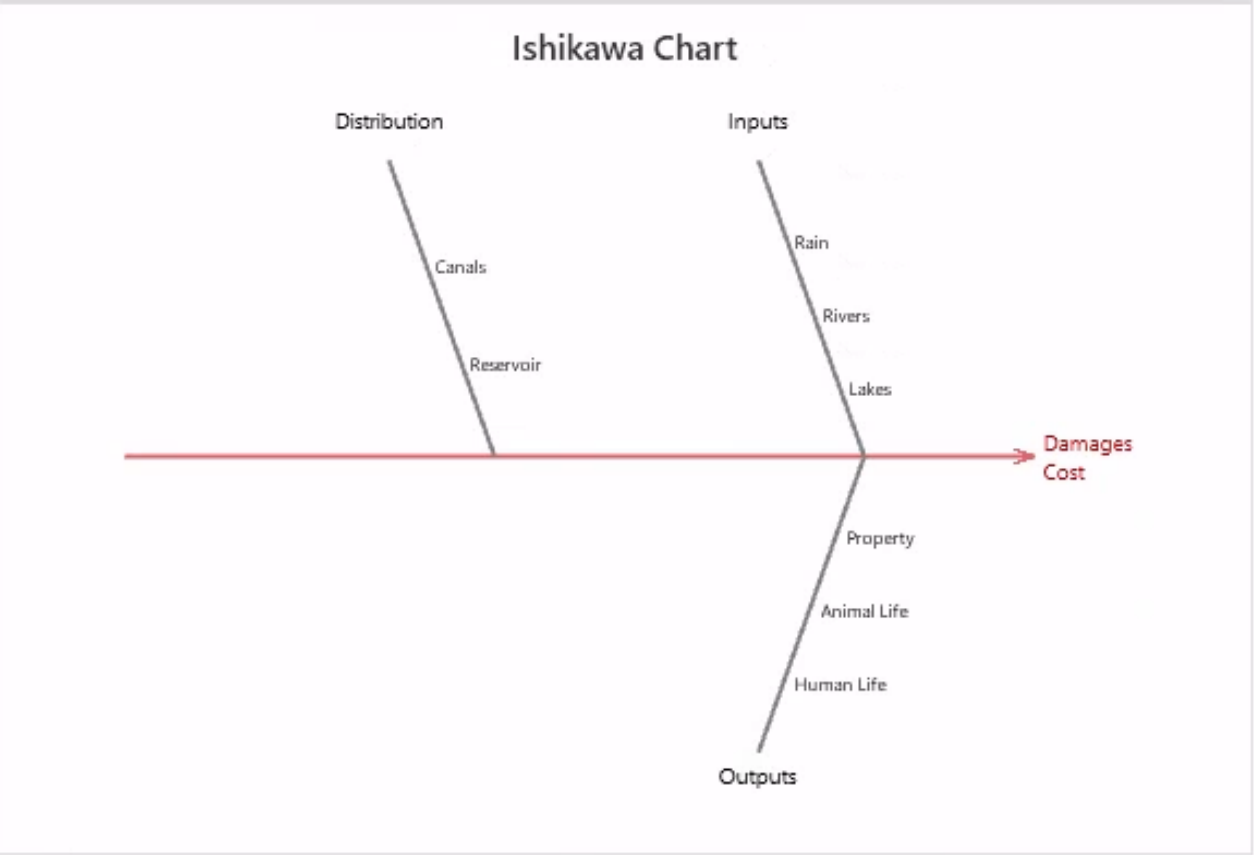
Pseudocode: Flooding

START
Is daily rain distribution known? No. Find it.
Is daily evacuation rate known? No. Find it.
Is upper limit of evacuation know? No. Find it.
Are number of canals know? No. Find it.
Are dimensions of canals know? No. Find it.
Are number of reservoirs known? No. Find it.
Is loss of life known? No. Find it.
Is damage in property and cattle known? No. Find it.
END
Implement a brainstorming session: analyze results
Implement a distribution analysis for key variables
Assess whether variables fulfill systems needs

Brainstorming and Ishikawa

Inputs	Outputs	Distribution
Rain	Human Life	Canals
Rivers	Animal Life	Evacuation Reservoirs
Lakes	Property	Pumps
Marsh		

Ichikawa/Fishbone Diagram: This provides a description of how problem factors affect responses or performance measures. This qualitative diagram can become a model for quantitative regression.

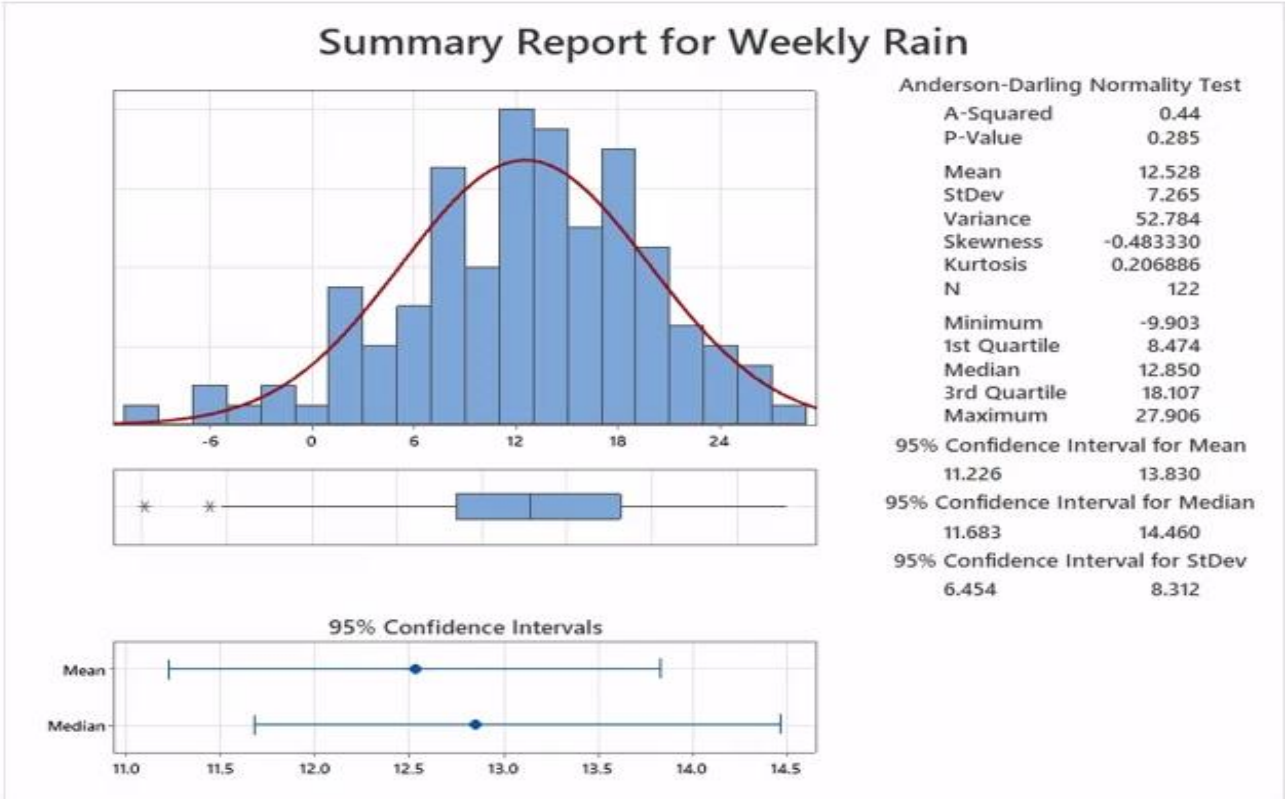


Cost of Poor Quality for Flooding

COPQ	Flooding			
Process	Internal Failures	External	Apprasials	Prevention
Evacutation Canals	Blocked Canals	Loss of life Property damage	Weekly inspection	Periodic Cleaning
Evacutation Canals	Small capacity	Loss of life Property damage	Weekly Measure	Canal Modification
Reserviors	Small capacity	Loss of life Property damage	Weekly Measure	Reservoir Modification

For flooding it is crucial to determine whether input (rainfall) is < output (water evacuated). If this condition is not met, improvement project will be to create a system that meets this requirement.

Weekly Rain Distribution (cm)



We will need the rain distribution to plan to meet the requirements of rain evacuation, or what additional resources will be necessary for this. Data has been found for total daily precipitation for Havana, Cuba. This data needs to be processed in Python, but it will give a realistic rain distribution, with proper standard deviation. (Current distribution is inaccurate, and shows “negative” rain)

Overview of Improvement Work

- Determine monthly rainfall, evacuation rate, storage
- Determine if current evacuation rate fulfills system requirements
- Determine canal number and capacity
- Determine if this capacity exists or needs to be created
- Determine how water will be evacuated, canals, rivers, reservoirs
- Determine how water will be distributed throughout evacuation system
- Determine how evacuation system will be managed
- Determine costs of Flooding and improvement project

Conclusion

- Excess water problem needs to be solved
- Cost of flooding is larger than cost of improvement project
- Key information needs to be found from pseudocode
- Continue by defining CTQ (critical) issues
- Rank critical issues by importance, monetary
- Leadership needs to be convinced of project need
- Concludes initial assessment phase
- Next is the Six Sigma analysis

Systematic Excess of Water: Floods
Part II: Six Sigma DMAIC

System exists, but is inefficient and needs improvement

MFE 634: Quality and Productivity

Jake Jock

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: SS black belt, civil and industrial engineers, accountant
- Brainstorming with community leaders/stake holders
  - Determine key CTQ elements

  Propose projects with their characteristics

  Project charter and operational plan

  Gann chart with personnel load

Initial COPQ

- After brainstorming sessions with the stakeholders, and after interviewing system users and technicians, the costs were found

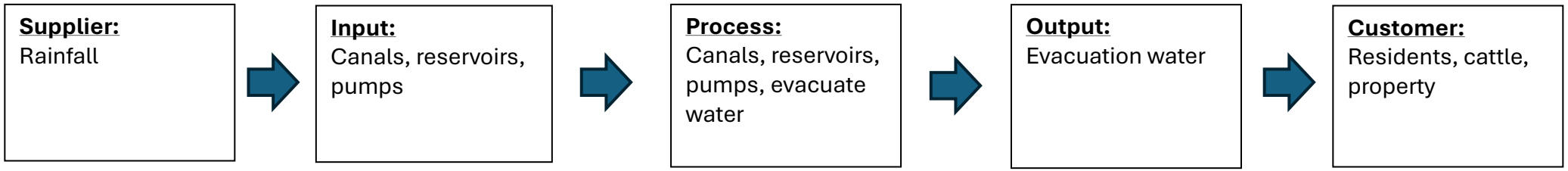
COPQ: Flooding				
Process	Internal Failures	External	Apprasials	Prevention
Evacuation Canals	Blocked Canals	Loss of life Property damage	Weekly inspection	Periodic Cleaning
Evacutation Canals	Slow Drainage	Loss of life Property damage	Weekly Measure	Canal Modification
Reserviors	Small capacity	Loss of life Property damage	Weekly Measure	Reservoir Modification
Marshes	Limit rainwater drainage	Loss of life Property damage	Weekly Measure	Addition of Pumps to Evacuate

Long-term material losses will be much higher than improvement costs. This situation justifies implementation of an improvement effort

System Operation

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

Water is obtained, distributed, and consumed by system users

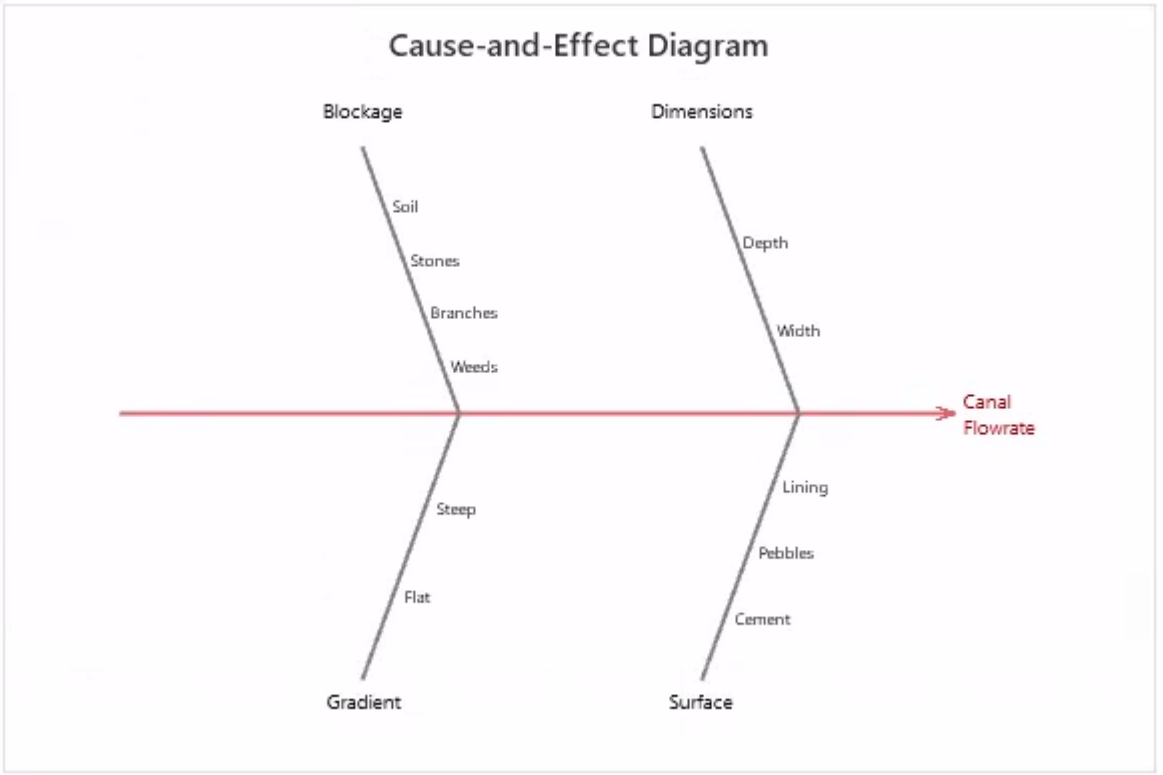


System needs to evacuate rainfall at the same rate the rain is falling. This system will be obtained by building canals with proper gradients and bedding, deeper reservoirs, and a pump system to drain marshes.

Project Selection

Solution	Savings	Prob	Cost	Time	PPI
A	100	0.3	50	1	0.6
B	900	0.6	400	1	1.35
C	1000	0.8	400	1	2
D	2000	0.9	800	1	2.25

A	Maintenance to clear blockages
B	Increase dimensions of canals
C	Install pumps to drain wetlands near ocean
D	Combination of A, B, & C



Project D, a combination of the above projects was select as it has the highest PPI = 2.25

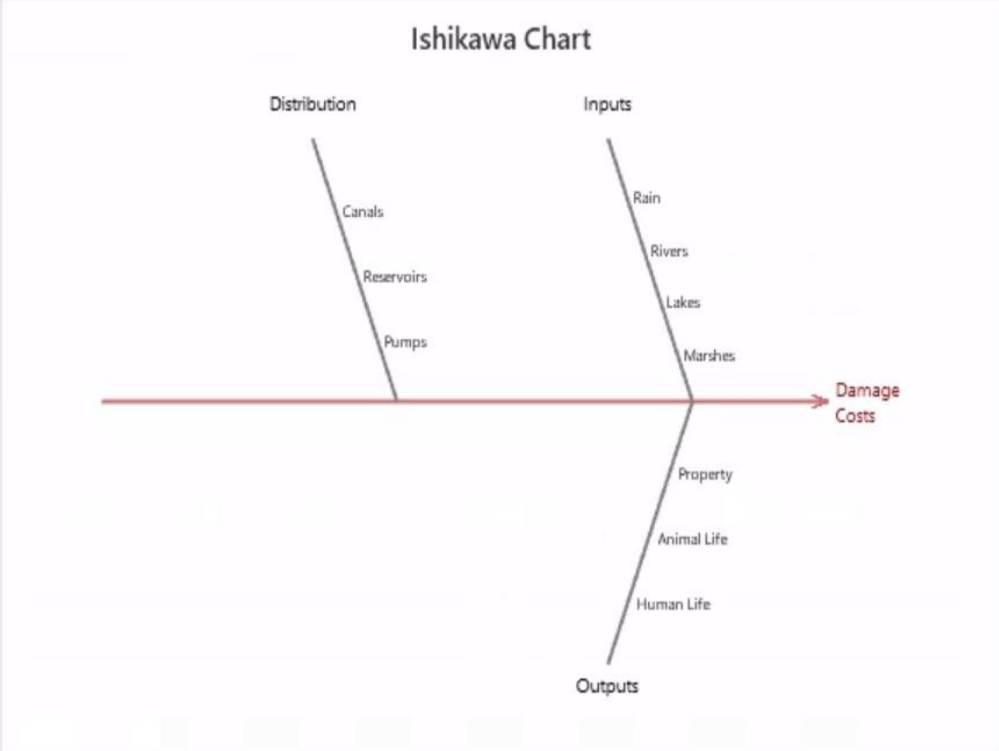
Some factors that affect flow rate of the canal, including dimensions, blockages, surfaces, and gradient.

Measure Phase

- Plan data collection: items and places
- Collect rainfall data and evacuation rates
  - Different sites from different users
- Establishment/discussion of LSL/USL values
- Initial Capability Analysis of Rainfall Evacuation
- Establishment of rainfall evacuation rules
- COPQ of Rainfall evacuation network
- FMEA of rainfall distribution network

Factors Affecting Rainfall Evacuation

Inputs	Outputs	Distribution
Rain	Human Life	Canals
Rivers	Animal Life	Evacuation Reservoirs
Lakes	Property	Pumps
Marsh		Drinking Reservoirs



Rainfall Evacuation Methods:
(1) Canals & Reservoir system, (2) Pumps
Rainfall Evacuation Schedule:
(1) Daily, (2) Weekly, (3) Other
Rainfall Evacuation

Rainfall evacuation methods (Canal & reservoir system, pump system), water sources (rainfall, rivers, lakes, marshes) and its unwanted displacement (homes, property, people, cattle) affect cost of damages.

Measurement System Analysis

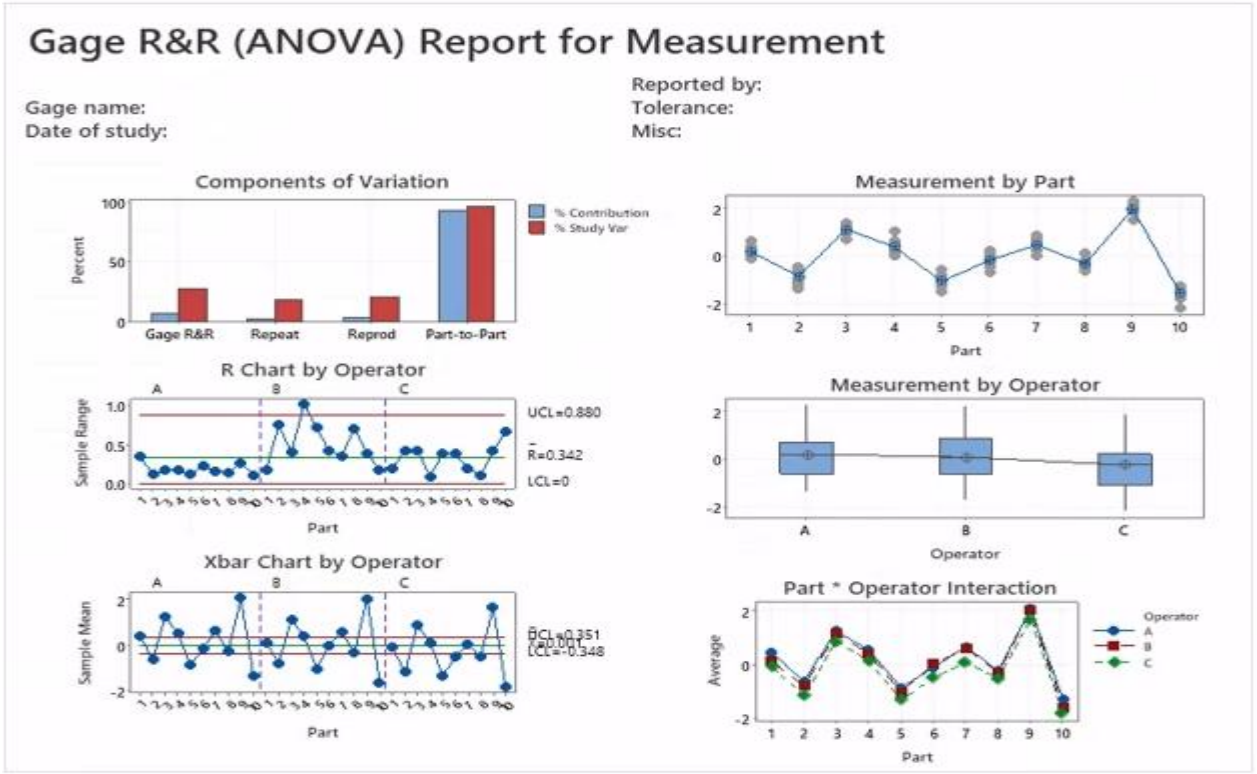
Gage R&R

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



Results: The measurement system is weak, the gauges (3.39) show repeatability error and the operators (4.37) show reproducibility error. The operators will need to be retrained, and the gauges will need to be recalibrated or replaced. After this, another R&R will need to be conducted.

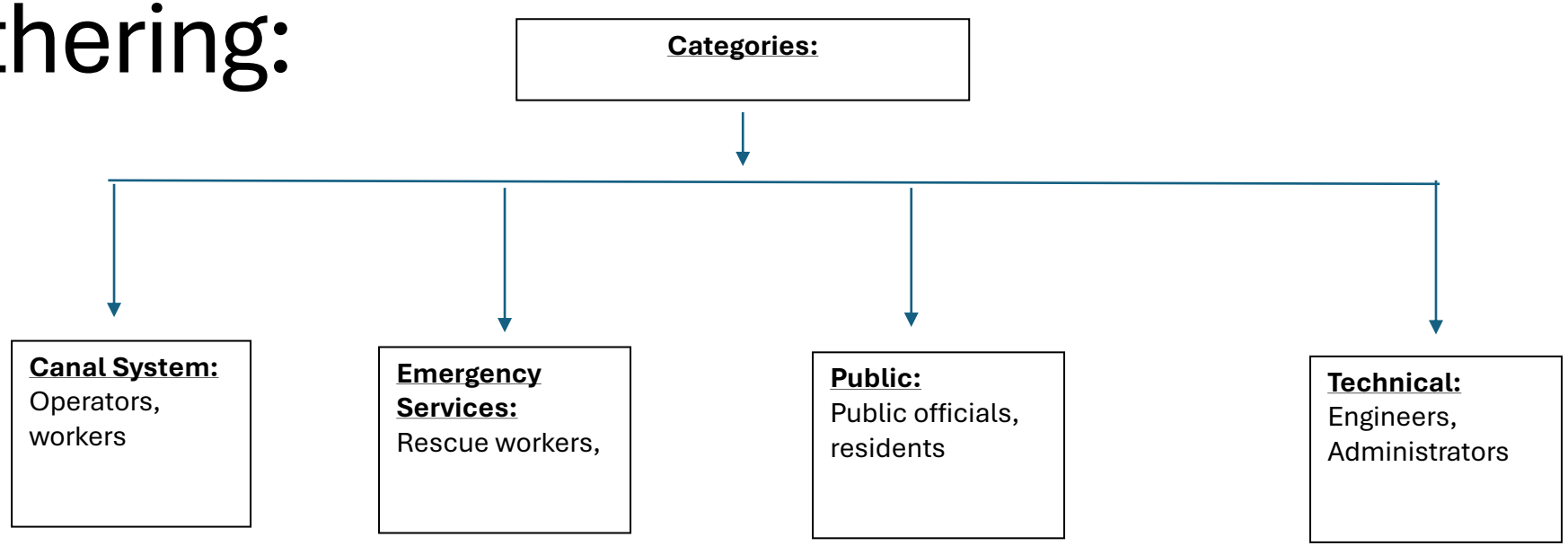
COPQ: Flooding				
Process	Internal Failures	External	Apprasials	Prevention
Evacuation Canals	Blocked Canals	Loss of life Property damage	Weekly inspection	Periodic Cleaning
Evacutation Canals	Slow Drainage	Loss of life Property damage	Weekly Measure	Canal Modification
Marshes	Limit rainwater drainage	Loss of life Property damage	Weekly Measure	Addition of Pumps to Evacuate

Additional Concerns and Questions about Rainfall Evacuation

- Rain schedule cannot be altered/modified
- Rainfall evacuation can be optimized
- Blockages can be minimized
- Evacuation system can work efficiently

Further investigate these issues by interviews with system stakeholders. Find the root-causes for each problem and propose solutions.

Organization Tree for Data and Information Gathering:

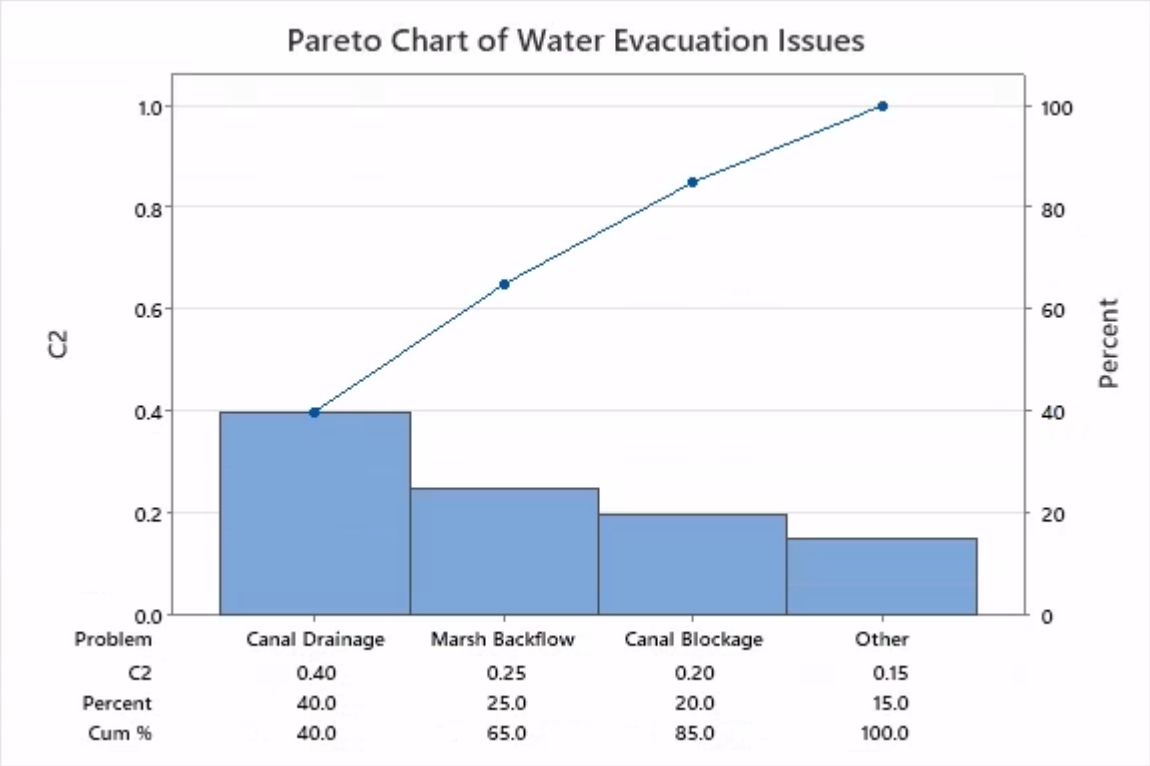


Interview individuals from each category, send them a questionnaire, set dates and times

Obtain information about possible problems, hypothesize cause and effects, and propose some solutions

From information implement pareto charts and FMEA analyses to rank possible projects to attack those with higher impact and probability of success.

Pareto Chart of Principal Problems



Problem	Canal Drainage	Marsh Backflow	Canal Blockage	Other
C2	0.40	0.25	0.20	0.15
Percent	40.0	25.0	20.0	15.0
Cum %	40.0	65.0	85.0	100.0

The pareto chart shows canal drainage is the critical cause of flooding; FMEA shows that improper design of the canals is a key factor; improving gradient and dimensions may be a solution.

FMEA Analysis of Initial System

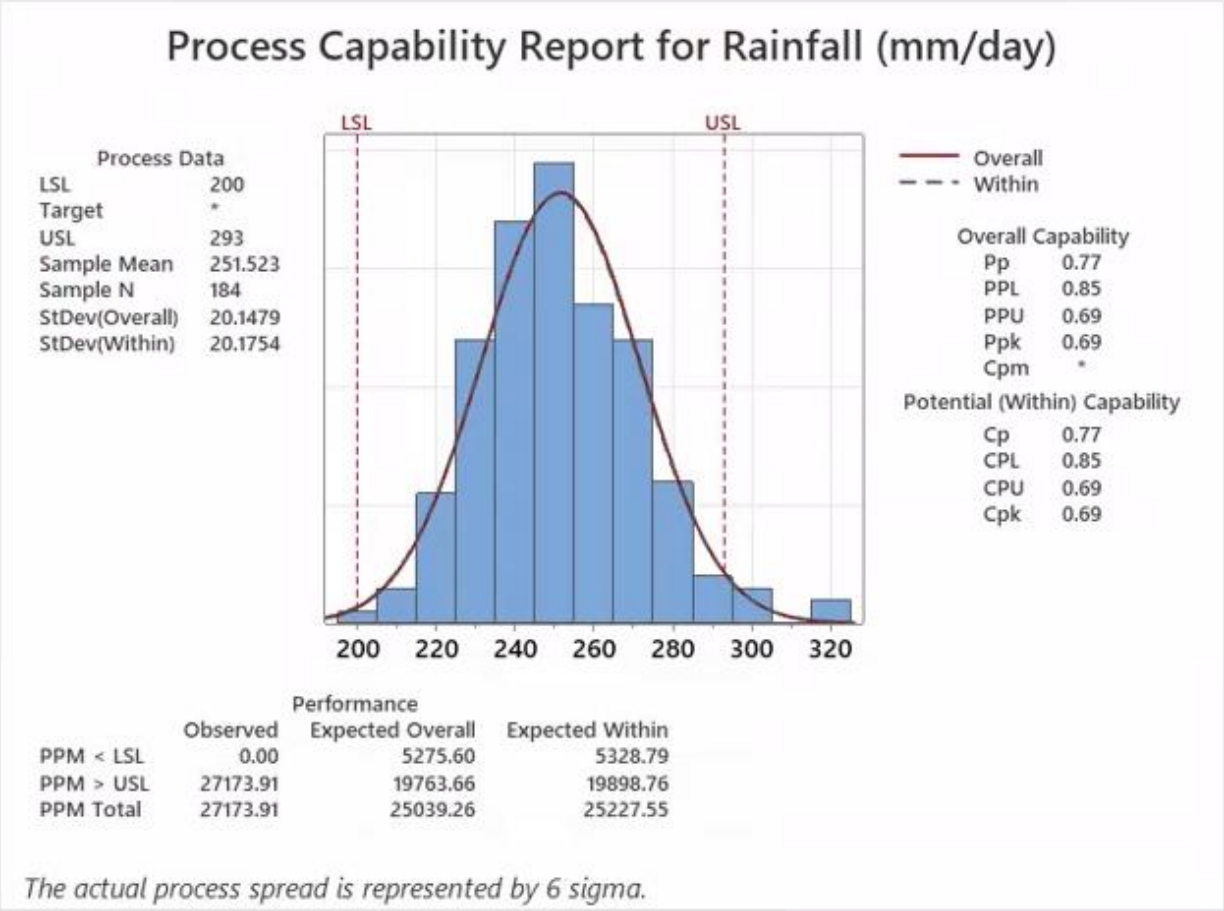
Function	FailMode	Effects	Causes	Detection	Actions
Canal	Blockage	Flooding	Debris	Ctr Chart	Maintainence
Canal	Slow Drain	Flooding	Improper Design	Ctr Chart	Improved Dimensions
Marsh	Backflow	Flooding	Slow Drainage	Ctr Chart	Pump/Canal Additions

Control charts will be used to measure water levels and flowrates through canals and help detect overflow of water.

Flooding can occur from improper specification of canals' gradients and dimensions. Control charts can be used to indicate increasing water levels, though this does not specify the cause of increasing water levels.

To determine root causes and provide solutions to avoid flooding a detailed root-cause analysis can be conducted.

Average Daily Rainfall during Flood Season (m^3/s)



Water specification limit (evacuation):
LSL: Less is irrelevant
USL: Over USL will cause flooding, loss of life, and damages to property as needs are unmet.

Initial Capability Ratio is 0.77 which is quite low. We are not able to control daily rainfall, however we can change the USL (Evacuation rate) by improving the gradient and dimensions of the canal during the drought season. USL is the water evacuation limit

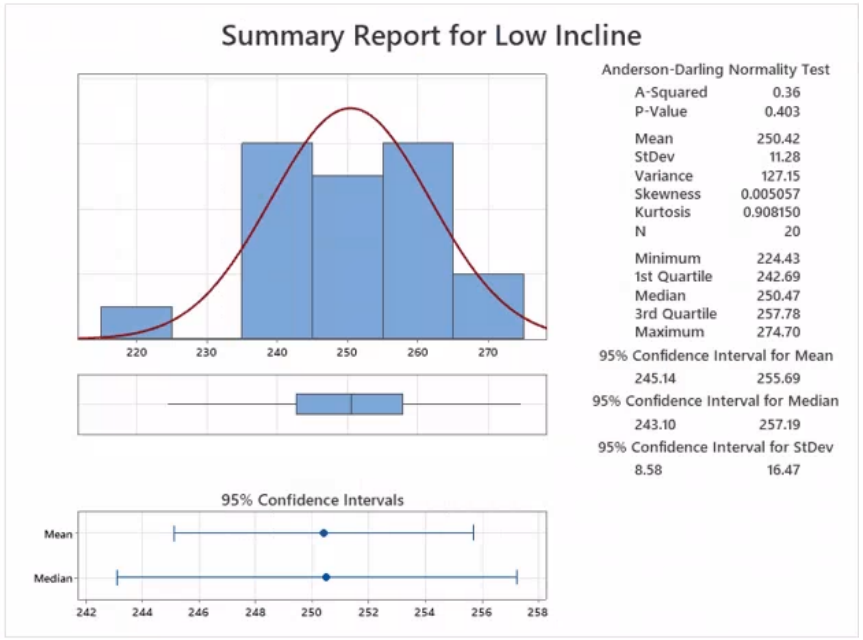
Analyze Phase

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 problems
Hypothesize possible solutions
Assess and Rank solutions

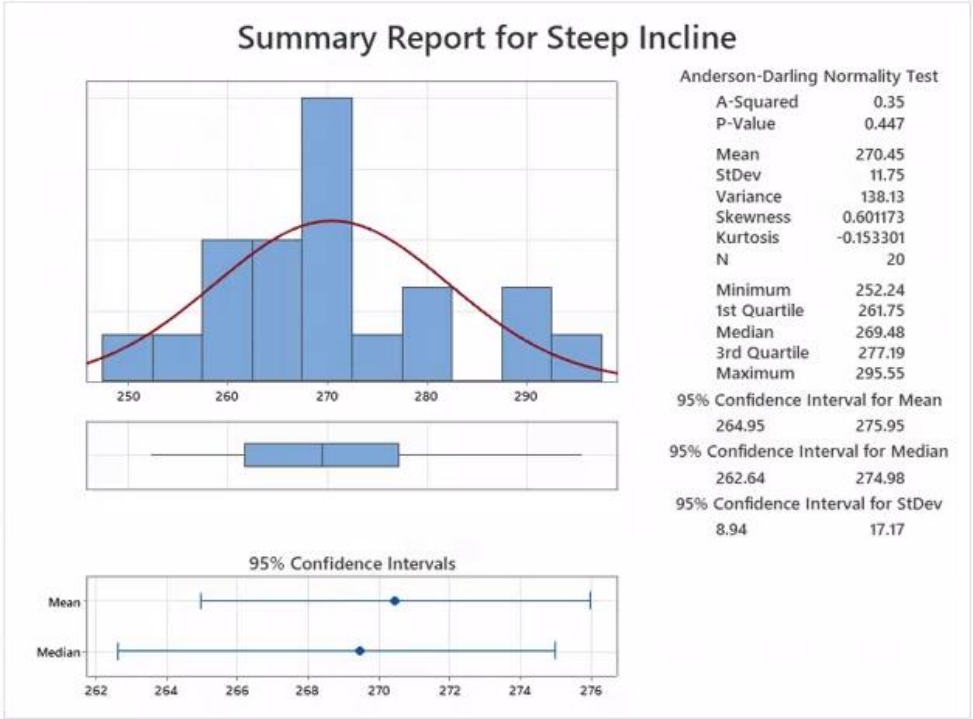
Examples

List of Theories:

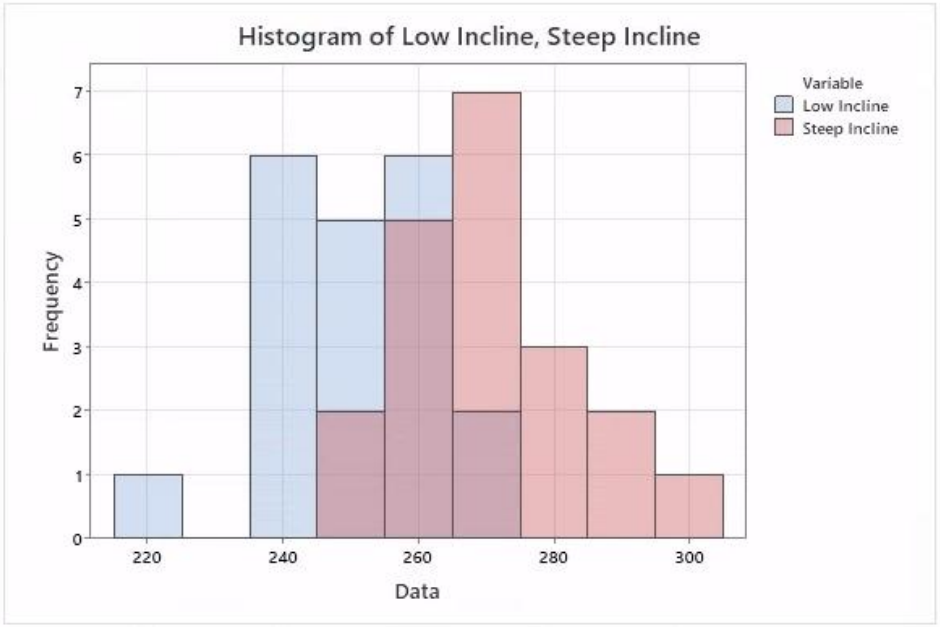
- Canals with steeper gradients perform better
- Deeper canals perform better
- Gravel at bottom of canals perform better
- Pumps to drain marshes increase drainage

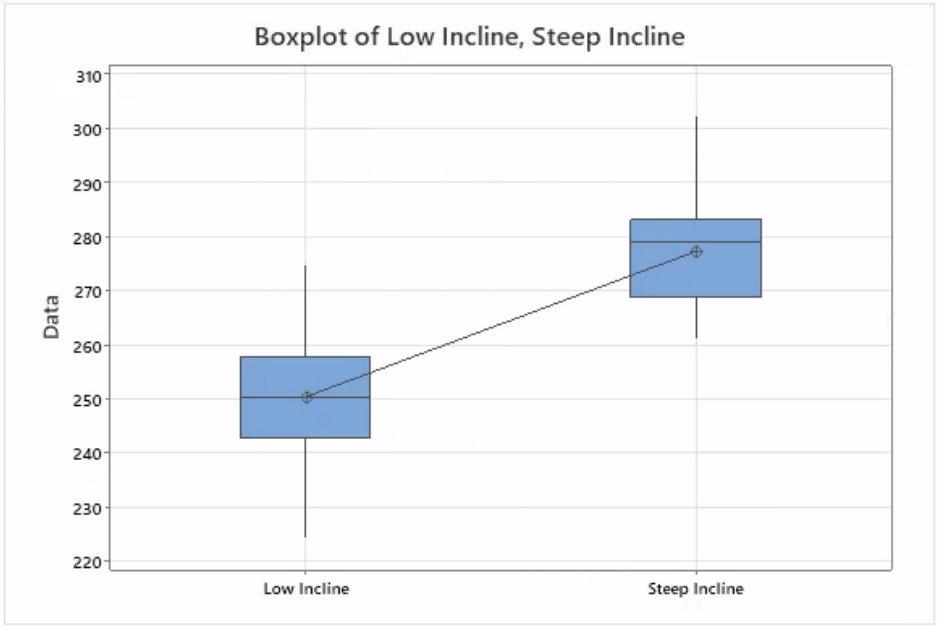


Statistics show that canals with steeper gradients evacuate water faster. We will need to perform physical experiments and perform statistical tests on collected data to demonstrate the theory.



Example of Statistical Analysis: Canal with steeper gradient evacuates more water





Test

Null hypothesis	$H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis	$H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-8.02	38	0.000

Descriptive Statistics

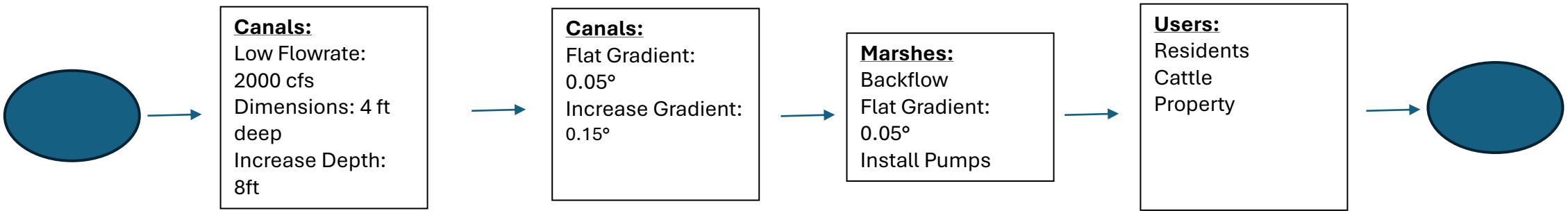
Sample	N	Mean	StDev	SE Mean
Low Incline	20	250.4	11.3	2.5
Steep Incline	20	277.34	9.91	2.2

Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
-26.92	10.62	(-33.72, -20.13)

A hypothesis test was implemented to assess the theory that flow rates differ. The results show that steeper canal gradients have significantly higher flow rates: (20.1 to 33.7)

Value Stream Map (VSM) (Current State)



VSM quantifies the operation of the rainfall evacuation systems so the process can be optimized. The current factors of dimensions of the canals, gradients, and benefiters of the systems, determine the efficiency of the rainfall evacuation system currently.

Two value stream maps will be developed: one before the system is improved and one after the system is improved. 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 FMEA and Process Map
Implement Solution as Pilot program
Upgrade the solution to the entire system
Address resistance to change issues

Selection of most cost/efficient solution (improvement strategy)

Solution	Savings	Prob	Cost	Time	PPI
A	100	0.3	50	1	0.6
B	900	0.6	400	1	1.35
C	1000	0.8	400	1	2
D	2000	0.9	800	1	2.25

A	Maintenance to clear blockages
B	Increase dimensions of canals
C	Install pumps to drain wetlands near ocean
D	Combination of A, B, & C

From the PPI index results, a combination steeperand deeper canals, blockage maintenance, and a pump system to drain wetlands causing backflow of flood waters near the ocean has been selected. The PPI index indicates that this solution is the most cost efficient as it has the best combination of time and probability to completion, flood damage savings, and development costs.

Design of Experiments (DOE) Description

The factors identified will need to be experimented to determine if they improve water evacuation in the system. From brainstorming, interviews, and FMEA analysis, we have determined that the flow of water is affected by the gradient of the canal.

We will implement a two factor DOE by using a sample of canals with the required length, width, and gradient. We will also sample canals without these desired dimensions. From these samples we will measure water flow among them under the same conditions (temperature, weather, etc.)

Factor A is an increase in depth and factor B is an increase in gradient of the canal (this will be done by reconstruction of canals in lands with steeper gradients). This results in four different possible combinations (experimental treatments). We will implement three replications for each treatment, in a random order, to avoid any correlations or effect of extraneous factors.

The results on the next slide demonstrate that both depth and gradient are statistically significant (impacts flow) and have interaction. This data for interaction of factor A and B yield a p-value = 0.045, this means that it is unlikely that this effect occurs due to randomness and is due to interaction. Furthermore, we obtained an R-squared valued of 96.98%, meaning the model and the interaction fit the data well.

Design of Experiments (DOE) - Minitab

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		7.128	0.390	18.28	0.000	
A	8.328	4.164	0.390	10.68	0.000	1.00
B	1.947	0.974	0.390	2.50	0.067	1.00
A*B	2.245	1.122	0.390	2.88	0.045	1.00

Model Summary

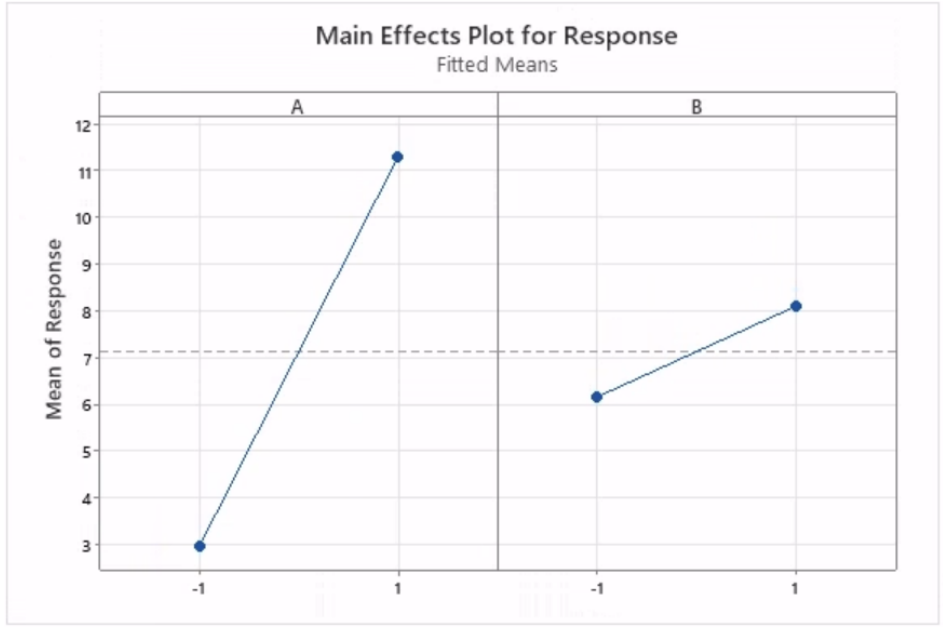
S	R-sq	R-sq(adj)	R-sq(pred)
1.10297	96.98%	94.72%	87.93%

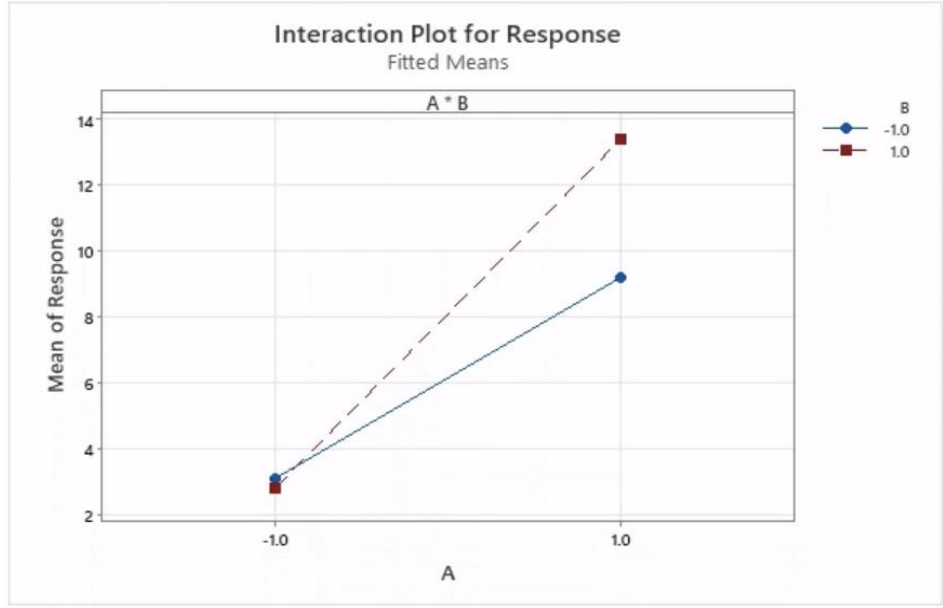
Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	156.388	52.129	42.85	0.002
Linear	2	146.311	73.155	60.13	0.001
A	1	138.727	138.727	114.03	0.000
B	1	7.584	7.584	6.23	0.067
2-Way Interactions	1	10.077	10.077	8.28	0.045
A*B	1	10.077	10.077	8.28	0.045
Error	4	4.866	1.217		
Total	7	161.254			

Regression Equation in Uncoded Units

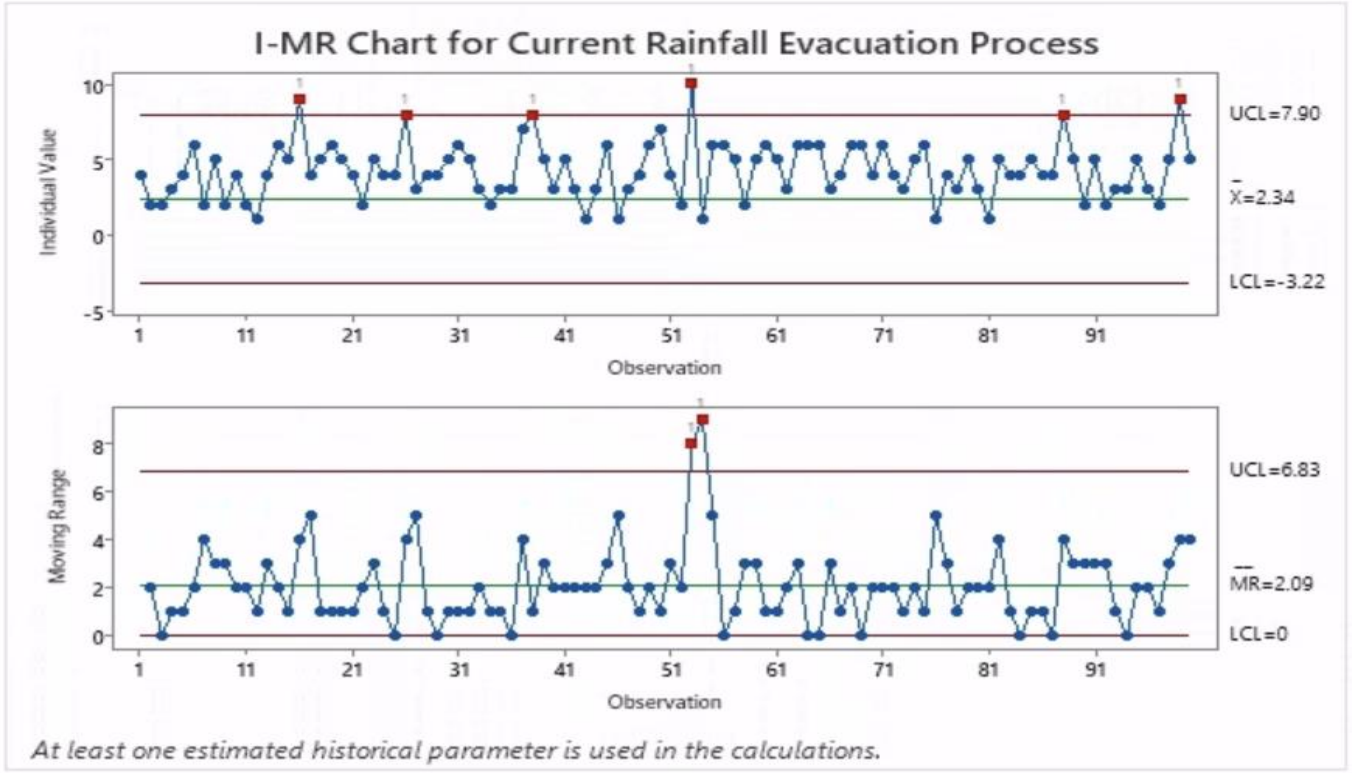
Response = 7.128 + 4.164 A + 0.974 B + 1.122 A*B





FMEA Analysis and Control Charts for the Improved System

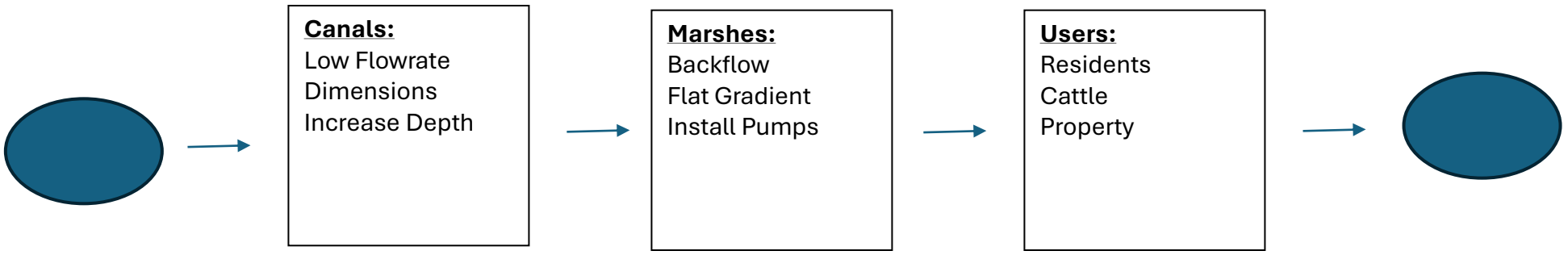
Canal	FailMode	Effects	Sev.	Causes	Occur	Detection	Ease	Risk	Actions
Canal	Blockage	Flooding	5	Debris	3	Inspection/CtrChrt	9	204	Clean
Canal	Slow Flow	Flooding	9	Depth	8	CtrChrt	7	260	Increase Depth
Canal	Slow Flow	Flooding	7	Gradient	8	CtrChrt	7	230	Relocate
Marsh	Backflow	Flooding	9	Gradient	5	Inspection/CtrChrt	6	310	Add Pumps



The new FMEA shows that increasing depth of the existing canals increases the flow rate of the canal. Root-cause analysis helped determine causes and provide solutions.

Control charts for the flow rate of the canal can be used to detect an increase in water due blockage, backflow, or the system is overloaded. Water should be evacuated at the specified levels. If some change occurs, there is a reason for said change. Control charts are used to flag such situations and investigate the issue. Once it is detected, it can be fixed.

Value Stream Map of Improved System



- VSM is used to describe the operations of the water evacuation system qualitatively which is now new and improved, and optimized. The improved factors canal depth and gradient of the marshes,

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 System Analysis

Gage R&R

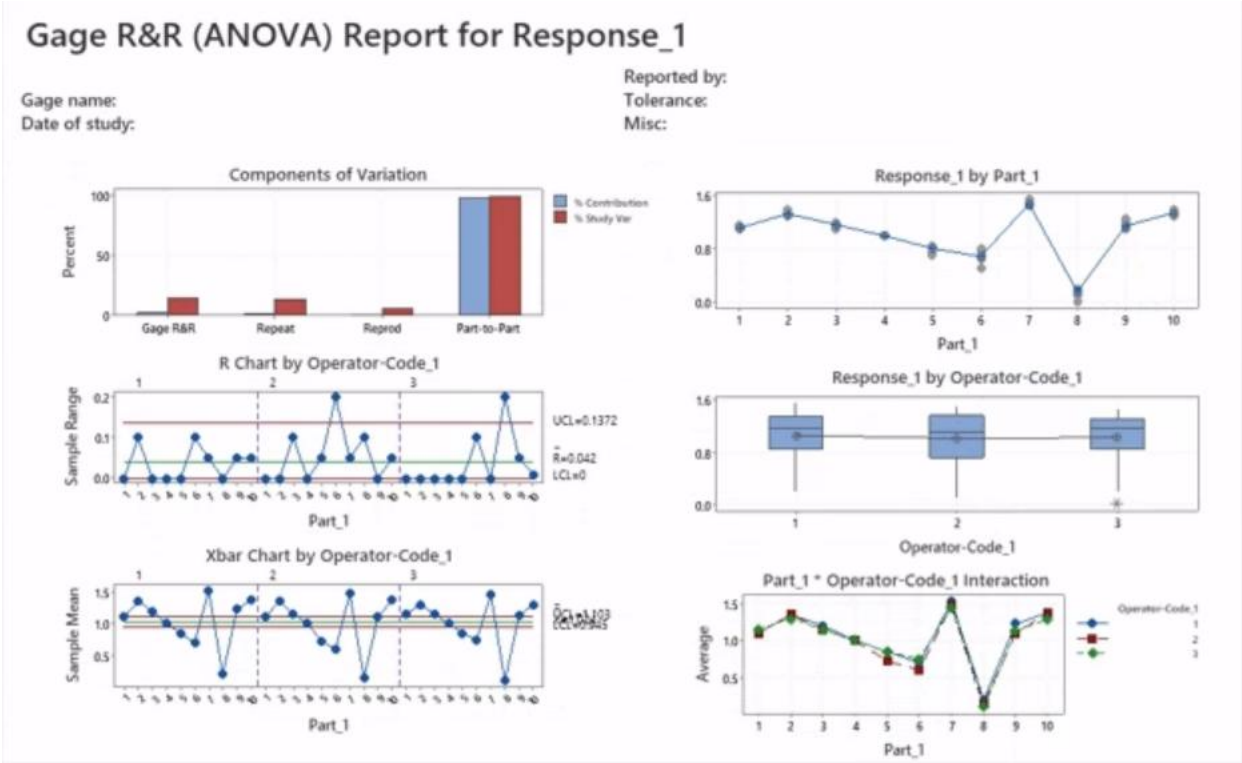
Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.003499	2.23
Repeatability	0.002987	1.91
Reproducibility	0.000512	0.33
Operator-Cod	0.000512	0.33
Part-To-Part	0.153247	97.77
Total Variation	0.156746	100.00

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.059154	0.35492	14.94
Repeatability	0.054651	0.32791	13.80
Reproducibility	0.022637	0.13582	5.72
Operator-Cod	0.022637	0.13582	5.72
Part-To-Part	0.391467	2.34880	98.88
Total Variation	0.395912	2.37547	100.00

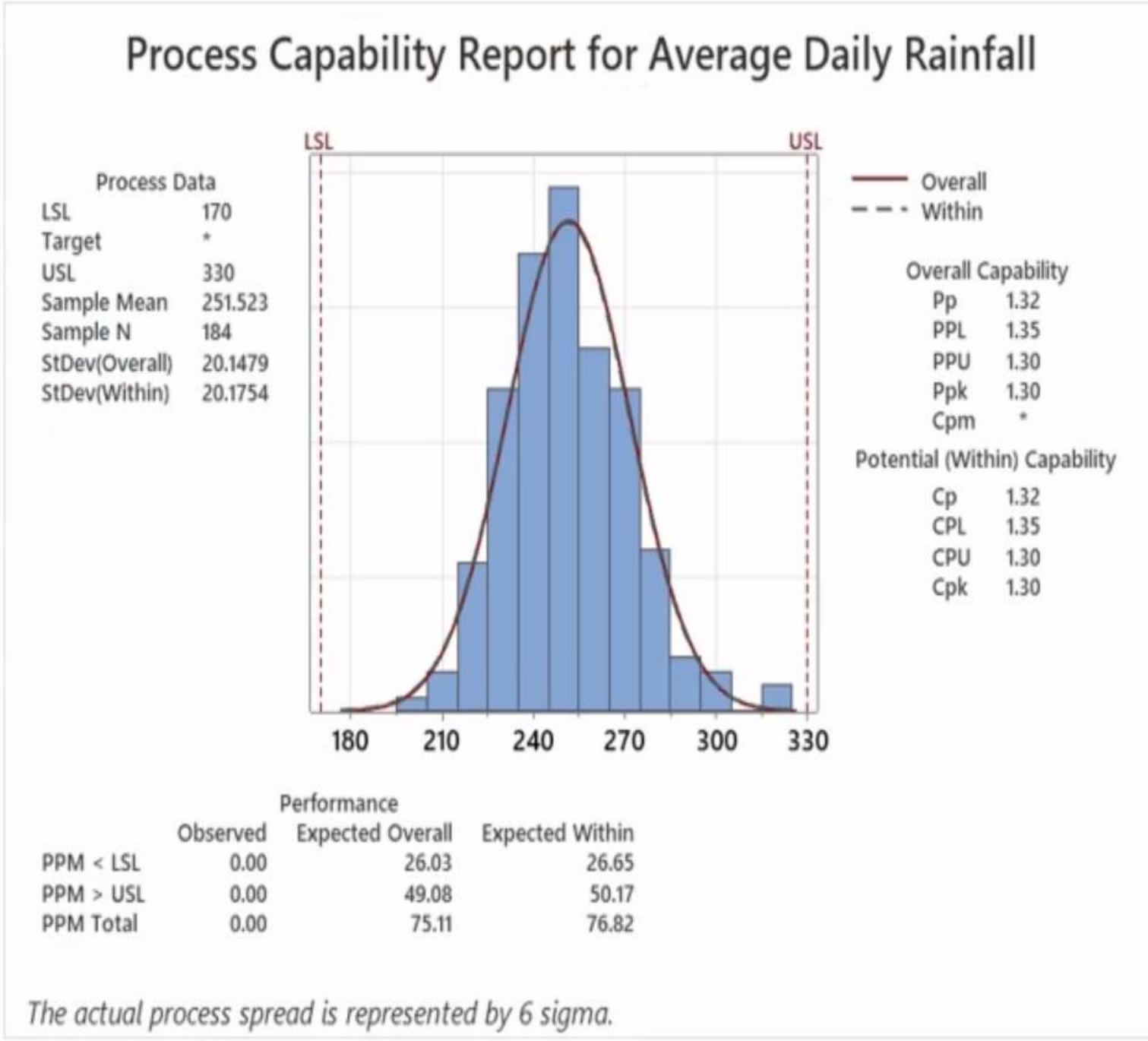
Number of Distinct Categories = 9



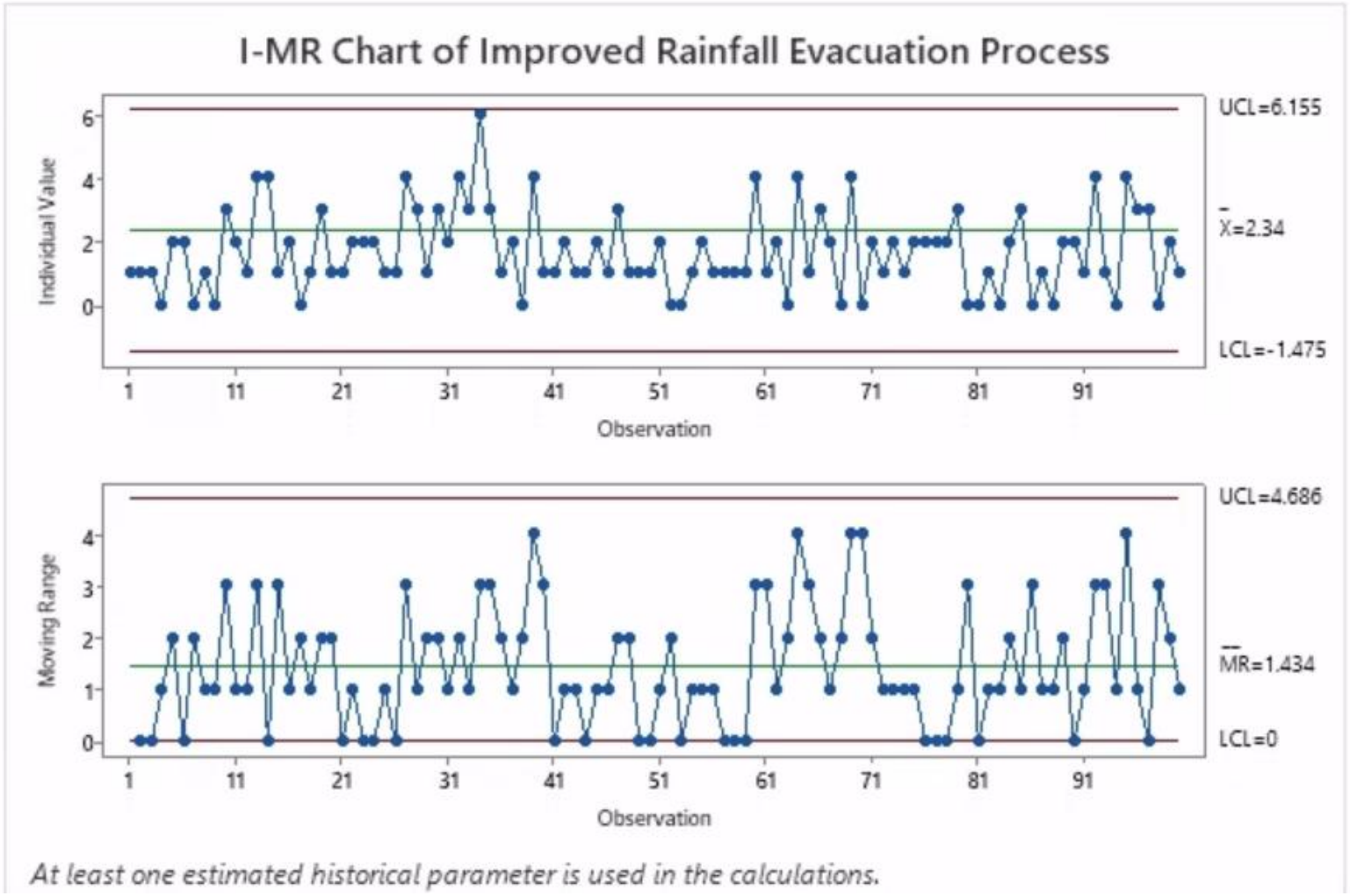
Results: The results are now acceptable: the measurement system provides a 97.77% of true item measure. Errors percentages by gages (1.91) and operators (0.33), have been reduced with better operator training and recalibration and/or replacement of faulty gauges.

Updated Process Capability

In this system, we do not have the option to modify the rainfall distribution. However, by implementing a capability analysis we can find the required LSL and USL to obtain a capability index (Cp) of 1.3 or better. For the average daily rainfall, we obtained an LSL = 170 and a USL = 330 yield a satisfactory Cp = 1.32. We can now develop an improvement effort that yields the needed water evacuation rate with such LSL/USL.



Control Charts (SPC)



After the system improvement, the evacuation system is stable and fulfills the customers needs. No data point in the control chart falls outside the UCL/LCL bounds, either for the mean or for the variance.

Conclusion

Problems from rainfall have been greatly improved:

- Rainfall evacuation system can handle more rainfall
- Residents are now less at risk from loss of life
- Cattle are less at risk from drowning in floods
- Property is less at risk of damage from floods

Systematic Excess of Water: Floods

Part III: Designing with Six Sigma
System Doesn’t Exist and Must be Designed

MFE 634: Quality and Productivity

Jake Jock, M.S. Chemical Engineering M.S. Student

Spring 2025

Phases of Six Sigma for Design (DFSS)

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

Define Phase

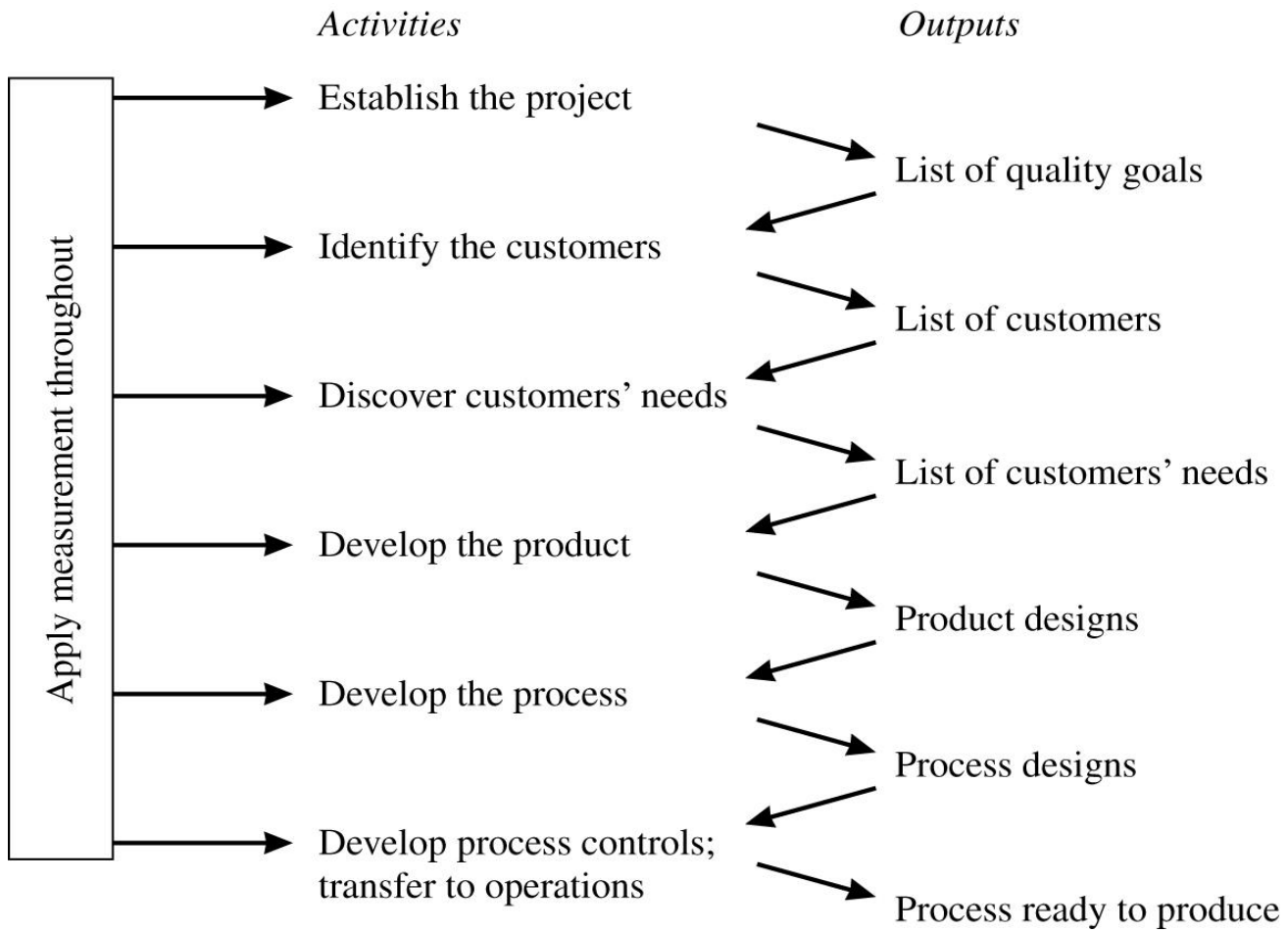
- Main uses of New Water Canals: Evacuation of Rainfall away from customers
  - To divert water to sinks (reservoirs, ocean, etc.), and provide population relief from excess water
    - Lives are saved as lower risk of flooding
  - To divert water from cattle
    - Lowers loss of cattle as lower likelihood of flooding
  - To divert water from property
    - Lowers cost of damages as lower likelihood of flooding

- Main sources of water comparisons: some evacuation methods are easier to build and more economical to operate;
  - Canals, reservoirs, pump systems; asses each option cost/efficiency

- Project team: civil engineers, emergency workers, accountant, health services, sociologist, administrators

- COPQ: Excess of water creates serious risk of loss of life for humans and cattle and high damage costs.

Quality Planning Steps:

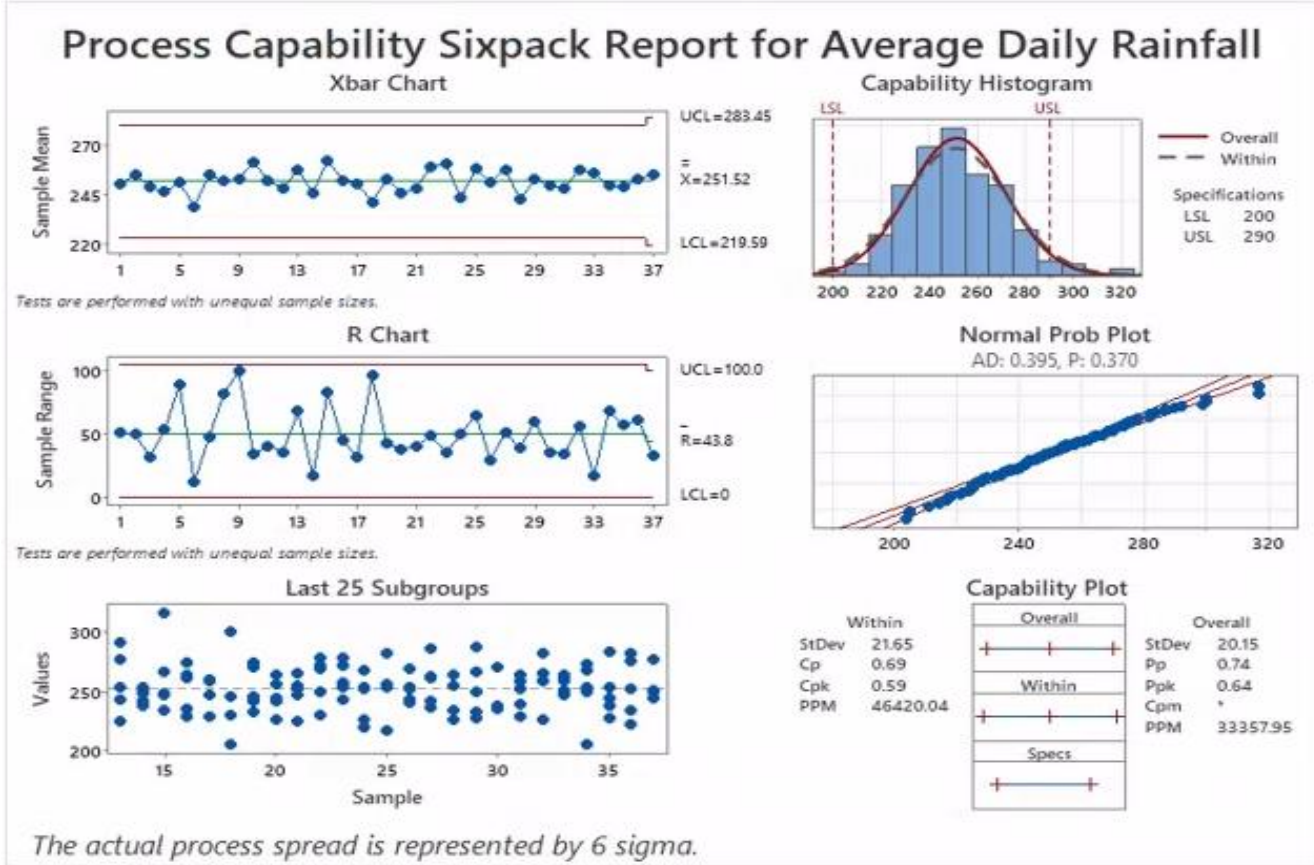


- Define the Project: distribution of excess rainfall during flood period
- Quality Goals: sufficient water removal by system
- Identify/list Customers: citizens, cattle, property
- Needs: Rainfall diversion from residents, cattle, property
- Product development consists in building canal, reservoir, and pump system
- Process control are charts and procedures to monitor/operate the system

Measure Phase

- Similar to DMAIC Phase (but system is not built yet)
  - Evaluate needs v. availability relationship through system process capability (Poor: 0.77)
  - Determine number/size of canals/reservoirs/pumps to meet system evacuation needs
  - Determine design alternatives for the system and their respective costs/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 = 0.69
    - The capability of the process is unacceptable and needs to be improved



From this data we see the new system has a low process capability (Cp) of 0.69 and the system needs to be improved. From the daily average rainfall data, we see that to increases the process capability, we will need to change the specification limits of the system by making improvements to the new system.

Measurement Systems Analysis (MSA):

Draw a random sample of measurement operators

Draw a random sample of gauges used

Draw a random sample of sites and measure

Apply the 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 the MSA analysis. Until results are OK

FMEA for Rainfall Water Evacuation from system to sinks

Failure Modes and Causes:

Dimensions: not large enough to evacuate rainfall away from customers. Need to increase size/number

Blockage: system is obstructed from debris that washes into system, limits flow, increases risk to stakeholders, workers will need to clean canals

Backflow: Wetlands limit flow to ocean due to flat gradient and saturation, pumps will be needed to evacuate water

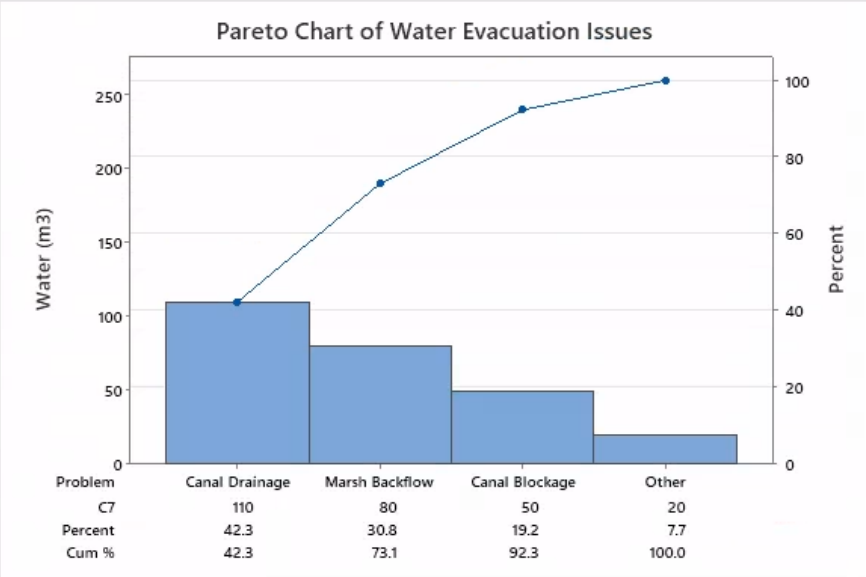
Effects: Prevents rainfall evacuation, reduces flow

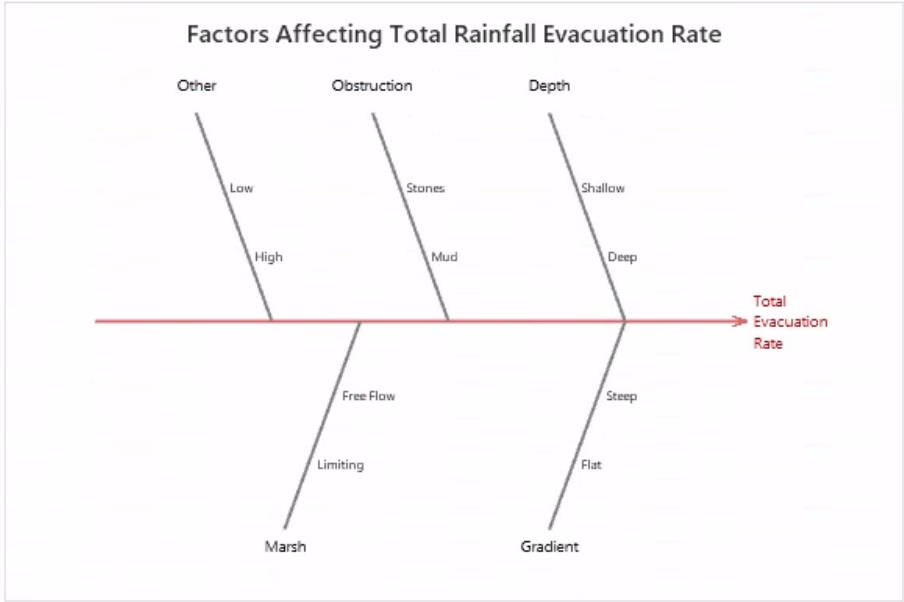
Problem Solutions:

Develop proper maintenance planning

Develop flow monitoring and SPC control procedures

Pareto and Ichikawa Charts





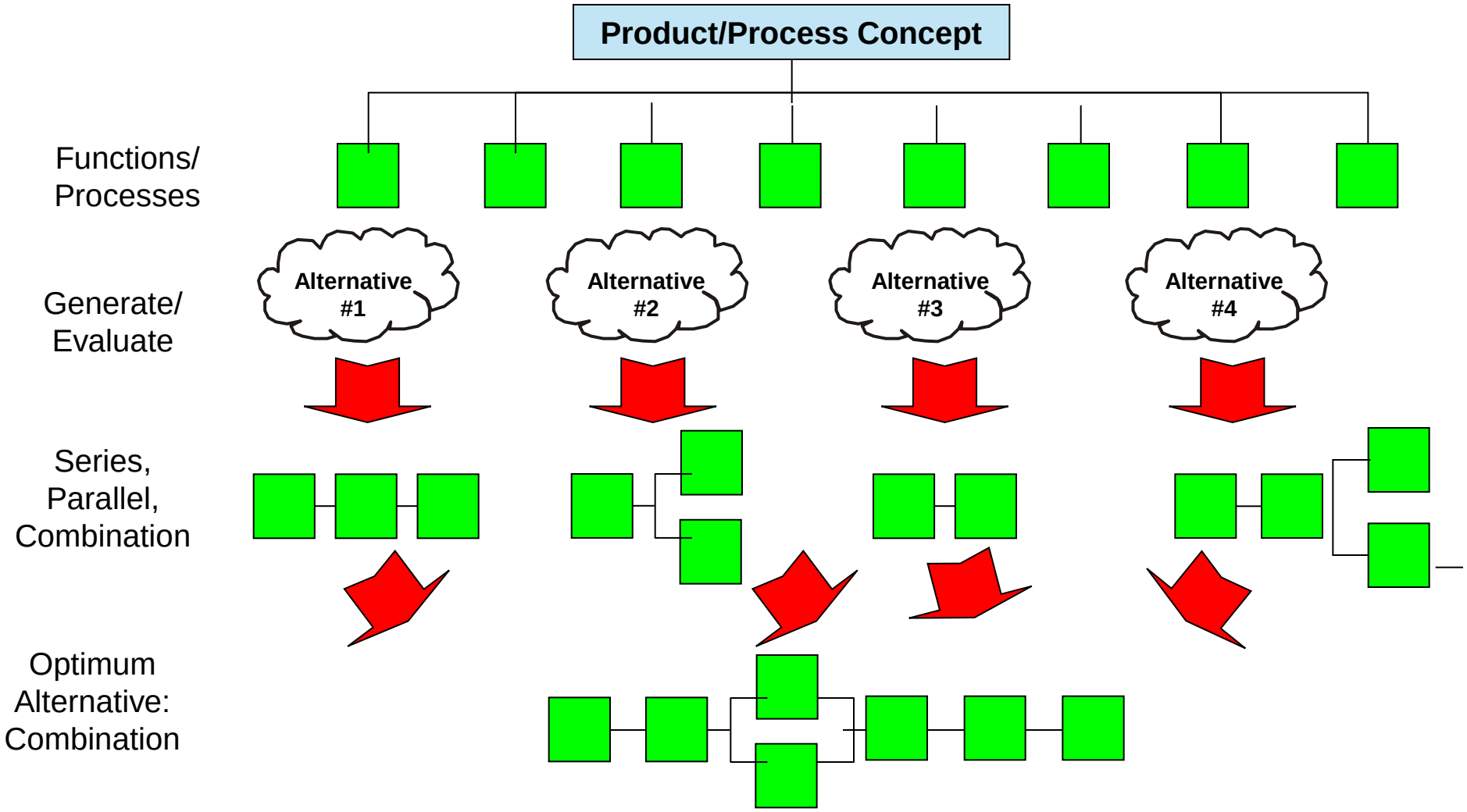
Our pareto chart shows that the canal drainage is a major causes of the floodwater evacuation issues which can be caused by improper dimensions for depth and width, and/or blockages in the canal from debris build up. Furthermore, the second major cause is backflow created from marshes near the ocean becoming saturated with water and causing slow drainage to the ocean, increasing water levels. Lastly, we see canal blockage as another major issue for floodwater evacuation. Debris can enter the canal through mudslides, fallen trees, and/or rocks that slow the flow of water causing the water levels in the system to rise and overload the system.

Analyze Phase

Establishing/Analyze Competing Designs

- Obtain estimates rainfall daily rainfall during flood period and water evacuation needs
- Obtain estimates of canal network capacity and evacuation flow rates sufficient to serve the system
- Evacuation system must be able to remove water away from all system stakeholders
- If not able to provide service, then consider feasible alternatives must be sought to be achieved
- More canals or pumps must be placed to support evacuation system
- Still unable to provide service, then consider expensive alternatives such as payment to relocate
- Consider alternative evacuation methods to canals, such as flood reservoirs
- Consider combination of evacuation means and methods, if feasible and efficient
- Simulate using computer languages (e.g. GPSS) the water evacuation system operation
- Alternatively, build a physical prototype of the water evacuation 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 system analyses

Series/Parallel/Combined Designs



FMECAs help identify problems in new designs and improve them

Function	FailMode	Effects	Severity	Causes	Occur	Detection	Ease	Risk	Actions
Canals	Blockage	LimitedFlow	6	Debris	4	CtrlChrt	7	212	Clean
Canals	Damage	Leak	8	Errosion/Mudslide	3	CtrlChrt/Inspection	8	150	Repair
Pump	Break	LimitedFlow	9	Mechanical Fault	3	CtrlChrt	6	300	Repair

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

Solution	Savings	Probs	Cost	Time	PPI
A	6	0.6	0.5	6	1.20
B	8	0.8	0.6	12	0.89
C	13	0.9	0.8	9	1.63

A	Design a series system for evacuation network
B	Design a parallel system for evacuation network
C	Implement combination of A & B

From FMEA we identified the major issues that need to be improved in the new design. From our pareto priority index we find that a combination of a systems that run in parallel and series is the optimal design solution for our system.

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

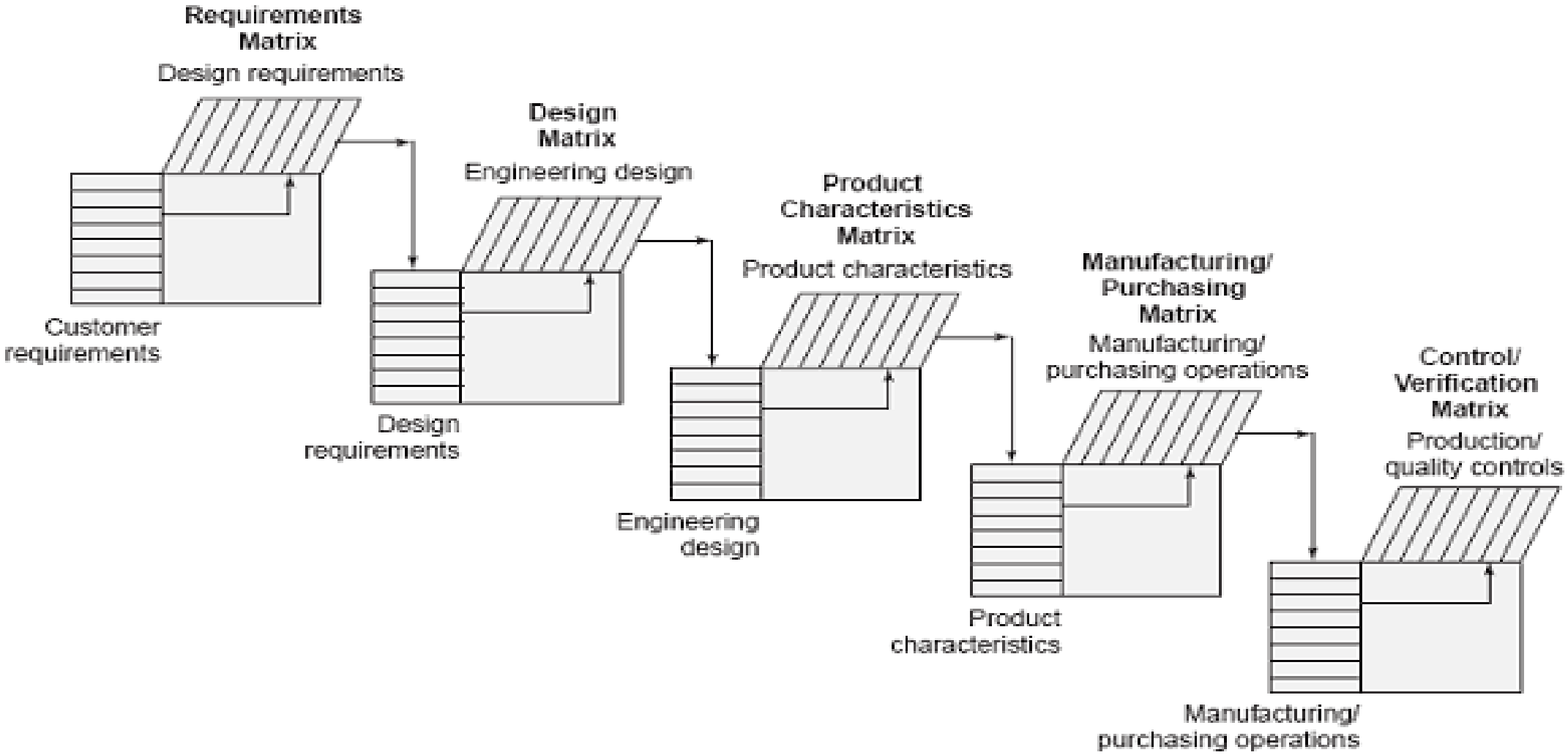
Example of QFD (House of Quality) Matrix

QFD Matrix to Help Design a Security System to Prevent Terrorist Attacks in Public Spaces. QFD correlates different Deterrence Options with different Types of Public Activities.

Event Ratings
0 Little/no impact
3 Low impact
6 Medium impact
9 Critical Event

VOC/VOE	Police	Covered	Militar	FBI/ATF	Chemic	CmpSW	Engineer	Medical	Citizens		Fitness	U. K.	France
Shop. Mall	6	9	3	6	3	0	3	6	9		3	2	2
Stadium/Parks	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/Railways											4		
Others											*		
Tot. Ratings	15	21	12	18	18	6	15	21	21				
. Importance	10.20	14.29	8.16	12.24	12.24	4.08	10.20	14.29	14.29				

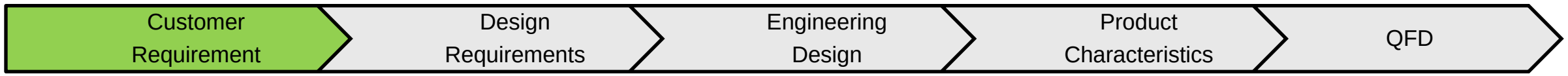
Figure 2 — Waterfall relationship of QFD matrices



QFD Cascade Matrix: Customer Requirements

Customer needs are satisfied via different solutions: population and cattle needs to be protected from excess water to provide safety, livelihood continuance, and disease protection from stagnant water; property needs to be protected from excess water; crops need to be protected from flooding.

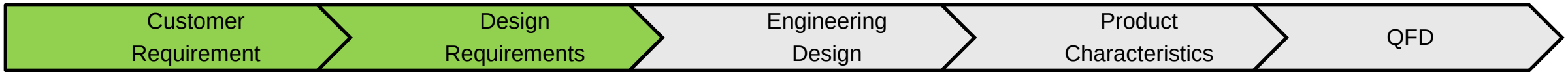
	Customer Needs			
Customers	Safety	Infrastructure Protection	Livelihood	Disease Protection
Population	9	6	9	9
Cattle	9	3	6	6
Property	-	9	-	-
Agriculture	3	3	6	-
Services	6	9	6	3



QFD Cascade Matrix: Design Requirements

To remove water the system needs drainage (9);

Design Requirements				
Needs	Drainage	Response	Overflow	Maintenance
Safety				6
Reliability	9	9	9	9
Evacuation	9	9		3
Durability	9			

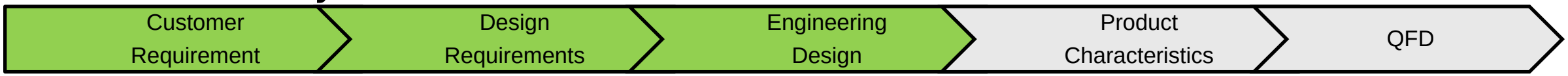


QFD Cascade Matrix: Engineering Design

Rainfall may be evacuated by flow through or to canals, reservoirs, and pumps. If need for rainfall evacuation becomes very strong, marshes/wetlands can be drained into ocean through emergency pumps and canal systems.

Rainfall can be evacuated to different sinks

Sinks			
RQMTs	Canals	Reservoirs	Pumps
Flow Rate	9		9
Storage	3	9	
Guidance	9	3	
Drainage	6	6	9



QFD Cascade Matrix: Transportation Means

Rainfall needs to be transferred to sinks via canal and pump networks to ensure water levels near stakeholders to do not cause flooding. This water will be transferred mainly to the ocean or emergency reservoirs for temporary storage.

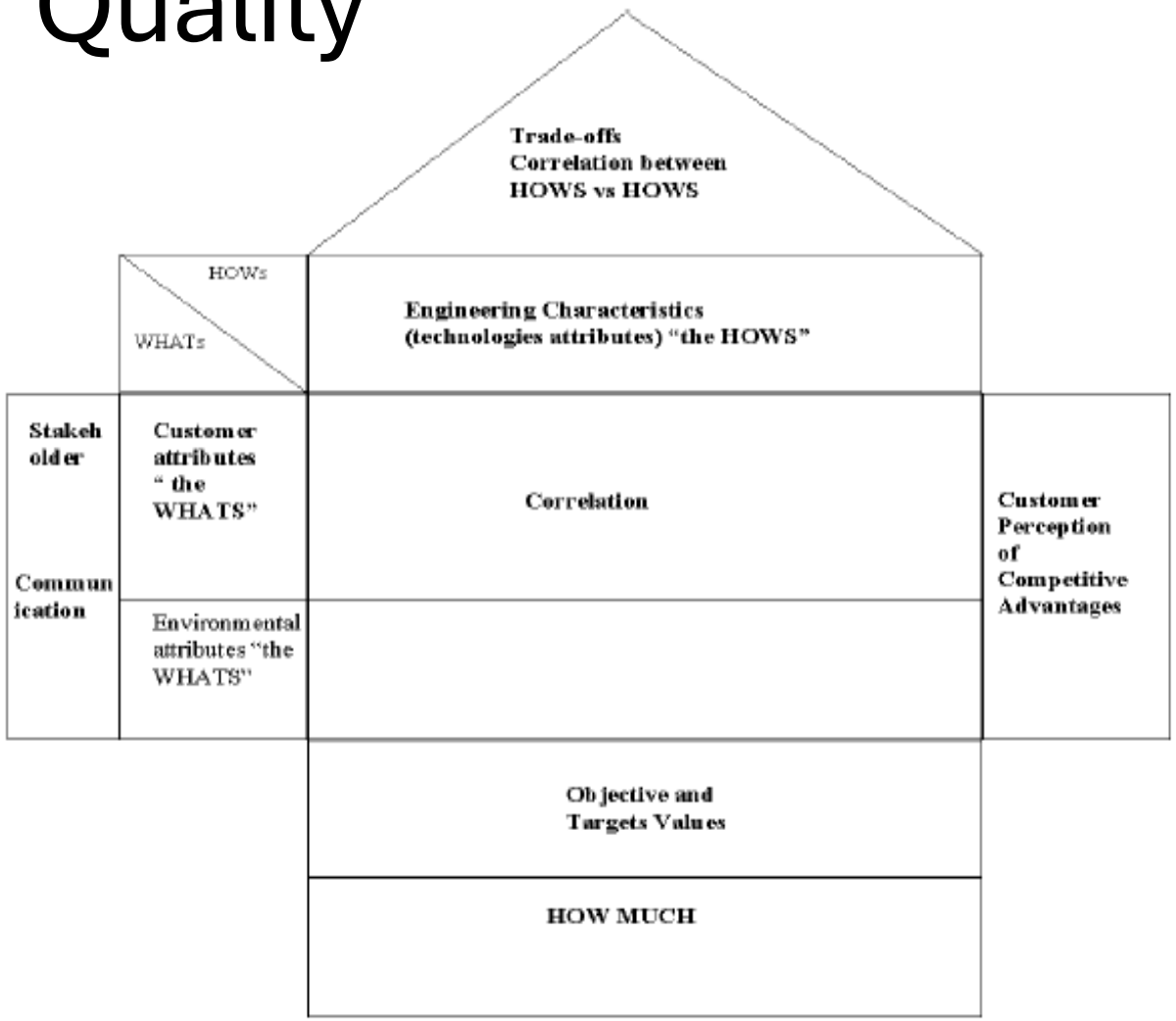
Pumps and canals are especially important near the ocean to limit backflow from accumulation of water in marshes/wetlands where the land gradient becomes flat.

Rainfall is transferred in to sinks in different ways

Transportation Means		
Sinks	Canals	Pumps
Ocean	9	9
Marshes	3	3
Rivers	3	3
Reservoirs	9	3

Skeleton for House of Quality

- <u>QFD Matrix Description:</u>
- **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

Emergency Portable Pump System

When the rainfall evacuation system is insufficient to satisfy customer needs, we can deploy emergency pumps to increase the evacuation of rainfall. This creates additional activities. **First,** we will need to allocated mobile pumps based on zone severity, water volume, and proximity to discharge points. **Second**, we will need to optimize time and number of mobile pumps to complete floodwater evacuation in a defined operational window, while minimizing disruption and hazards. We can use a similar approach to takt-time to calculate how to evacuate the floodwater and the number of pumps required to do so.

Assume there are 5 regions that are prone to flooding and each zone will accumulate the same volume of floodwater, and that the evacuation of the flood water will be done in a single day from 6 am to 12 pm, to minimize damage (6 hours). Then pace = 6/5 (~72 minutes) is the time allotted to resolve each instance. Assume that it there are 500,000 gallons of flood water for each region and each pump has a flow rate of 3,000 GPM, then it will take 166.7 minutes to evacuate one region. Then we need 166.7/72 = 2.3 (~3 pumps) to process floodwater at each location to limit flood damage. We will need 15 pumps total to service the region.

Verify Phase

Using the physical prototype or the simulation model:

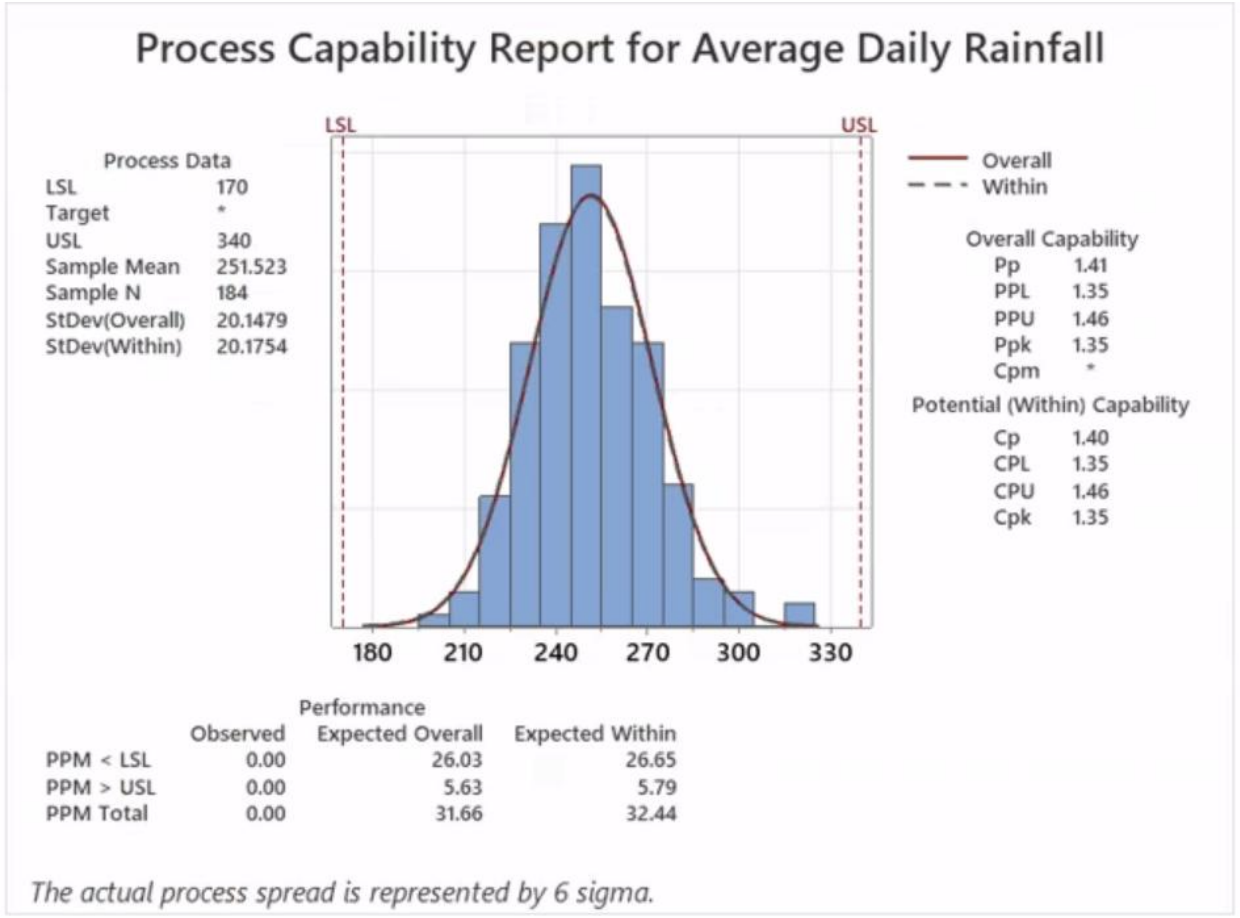
- Perform a final Measurement Systems Analysis
- Perform an FMEA of the final version of the system
- Perform a final Risk Analysis of the distribution system
- Perform a final systems Process Capability analysis
- Prepare the final project documentation
- Plan full deployment to build the system
  -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

FMECAs help assess problems in the improved designs and correct them

Function	FailMode	Effects	Severity	Causes	Occur	Detection	Ease	Risk	Actions
Canals	Blockage	LimitedFlow	6	Debris	4	CtrlChrt	7	212	Clean
Canals	Damage	Leak	8	Errosion/Mudslide	3	CtrlChrt/Inspection	8	150	Repair
Pump	Break	LimitedFlow	9	Mechanical Fault	3	CtrlChrt	6	300	Repair

The improved system's design now has different failure modes and risks. We can see that canals can fail through obstructions or damage from the environment resulting in overflow or limited flow rate of rainfall. Pumps can by mechanical wear over time which results in limited rainfall flow rate and drainage. These failures were detected by systematic measurement of the control charts. The greatest risk (300) is due to pump failure, which makes it the first and most important failure to resolve.

Improved System's Process Capability and Measurement System



Gage R&R

Variance Components

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

With the improved system the process capability of 1.41 meets the accepted value of 1.3; The MSA loss due to errors in operator and gauges is less than 3%. Both can still be improved, but system operation can be started.

Conclusion

- Rainfall evacuation problems have been greatly improved:
  - Population is now more protected from risk of flooding
  - Residents are safer in homes
  - Cattle is more protected from drowning
  - Property is less at risk of damage
  - Agriculture is less at risk of destruction from flooding
- Cost of system is less than cost of loss/replacement
  - Prior flood damage exceeds the cost of new system
  - Future flood damage will greatly exceed cost of new system.

Systemic Excess of Water: Floods
Part IV: Lean and Kaizen Projects

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

MFE 634: Quality and Productivity

Jake Jock; M.S. Chemical Engineering Student

Spring 2025

The Eight Wastes Lean Fights Against

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

Application Examples of these Wastes

Waste	Example	Implication
Defects	Pump fails to operate	Water levels rise in system
Overproduction	System over specified for needs	Waste of resources and funds
Excessive Inventories	Canal is too large	Waste valuable resources
Excessive Motion	Too many transfers between canal networks	Waste of time and resources
Excessive Processing	Too many mechanical functions	More staff needed
Transportation	Canal system not optimized	Waste of time and resources
Waiting	Waiting for operators to open floodgates	Water levels rise in system

Examine all waste, 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

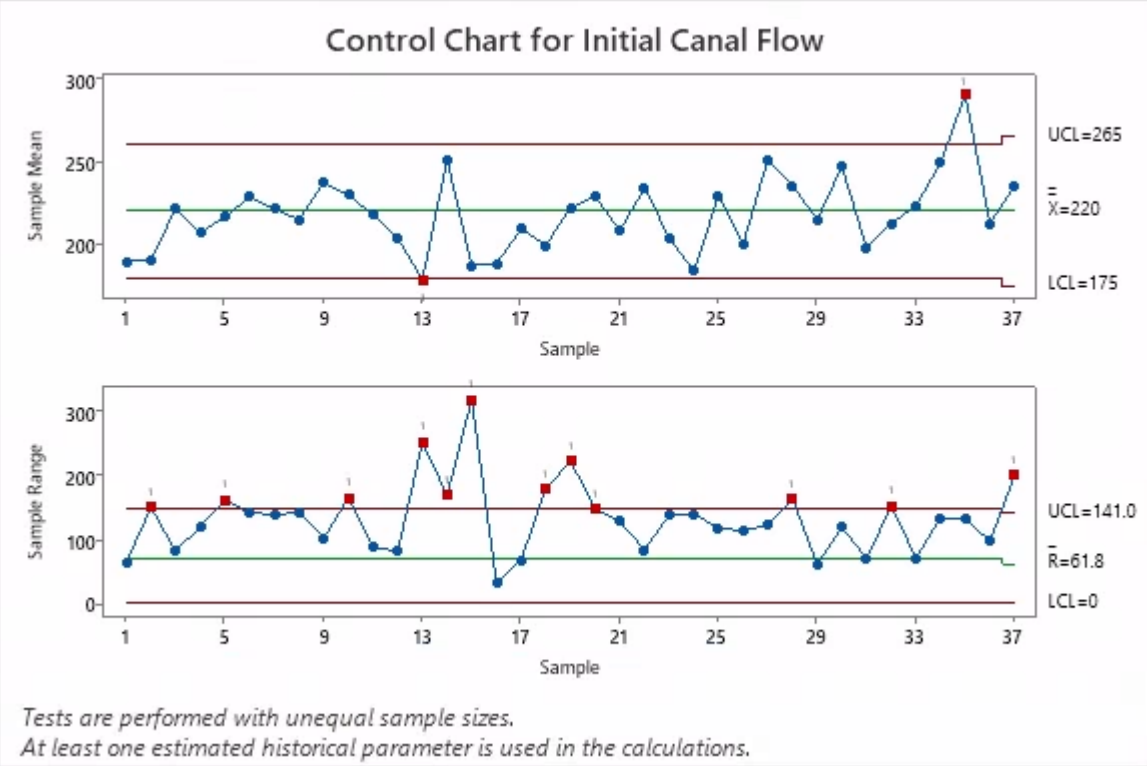
Five S System

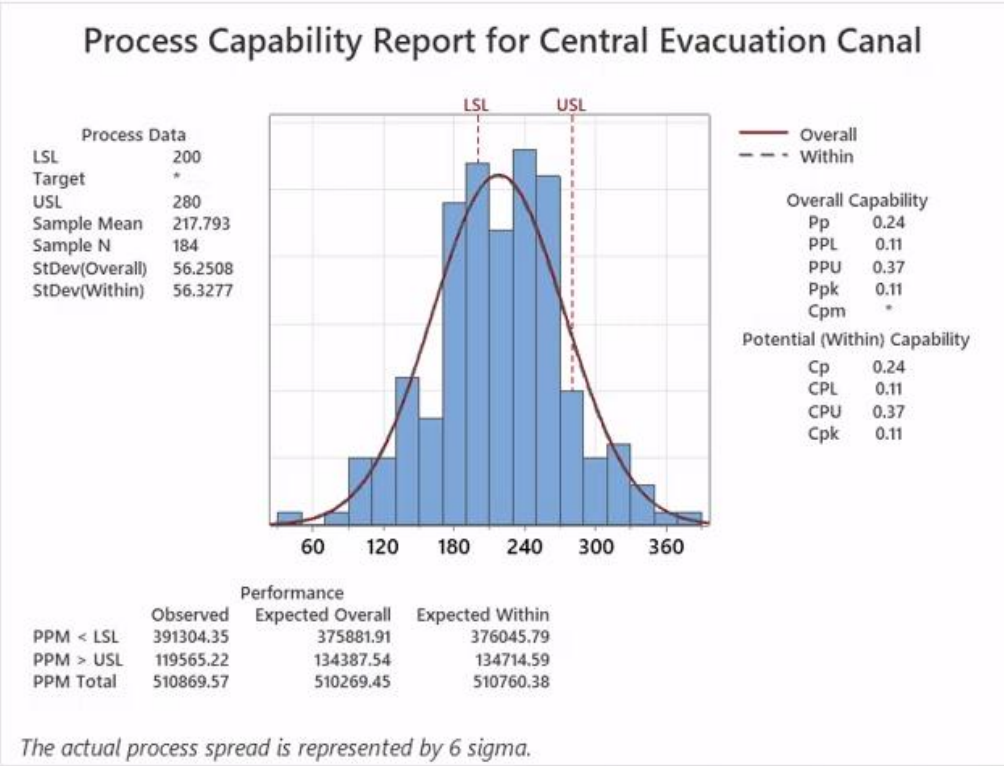
- **Sort:** keep only necessary things
    - Maintenance crews keep only key tools
- **Set in order:** arrange efficiently
    - Use an organized metal toolbox
- **Shine:** maintain cleanliness/avoid clutter
    - Keep toolbox stored under lock and key
- **Standardize:** proceed consistently
    - Have all maintenance crews keep same tools
- **Sustain:** a cooperative working environment
    - Maintenance crews good working relationships

Five Why's System

- **Why-1:** Why are people dying?
  - Because rainfall evacuation is too slow and areas are flooding
- **Why-2:** Why isn't water being evacuated fast enough?
  - Because rainfall evacuation canals and reservoirs are too small
- **Why-3:** Why is rainfall evacuation canals/reservoirs too small?
  - Because canals and reservoirs were underspecified for system needs
- **Why-4:** Why were canals and reservoirs underspecified?
  - Because canal and reservoir planning and design was poorly conceived
- **Why-5:** Why was design poorly conceived?
  - Because the rainfall evacuation team did not follow DFSS procedures

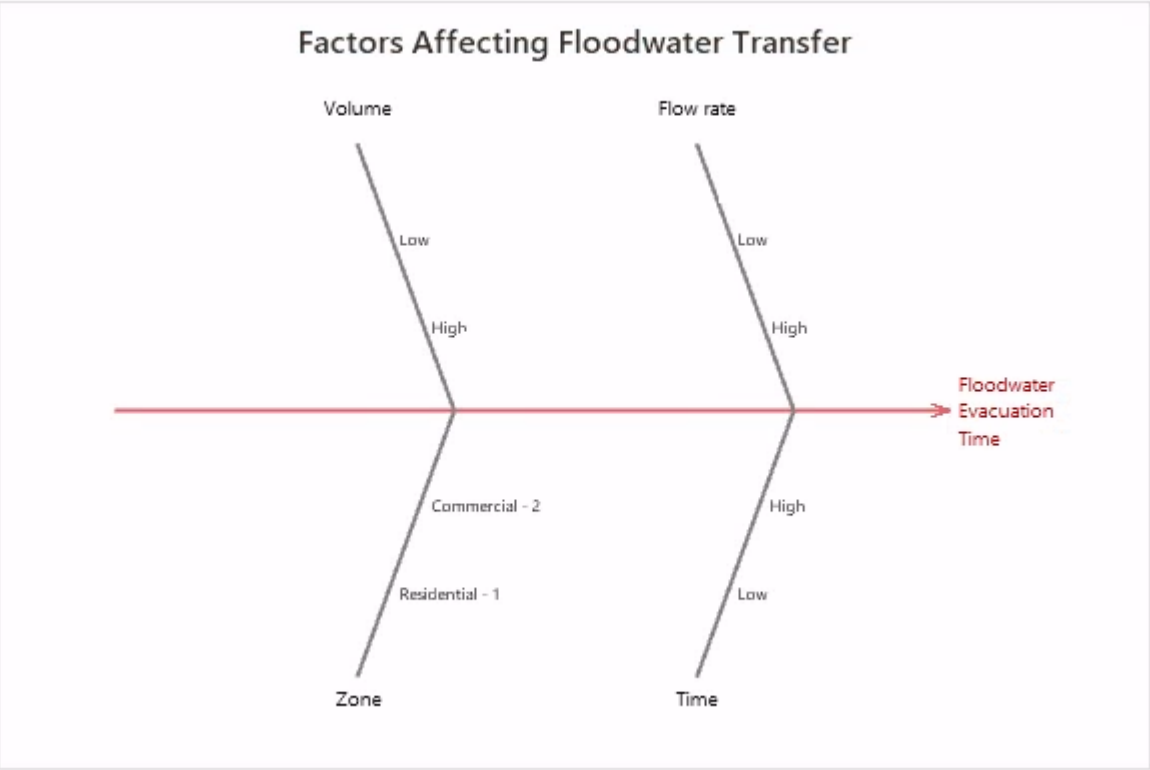
Initial Analysis of Canal Water Flow





Initial data on the central canal flow (Cubic feet/unit time) was collected to establish the baseline: Mean = 217.8; Std-Dev = 56.2. The mean/range SPC chart shows a large variability. Water needs defined specification range: LSL = 200; USL = 280. Process capability is extremely low Cp = 0.24.

Analysis of Canal Evacuation Times and Potential Factors



Time	Volume	Distance
38.8	57.7	1277.1
129.1	429.2	1004.0
445.4	134.1	1168.5
117.3	467.4	108.8
27.9	51.2	1165.0
1786.2	41.5	960.5
365.7	533.2	105.7
191.9	962.3	16.9
333.3	602.0	2135.4
151.2	119.3	592.6
46.8	473.5	69.6
828.6	137.8	608.9

Floodwater is evacuated according to flood volume (x1000 gal), distance to discharge point, and zone type (Residential = 1, Commercial = 2). Analyze whether total water evacuation time depends on flood volume, distance, or zone type.

Current Average Floodwater Evacuation Time = 372 units; Std-Dev = 501

What is VSM?

- A value stream consist 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 = 165.8 + 0.001 **Vol** - 0.068 **Dist**

Model Summary

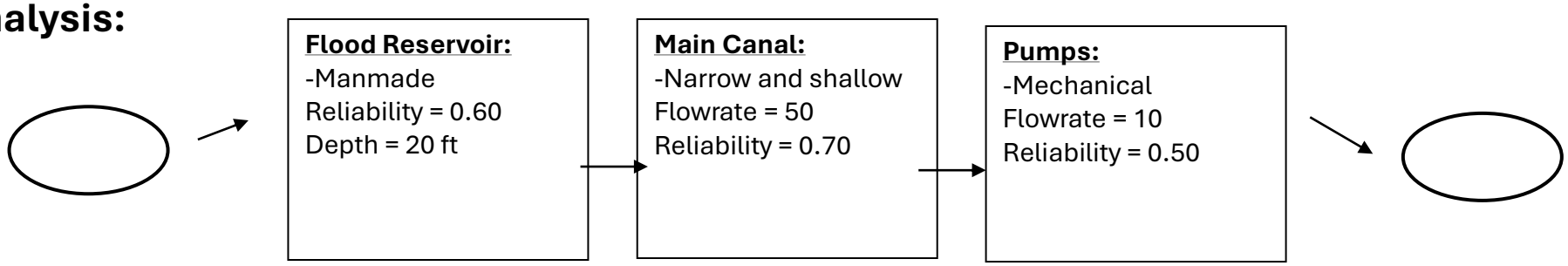
S	R-sq	R-sq(adj)	R-sq(pred)
35.6831	3.49%	0.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	165.8	97.2	1.71	0.122	
Vol	**0.001**	**0.192**	**0.01**	**0.994**	**1.01**
Dist	**-0.068**	**0.120**	**-0.57**	**0.584**	**1.01**

Factors are nonsignificant (p-values > alpha = 0.05. Total evacuation time doesn't depend on factors

VSM Analysis:



Current State VSM

Time for floodwater evacuation is independent from discharge distance, floodwater volume, and zone type. Current floodwater evacuation system value stream map using existing evacuation network system shows a need for improvement project.

Reliability: Quality in Time

We use the previous 12 data points to estimate the Mean Floodwater Evacuation Time confidence interval (CI). Let T be Total Evacuation Time of said 12 data points: T = 4463. The distribution 2T/μ, where μ is the Exponential mean, is distributed Chi Square (χ^2), with 2n = 2*12 = 24 Degrees of Freedom (Y). A 1- α = 95% CI for the unknown Exponential Mean (μ) is obtained using the formula:

$$[2T/\chi^2(\alpha/2, Y),\ 2T/\chi^2(\alpha/2, Y)] = [2*4463/39.4;\ 2*4463/12.4/] = [226.5,\ 719.8]$$

(where $\chi^2(\alpha/2, Y)=12.4$; $\chi^2(1-\alpha/2, Y)=39.4$, are the χ^2 percentiles)

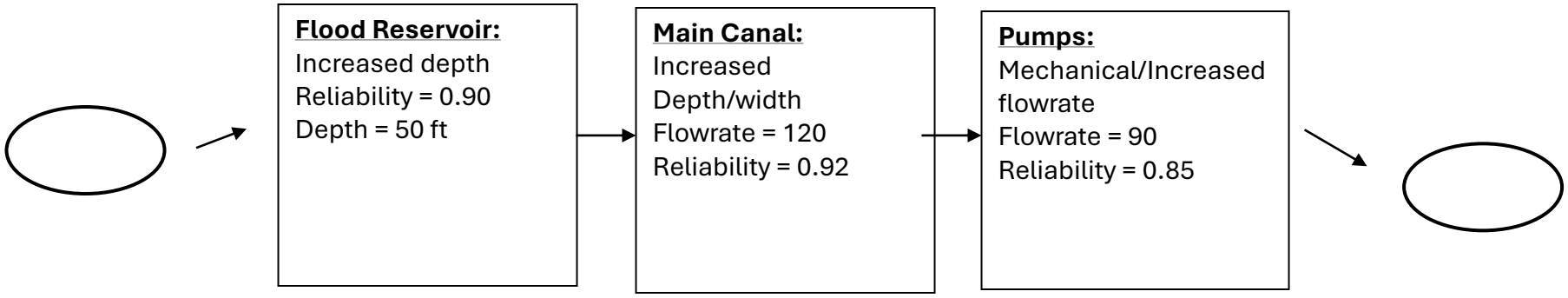
Using the Lower/Upper CI limits and the Average(226.5, 359.9, 372.2) as regular exponential mean estimations, we obtain corresponding Reliability Estimations R(To), of the probability that the total water evacuation of the canal takes over 120-time units (Mission Time To = 120):

Optimist Reliability for Mission Time To(120) = Exp(-300/226.5) = 0.266

Regular Reliability for Mission Time To(120) = Exp(-120/136.2) = 0.447

Pessimist Reliability for Mission time To(120) = Exp(-120/263.5) = 0.669

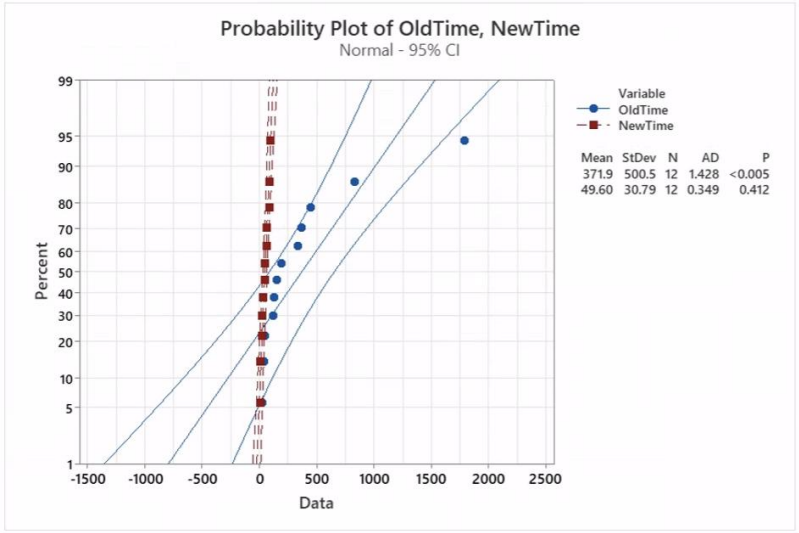
Future State VSM

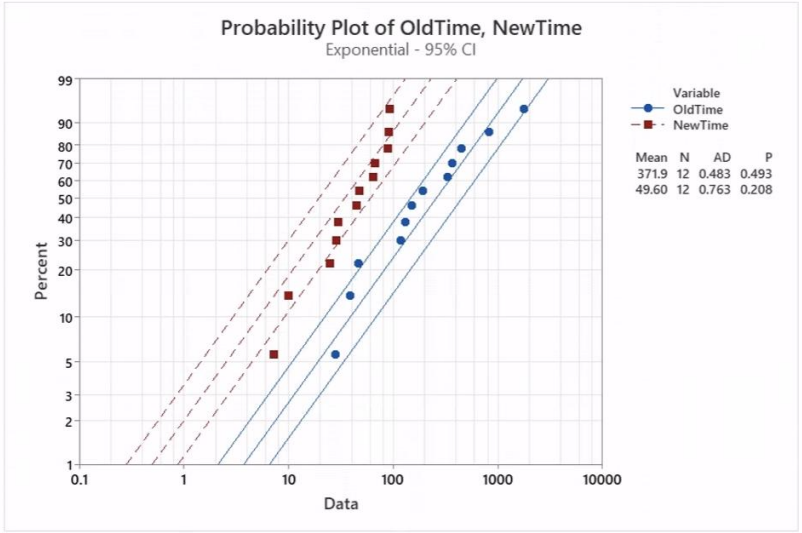


Above is the future state value stream map (VSM). This includes changes made to the system. The rainfall distribution system was improved by widening and deepening canals, automating canal systems to redirect throughout system to maintain lower water levels, and adding pumps to canals with low gradients. These improvements reduced rainfall evacuation times by allowing flow rates to increases in the system and keep water levels low throughout the evacuation network. This also reduced non-value-added steps. From the VSM the number of successful evacuations (Reliability), and velocity has also improved significantly.

New times for the improved floodwater evacuation system are significantly smaller:
Average floodwater evacuation time = 62.3 and Standard Deviation = 20.2

Comparison of Evacuation Times: Before/After System Improvement





Test

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

W-Value	P-Value
200.00	0.004

Descriptive Statistics

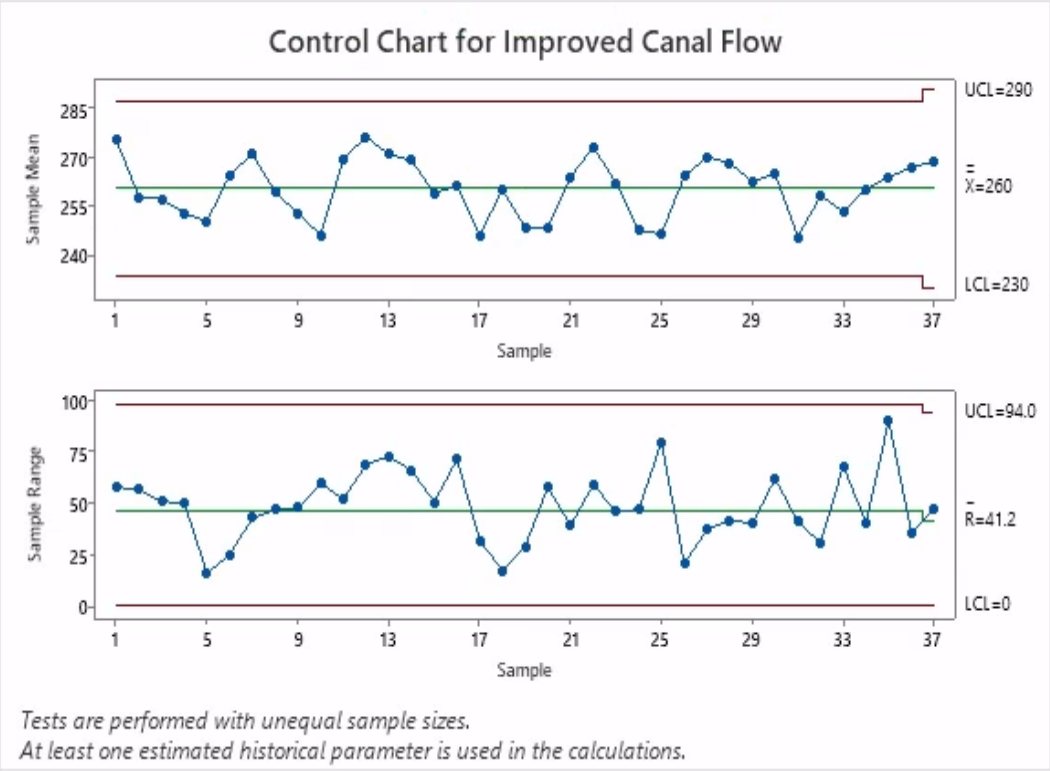
Sample	N	Median
OldTime	12	171.590
NewTime	12	45.936

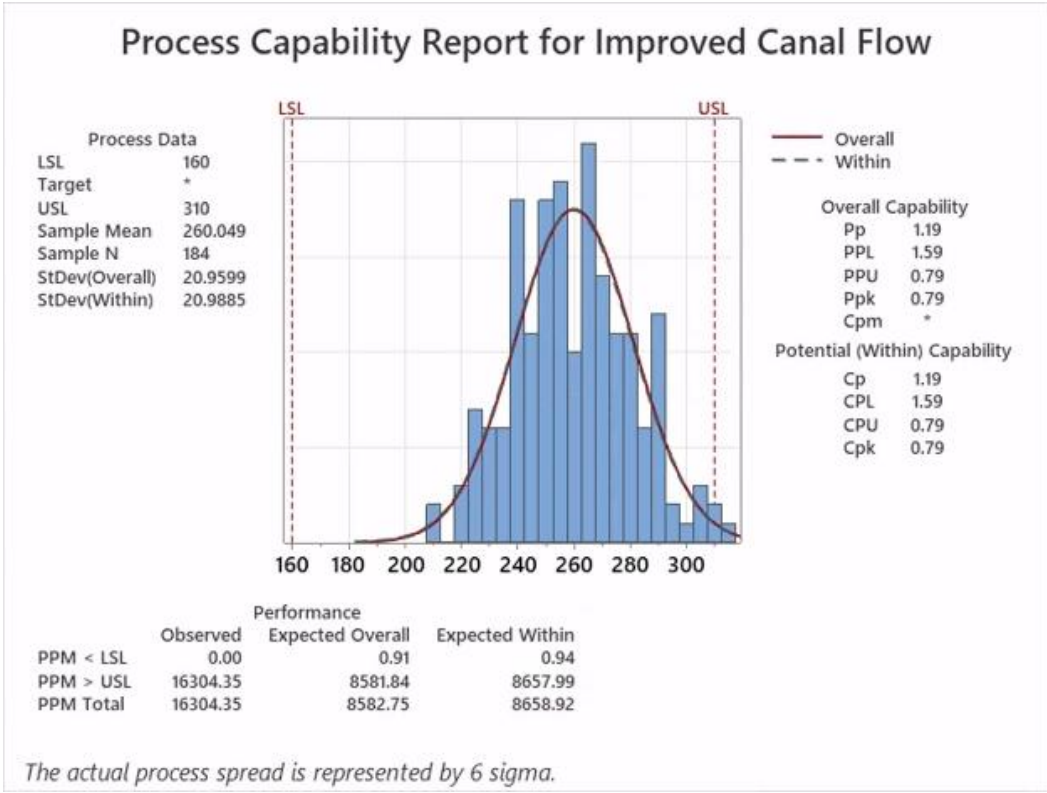
Estimation for Difference

Difference	CI for Difference	Achieved Confidence
124.113	(36.0471, 352.319)	95.36%

Old v. New Floodwater Evacuation Time was tested using Wilcoxon Non-Parametric test for exponential data (see plots). The Wilcoxon tests shows that the new floodwater evacuation times are significantly faster. After improvements we see a large drop in median values which shows significant improvement, the CI for difference is 95% which means the new system is very likely to reduce evacuations times by at least 36 time units, and the p-value is 0.004 meaning the null hypothesis is rejected and there is a difference in evacuation times.

Analysis of Canal Water Flow for Improved System





The final canal water flow collected: Mean = 222.0 cu-ft; Std-dev = 17.5. Comparing to the initial flow, the mean has increased 18%; variability decreased by a factor of 3. Stability of the rainfall evacuation system reduces risk of overloading the system and floodings residents, cattle, and crops, and reduces damage and repairs costs to property.

Advantages of Lean-Six Sigma Combination

- **Lean**: reduces waste and improves flow
    - Streamlines your operation to new level
- **Six Sigma**: reduces process variation
    - Optimizes system current 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 more stable canal water flows

- System has been greatly improved by getting rid of defects in the system such as improving dimensions of canals and reservoirs

- Wait times in system decreased by automating floodgates and pumps

- Improvements significantly reduced flood evacuation times in the system