Scrap reduction in CNC Machining in Aerospace Component Manufacturing

Saiprudhvi

ROADMAP

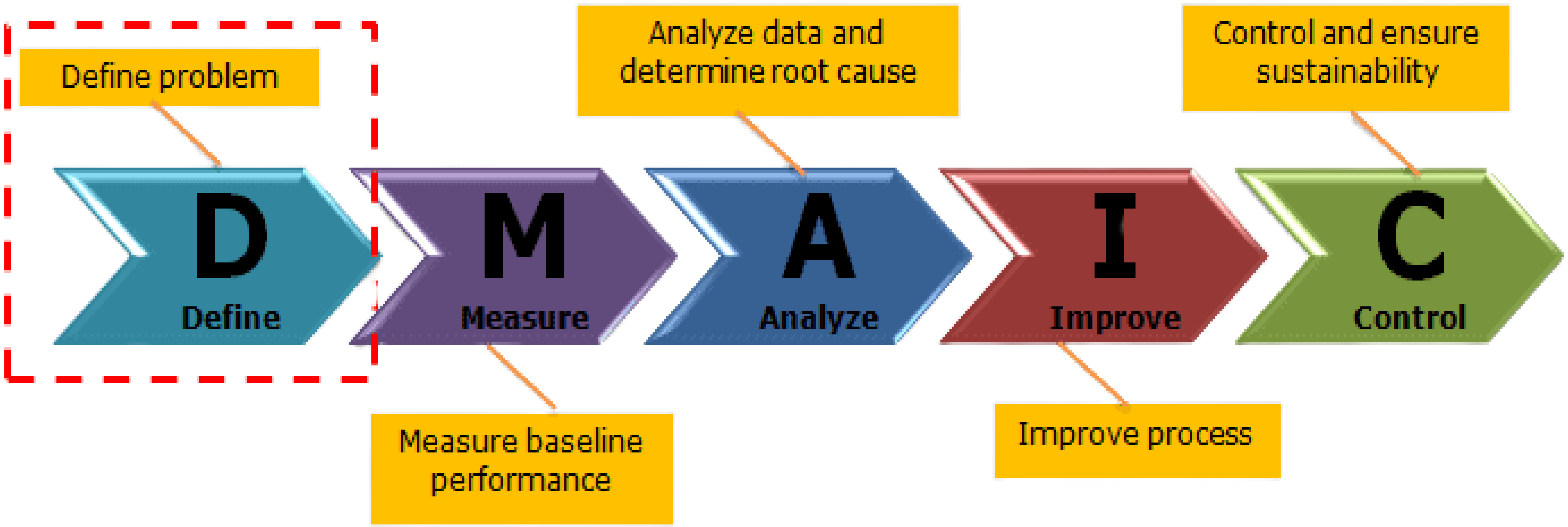
- Overview
- Define
- Measure
- Analyse
- Improve
- Control

OVERVIEW

Background

- In Manufacturing of aerospace component, frequent machine breakdowns and quality rejections have caused production loss of approximately 60 hours per month, leading to:
  - Output loss: ~₹3.5 lakhs/month
  - Increased maintenance costs and rework labor hours
  - Missed delivery commitments to customers
- By improving machine uptime and reducing rejections, the company can save ₹2.5–3 lakhs per month, increase throughput, and strengthen customer confidence in quality and delivery reliability.

DEFINE PHASE

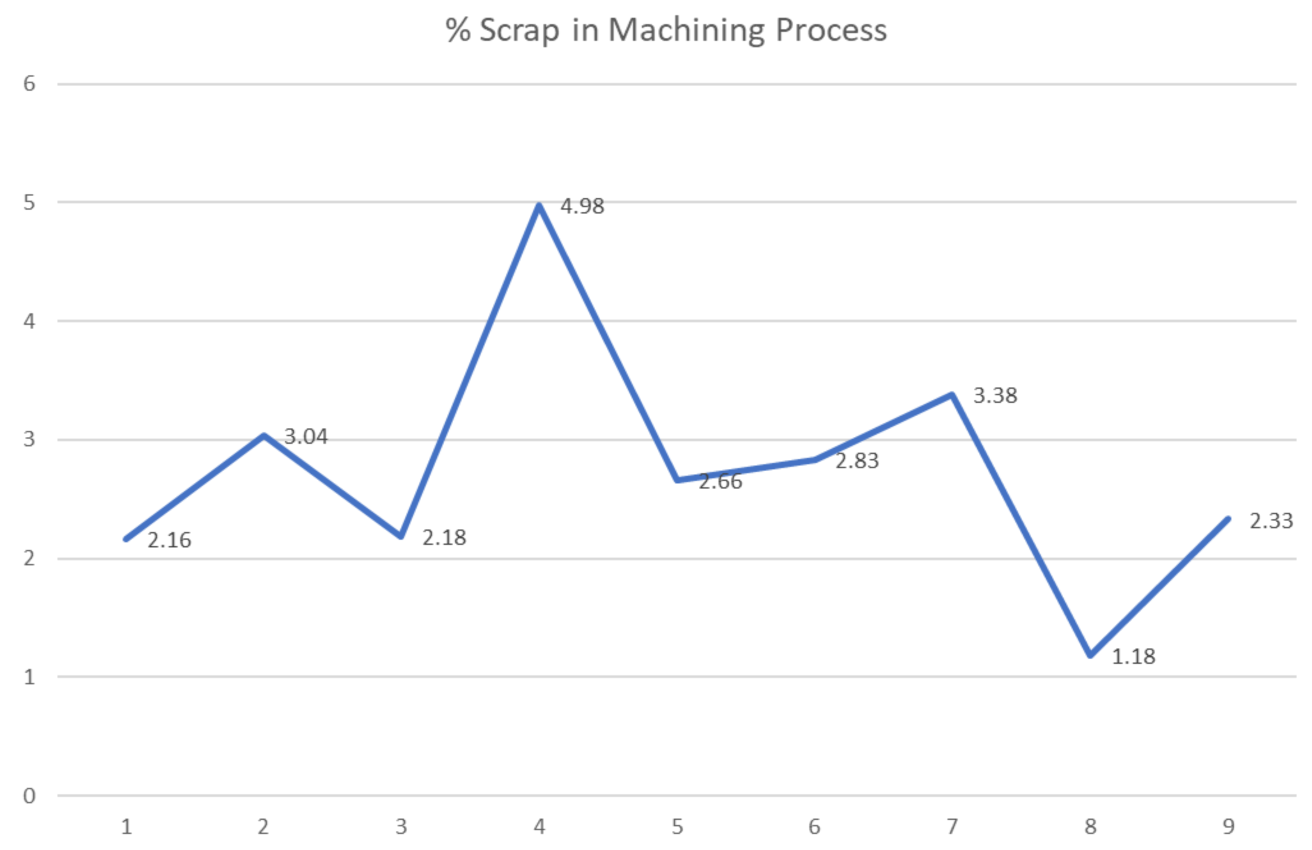


VOC & CTQ

CTQ Tree :

Voice of customer	Critical to X	Primary Metric for improvement
We need dimensionally accurate, defect-free machined parts that meet tolerance and quality requirements consistently.”	CTC – Cost	**Primary Metric -** Y = % Scrap in machining process **Secondary Metric -** Productivity

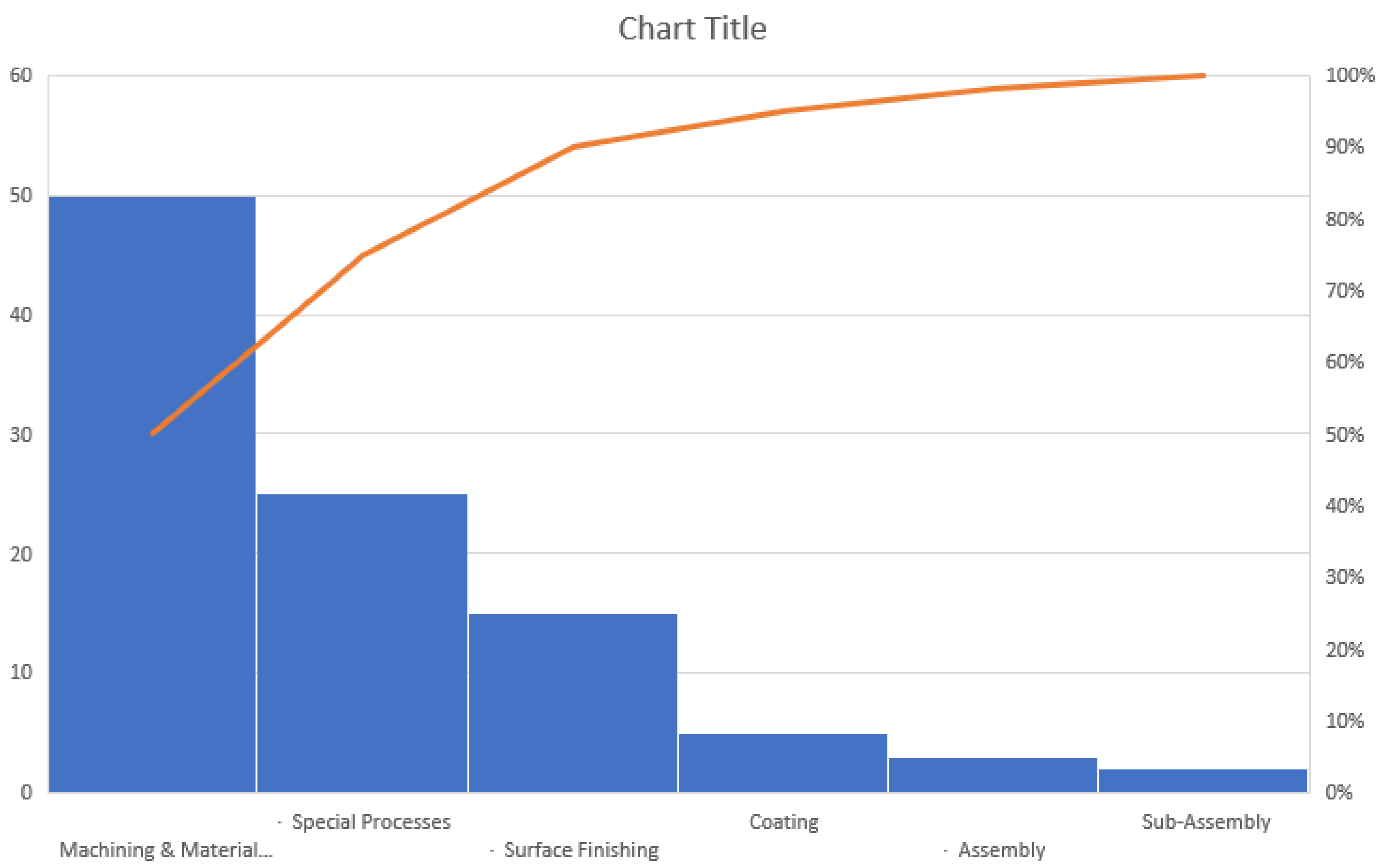
Baseline Performance of Primary Metric (9 months data as Line chart)



Inference :

- Last 9 months scrap percentage data shows a significant variation and hence ideal problem to be taken up as a Six Sigma Project.

Pareto chart



Inference :

- Machining Process contributes substantially for the scrap and included in the scope of the project

SIPOC

Suppliers (S)	Inputs (I)	Process (P)	Outputs (O)	Customers (C)
Raw material suppliers	Aerospace-grade raw materials (Titanium, Al, composites)	1. Receive raw material 2. Setup machining parameters 3. CNC machining (turning, milling, drilling, grinding) 4. In-process inspection 5. Handling & transfer	Machined aerospace parts Scrap (defective parts)	Internal: Assembly, Surface Treatment, QC External: OEMs (Airbus, Boeing, HAL), MRO, Regulators
Tooling suppliers	Cutting tools, jigs, fixtures		Dimensionally accurate parts	
Maintenance department	Machine availability, calibration		Reduced scrap % (from 3% → 1%)	
Operators / Machinists	Skilled manpower, standard operating procedures		Inspection reports, process data	
Quality department	Inspection standards, gauges, CMM programs		Customer satisfaction (quality + delivery)	

Project Charter

Project Title:	Reduction of Scrap% in Machining process from 3% to 1%
Project Leader	**Project Team Members:**
Sai Prudhvi Pinupolu	R. Kumar P. Reddy S. Naresh M. Harsha
Champion/Sponsors:	**Key Stake Holders**
Plant Head – Production	Production Department Maintenance Team Quality Department Suppliers / Vendors
Problem Statement:	**Goal Statement:**
Scrap in machining process is very high (@ 3 %) based on the data for the last 9 months	Reduce the scrap in machining process from 3% to 1% within 6 months.
Secondary Metric	**Assumptions Made:**
Productivity	50% of scrap comes from Machining process as per sample

Project Charter

Tangible and Intangible Benefits:

Estimated saving =
- $ 200,000

Other benefits –
- Customer Satisfaction
- Accuracy on delivery time

Risk to Success:

In Scope:

Machining and material removal operations (turning, milling, drilling, grinding) within aerospace component manufacturing

Out of Scope:

Casting, forging, heat treatment, coating, and assembly processes

Signatories:

Project Head : Shaiek Salman

Sponsor : Ali

Master Black Belt : Annamalai

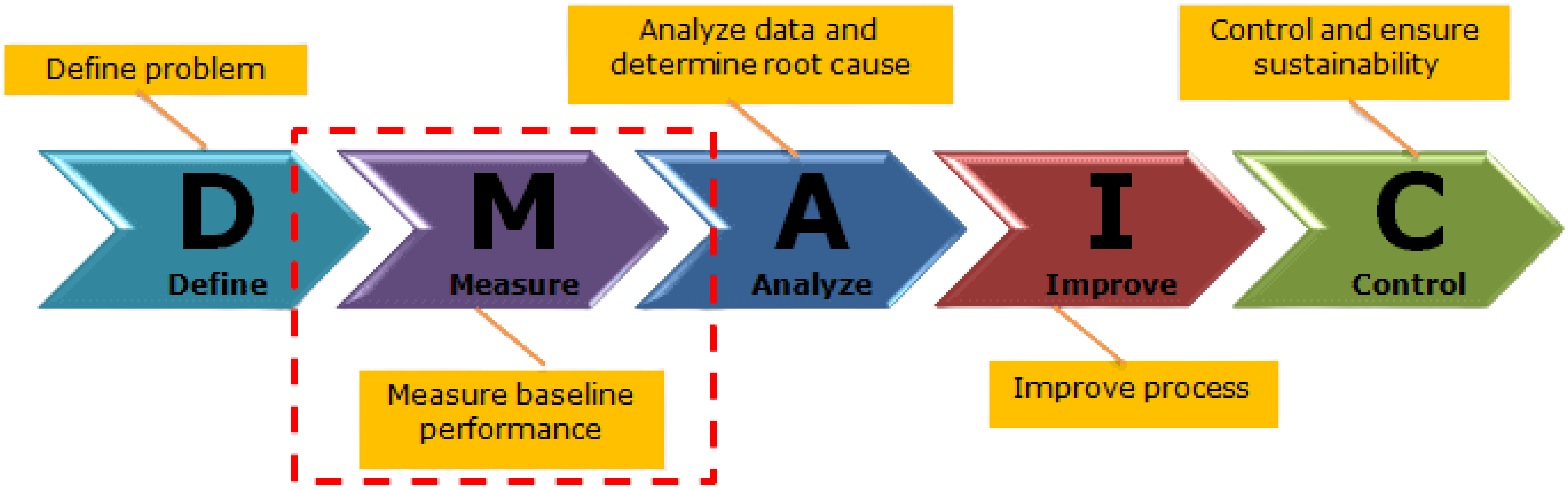
Finance Representative :

Project Timeline:

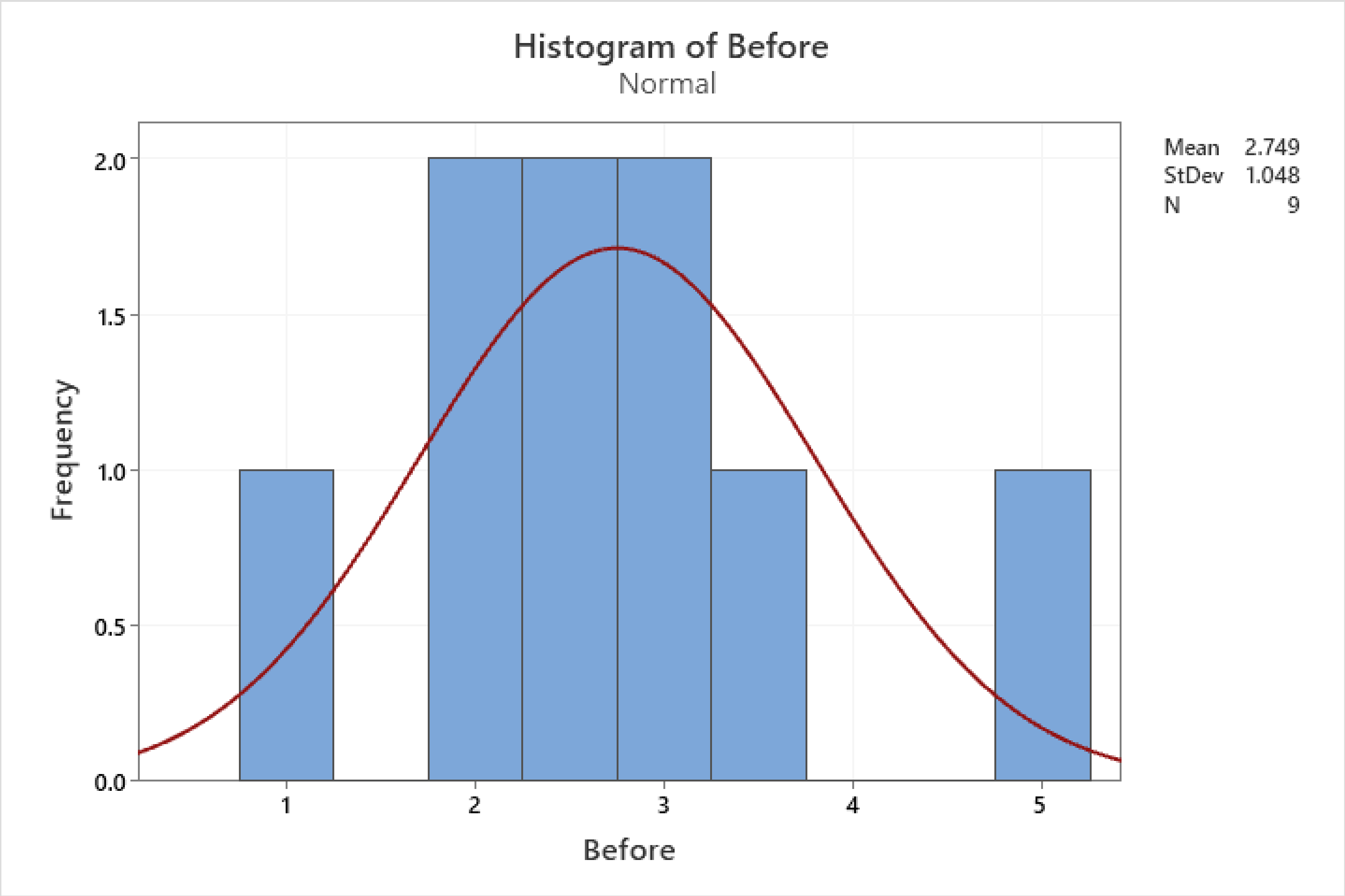
6 Months

Stages	Start	End
Define	1st January 2022	31st January 2022
Measure	1st February 2022	28th February 2022
Analyze	1st March 2022	15th April 2022
Improve	16th April 2022	31st May 2022
Control	1st June 2022	30th June 2022

MEASURE PHASE



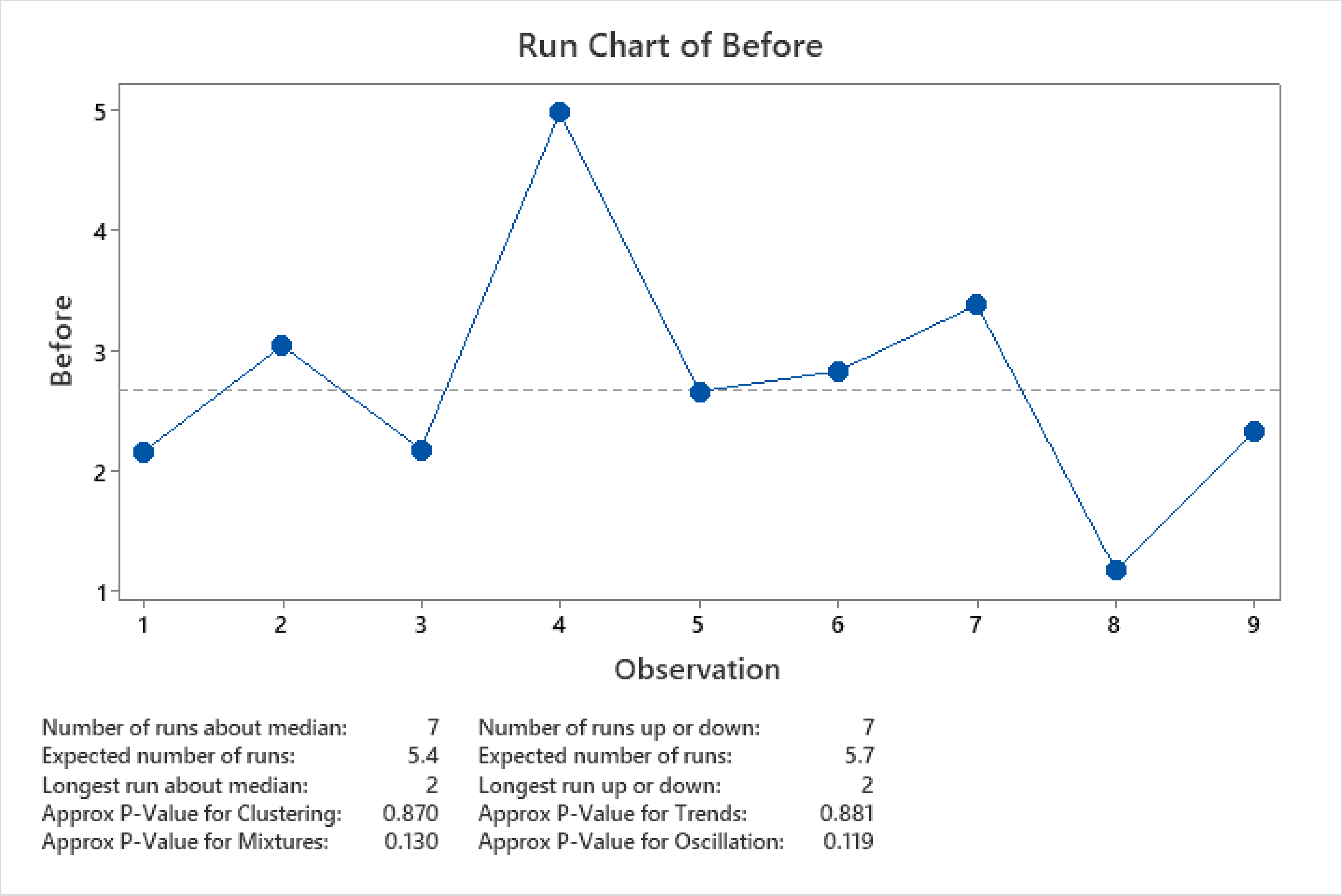
Data collection – Histogram (Before improvement)



Inference :

- Data is normally distributed over the mean

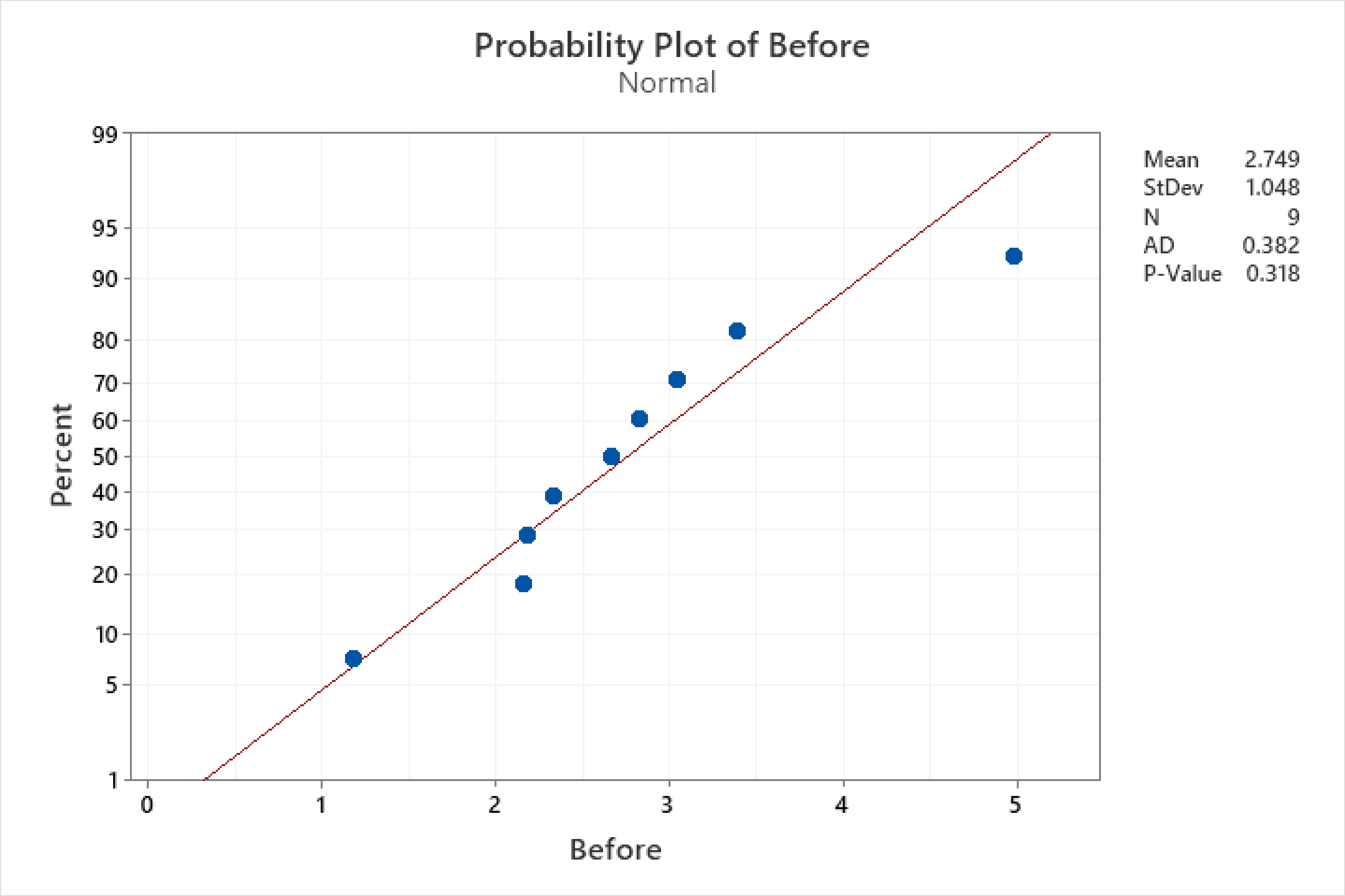
Data collection – Run Chart (Before improvement)



Inference :

P > 0.05 – No special causes in the process. Data can be used for further analysis

Data collection – Normality plot (Before improvement)



Inference :

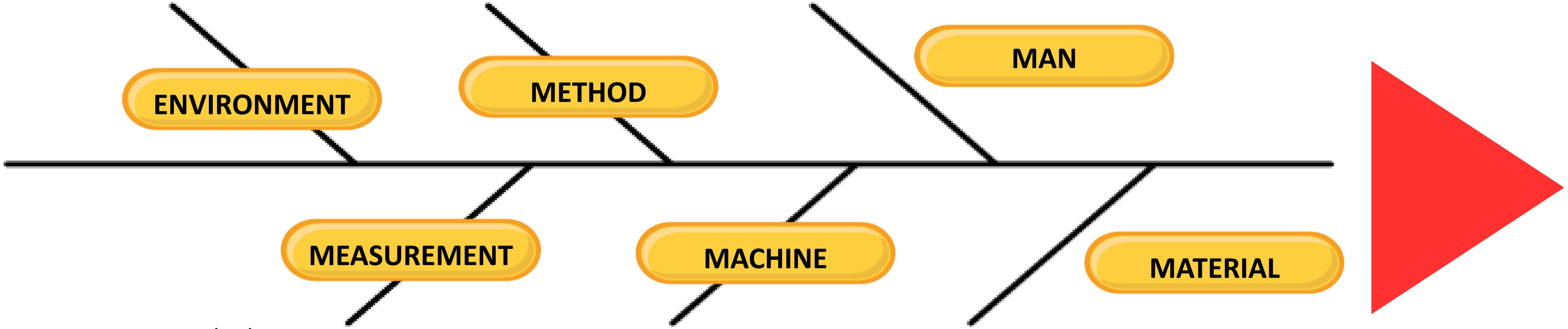
- P > 0.05 in all scenarios, thus all the data is normally distributed

Fish Bone Diagram

1. Temperature variations on shop floor affecting tolerance.
2. High humidity causing corrosion on workpiece/tools.
3. Poor lighting at workstations leading to inspection misses.
4. Dust/contamination in machining area.
5. Inadequate ergonomics leading to operator fatigue/errors.

1. Incorrect machining parameters (feed, speed, depth of cut).
2. Poor clamping / fixturing methods causing part movement.
3. Lack of standardized work instructions for complex parts.
4. Ineffective process control plans.
5. Inefficient sequencing of machining operations

1. Operator skill variation in CNC setup.
2. Inconsistent adherence to SOPs.
3. Fatigue and human error during long shifts.
4. Insufficient training on aerospace tolerances.
5. Communication gaps between operators and quality inspectors.



1. Inaccurate gauges or worn-out measuring instruments.
2. CMM program errors or misalignment.
3. Lack of gauge R&R validation.
4. Environmental effects on measurement (temperature drift).
5. Inconsistent inspection practices among inspectors.

1. CNC machine tool wear or spindle run-out.
2. Improper machine calibration / alignment.
3. Inadequate preventive maintenance schedules.
4. Coolant system malfunction leading to poor surface finish.
5. Vibration in machines affecting dimensional accuracy.

1. Variation in raw material hardness (different heat lots).
2. Micro-cracks or porosity in incoming material.
3. Surface defects on raw stock before machining.
4. Inconsistent grain structure in alloys.
5. Wrong grade of material supplied or mixed batches.

3M Analysis for Waste

MUDA

- Reworking parts due to out-of-tolerance machining.
- Excessive material scrap from trial cuts and tool offsets.
- Waiting time for inspection approval before moving to the next operation.

Mura

- Variation in cycle time between operators for the same CNC program.
- Inconsistent surface finish quality across different machining shifts.
- Fluctuations in raw material hardness from different suppliers/lots.

Muri

- Overloading operators with multiple machines simultaneously.
- Forcing cutting tools to run beyond recommended life, causing tool breakage.
- Running machines continuously without scheduled maintenance, leading to sudden breakdowns.

8 Wastes Analysis

Defects

- Parts scrapped due to out-of-tolerance dimensions.
- Surface defects like scratches, chatter marks, or poor finish.

Overproduction

- Producing extra machined parts “just in case” customer orders increase.
- Running trial cuts in excess before stabilizing CNC settings.

Waiting

- CNC operators waiting for quality inspection clearance.
- Machines idle due to delayed raw material issue from stores.

Non-Utilized Talent

- Operators not involved in problem-solving or improvement discussions.
- Lack of training opportunities to enhance skill in precision machining.

Transportation

- Unnecessary movement of semi-finished parts between machining centers.
- Long-distance movement to CMM lab for inspection.

Inventory

- Excess WIP (work-in-progress) parts piled near machines.
- Overstock of cutting tools and inserts not immediately required.

Motion

- Operators walking repeatedly to fetch gauges or tools.
- Manual handling of heavy parts without fixtures or trolleys.

Overprocessing

- Multiple re-cuts to achieve tolerance due to unstable setup.
- Extra polishing of surfaces beyond customer requirement.

Action Plan for Low Hanging Fruits

Special Causes (sudden failures / abnormalities)

Issue Observed	Lean Tool	Action Plan	Benefit
Sudden CNC spindle failure	TPM (Total Productive Maintenance)	Implement preventive maintenance schedule and operator-led daily checks	Reduced downtime, stable machining accuracy
Coolant system breakdown	Visual Controls + TPM	Add coolant level indicators and checklists	Avoid surface defects, improve tool life
Out-of-spec raw material batch	Incoming Quality Control (Poka Yoke)	Strengthen supplier certification and incoming lot checks	Fewer rejections, reduced scrap
CMM program crash	Standardized Work	Create validated backup CMM programs	Faster recovery, less delay
Abrupt power fluctuation	**Andon System + Backup**	**Install voltage stabilizers and surge protectors**	Avoid unexpected stoppages

Action Plan for Low Hanging Fruits

Muda (Waste)

Waste Type	Lean Tool	Action Plan	Benefit
Rework due to defects	Poka-Yoke	Error-proof clamping and tool offset checks	Lower rework hours
Waiting for inspection	Point-of-Use Inspection	Provide in-line gauges / go-no-go tools at CNC	Reduced waiting time

Mura (Unevenness)

Issue	Lean Tool	Action Plan	Benefit
Variation in cycle times	Standard Work + SMED	Standardize CNC setup parameters and quick-change tooling	Consistent productivity
Inconsistent finish quality	SPC Control Charts	Monitor process stability and provide operator feedback	Stable surface quality

Muri (Overburden)

Issue	Lean Tool	Action Plan	Benefit
Overused cutting tools	Kanban for Tool Change	Visual tool life tracking and Kanban cards	Prevents tool breakage, reduces scrap
Operators overloaded	Work Balancing / Line Balancing	Redistribute machine responsibilities	Reduced errors, improved focus

Action Plan for Low Hanging Fruits

Waste	Lean Tool	Action Plan	Benefit
Overproduction	Kanban Scheduling	Produce only to customer demand	Lower WIP, reduced scrap risk
Transportation	Cellular Layout	Group machines closer by sequence	Faster flow, less handling damage
Motion	5S	Place gauges and tools near point of use	Reduced operator walking time
Inventory	Pull System	Limit WIP using Kanban bins	Lower storage cost, better flow
Overprocessing	Standard Work	Eliminate extra polishing or redundant machining	Saves time & cost
Defects	Poka-Yoke	Error-proof setups and in- process checks	Scrap reduced from 3% → 1%
Waiting	Andon / Visual Boards	Signal delays to supervisors immediately	Quick problem resolution
Unused Talent	Kaizen Events	Involve operators in daily improvements	Engaged workforce, continuous ideas

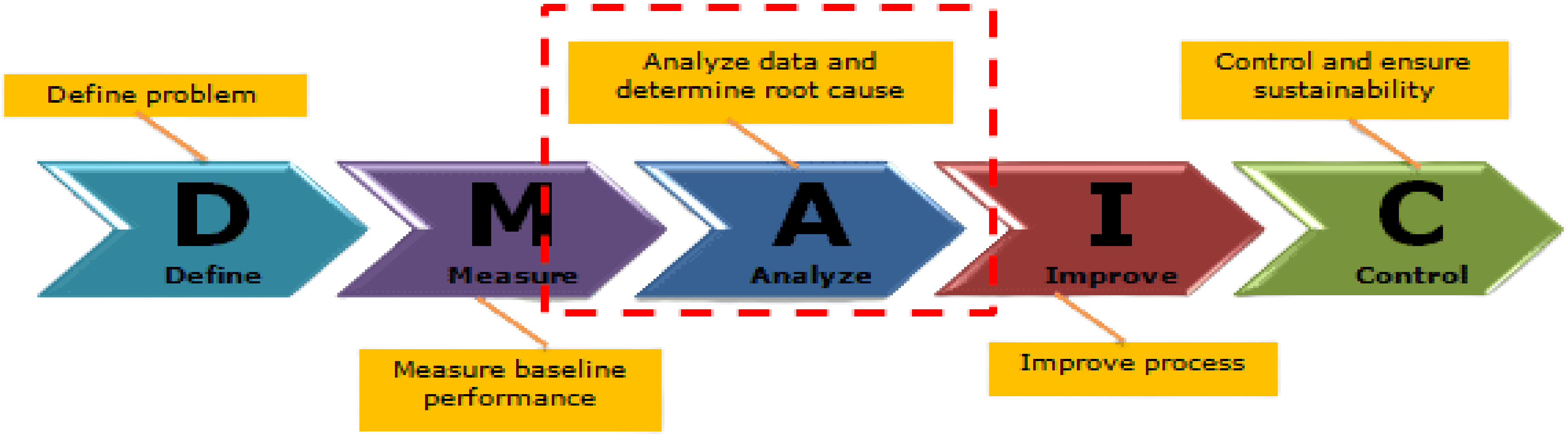
Top 12 Prioritized Root Causes (Based on Net Score)

Root Cause	Score
Tool wear	**306**
Overuse of cutting tools	**306**
Cutting parameters	**264**
Vibration in machines	**264**
Machine calibration	**258**
CMM program errors	**242**
Operator skill variation	**216**
Fixturing/clamping	**216**
Raw material hardness variation	**216**
Raw material surface defects	**216**
SOP adherence	**200**
Gauge accuracy/calibration	**200**

Data Collection Plan

Output / Input	Type of Data	Measurement Method	Unit	Frequency	Responsibility
% Scrap (Primary Y)	Continuous	Scrap count / production log	%	Daily	Production Engineer
Surface Finish (Ra)	Continuous	Surface profilometer	µm	Daily	Quality Inspector
Tool Wear	Continuous	Tool inspection (flank/length wear)	mm	Daily	Operator / QC
Cutting Parameters (speed, feed, depth)	Continuous	CNC machine readout	rpm / mm/min	Daily	Production Engineer
Machine Vibration	Continuous	Vibration meter	mm/s	Weekly	Maintenance Eng.
Machine Calibration	Attribute	Calibration record	Yes/No	Monthly	Maintenance Eng.
Fixturing / Clamping Method	Attribute	Visual check / setup log	Std/Non-std	Daily	Operator
Raw Material Hardness	Continuous	Rockwell hardness tester	HRC	Lot-wise	QC Lab
Raw Material Defects	Attribute	Visual inspection	Pass/Fail	Lot-wise	QC Lab
Operator Skill	Attribute	Training record	Certified/Not	Once / operator	HR / Training
SOP Adherence	Attribute	Audit checklist	Yes/No	Weekly	Supervisor / QA
Gauge Calibration	Attribute	Calibration certificate	Pass/Fail	Monthly	QC
First Pass Yield (FPY)	Continuous	Production & inspection log	%	Daily	Production Engineer
On-Time Delivery (OTD)	Continuous	Planning report	%	Weekly	Planning Dept.

ANALYSE PHASE



Analyse – Hypothesis testing

Regression Equation

Scrap_Machining_% = 0.572 + 22.543 Tool_Wear_VB_mm + 0.19861 Tool_Life_Overrun_%
+ 0.4646 CutParam_Dev_%

Coefficients

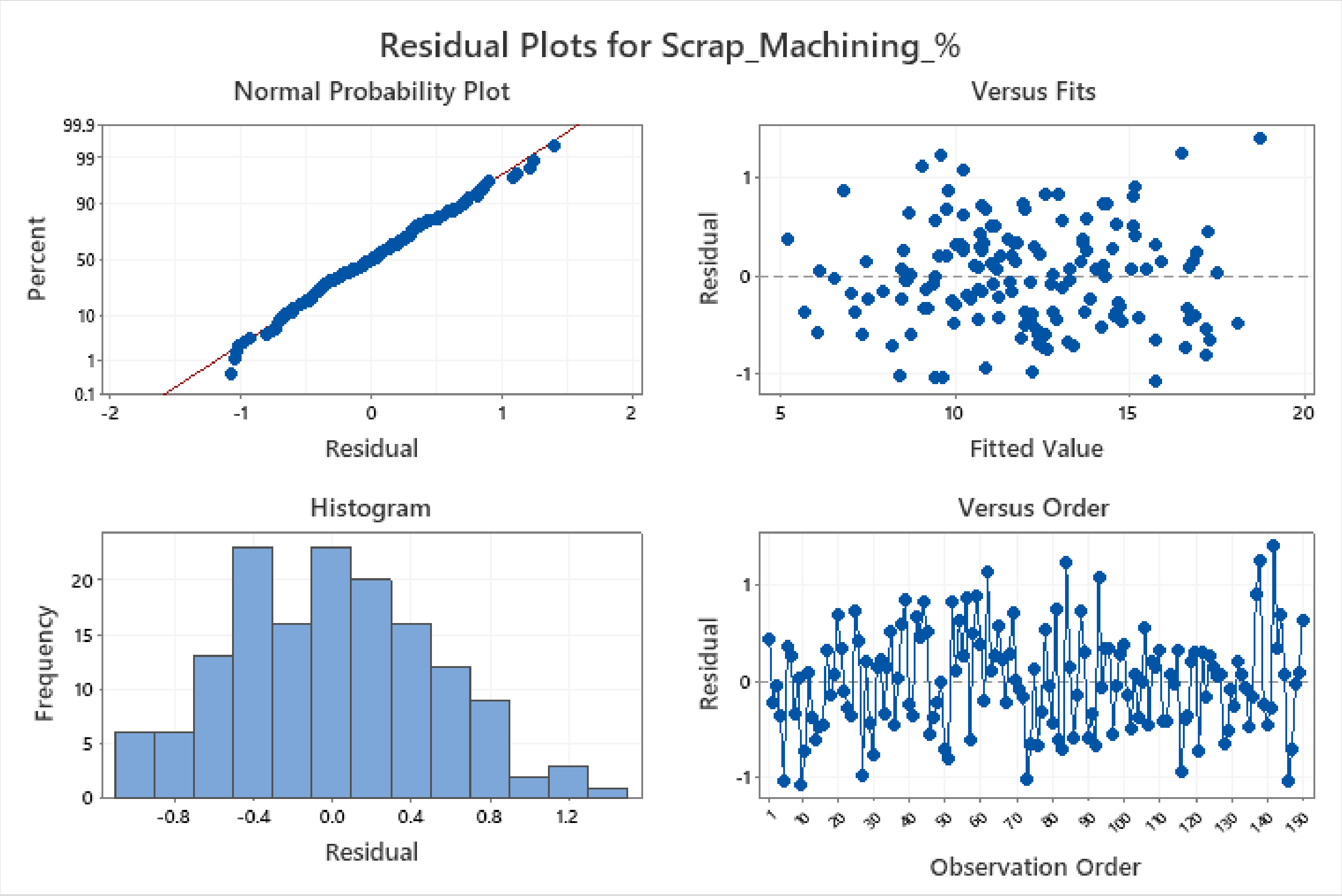
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.572	0.182	3.14	0.002	
Tool_Wear_VB_mm	22.543	0.815	27.68	0.000	1.00
Tool_Life_Overrun_%	0.19861	0.00419	47.45	0.000	1.01
CutParam_Dev_%	0.4646	0.0103	45.17	0.000	1.01

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.520512	96.95%	96.89%	96.78%

Analysis of Variance

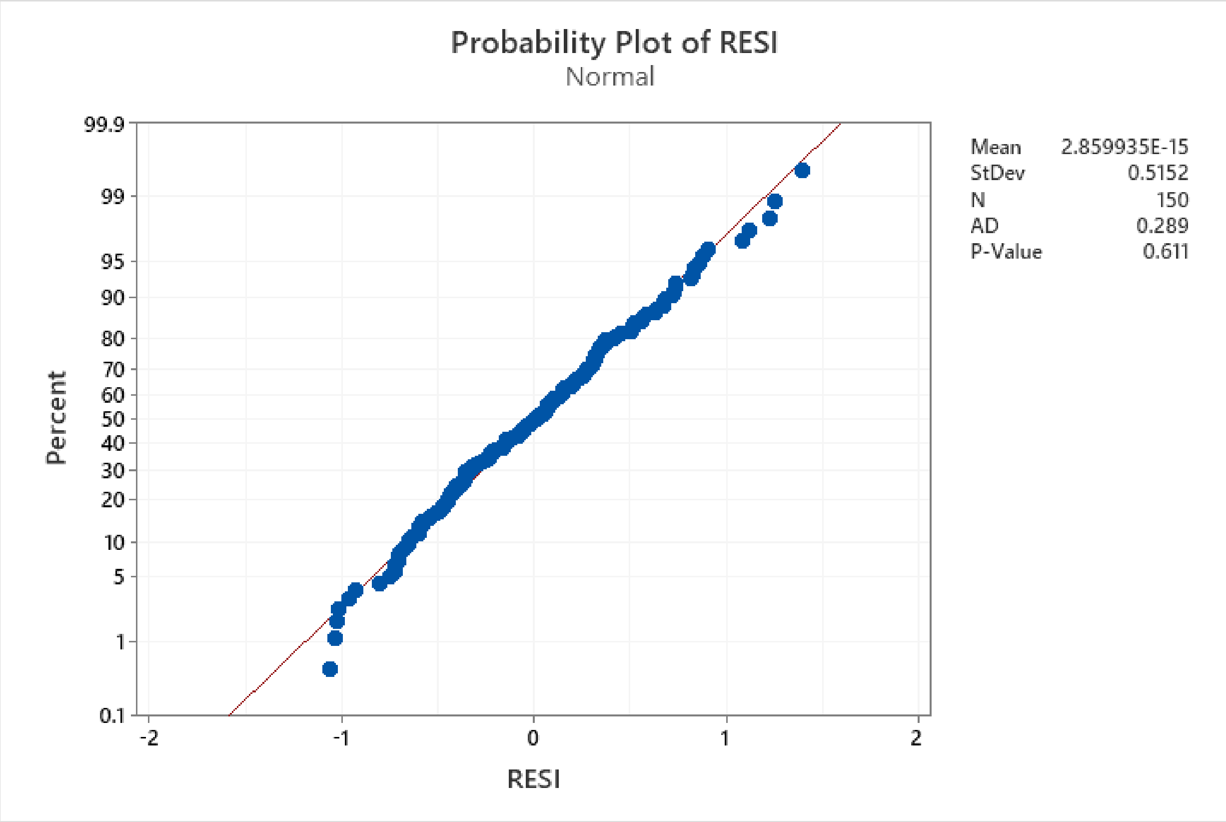
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1258.76	419.588	1548.68	0.000
Tool_Wear_VB_mm	1	207.52	207.524	765.96	0.000
Tool_Life_Overrun_%	1	610.11	610.114	2251.90	0.000
CutParam_Dev_%	1	552.69	552.692	2039.96	0.000
Error	146	39.56	0.271		
Total	149	1298.32			

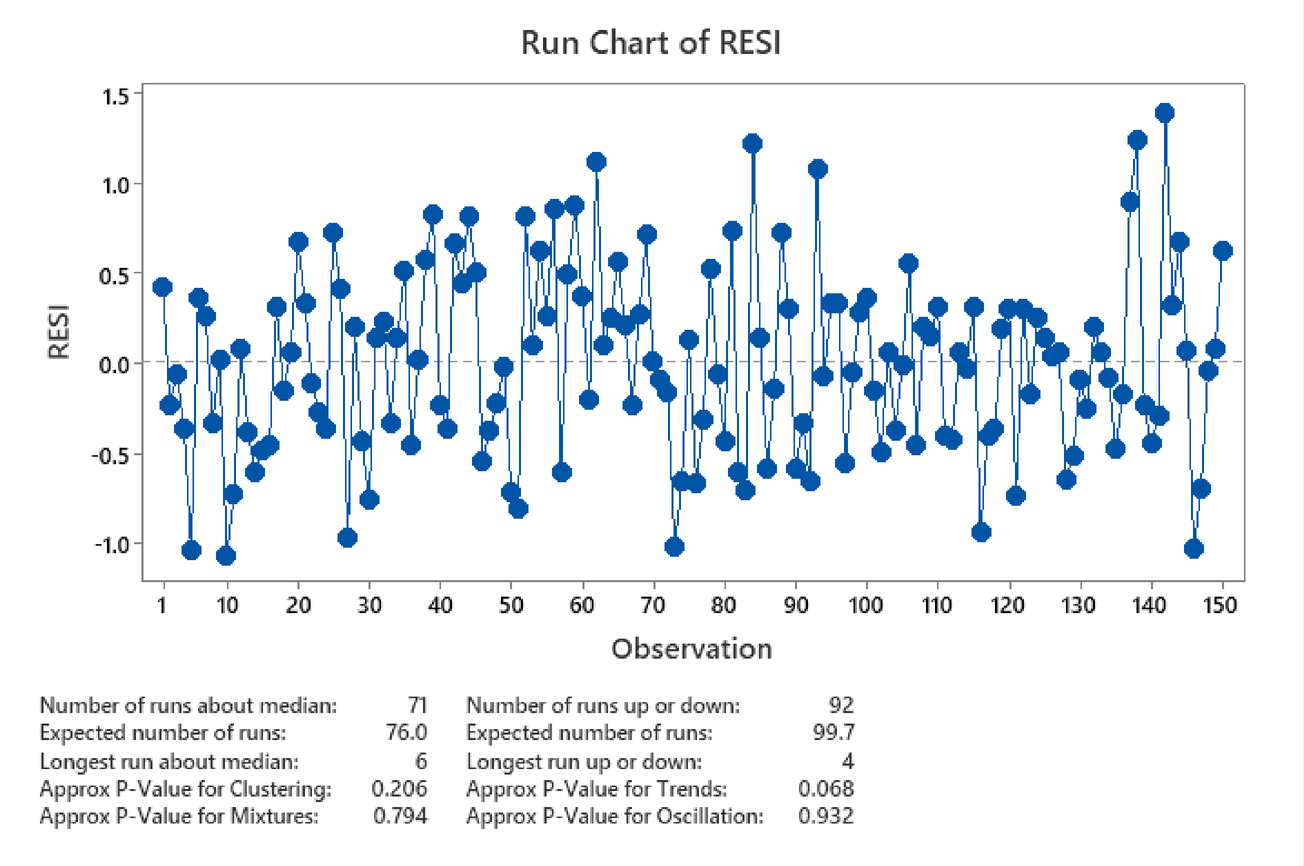


Inference :

- Since $p < 0.05$, thus not all means are equal

Analyse – Hypothesis testing





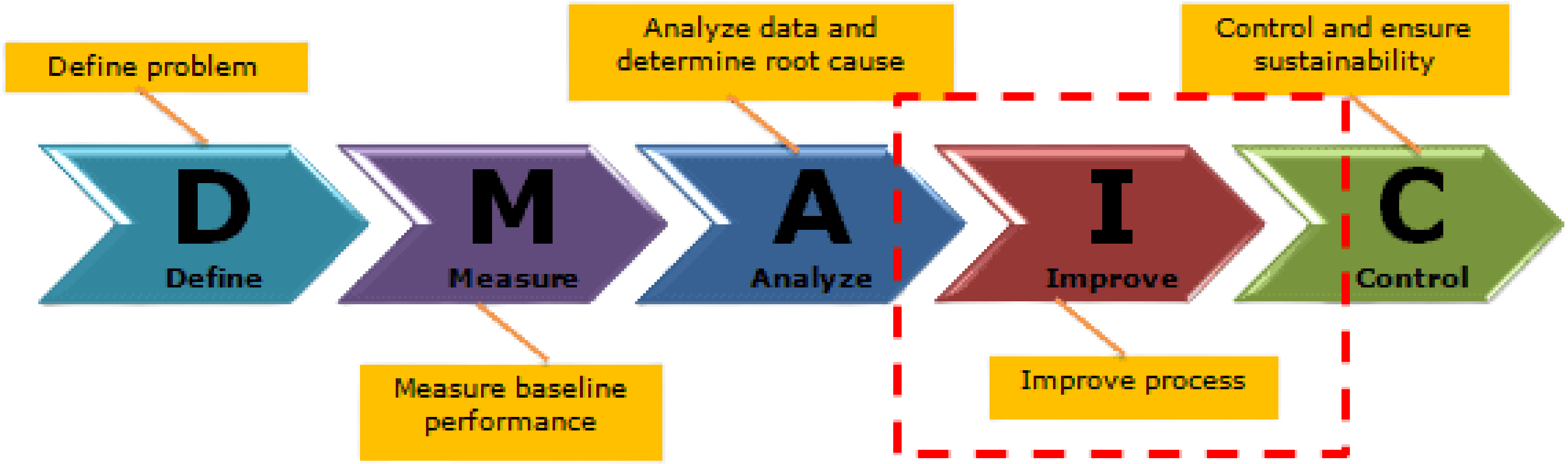
Inference :

- Both plots confirm that the residuals are normal, independent, and random — meaning the model fits the data well, and the underlying assumptions for regression or process analysis are satisfied.

Summary of Statistically validated Root causes

- Tool wear out, Over use of cutting tools and Cutting parameters are validated as critical root causes

IMPROVE PHASE



Improve Design of Experiment

Run Order	Type	A_ToolWear_code	B_ToolLifeOverrun_code	C_CutParamDev_code	Tool_Wear_VB_mm	Tool_Life_Overrun_%	CutParam_Dev_%	Scrap_Machining_%
1	Factorial	1	1	-1	0.25	40	3	0
2	Factorial	-1	-1	-1	0.05	0	3	0.94
3	Factorial	-1	-1	1	0.05	0	13	0
4	Center	0	0	0	0.15	20	8	9.61
5	Factorial	1	-1	1	0.25	0	13	0
6	Center	0	0	0	0.15	20	8	9.43
7	Factorial	-1	1	1	0.05	40	13	30.68
8	Center	0	0	0	0.15	20	8	9.52
9	Factorial	1	1	1	0.25	40	13	38.14
10	Factorial	1	-1	-1	0.25	0	3	27.7
11	Factorial	-1	1	-1	0.05	40	3	0

Improve

Factorial Regression: Scrap_Machining_%_Dummy versus Tool wear, Tool life, cutting parameter

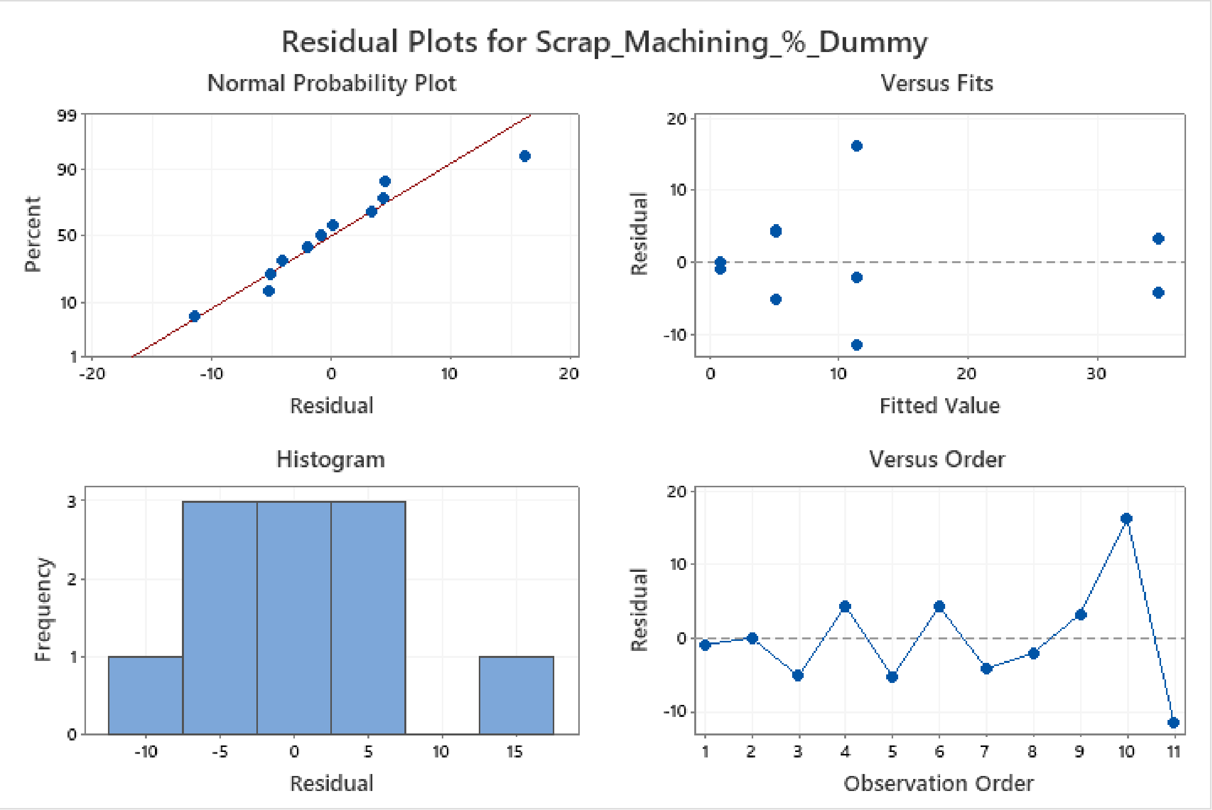
Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		11.46	2.60	4.41	0.003	
Tool wear	17.02	8.51	3.04	2.80	0.027	1.00
Tool life	12.68	6.34	3.04	2.08	0.076	1.00
Tool wear*Tool life	16.93	8.46	3.04	2.78	0.027	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
8.60876	73.96%	62.80%	54.67%

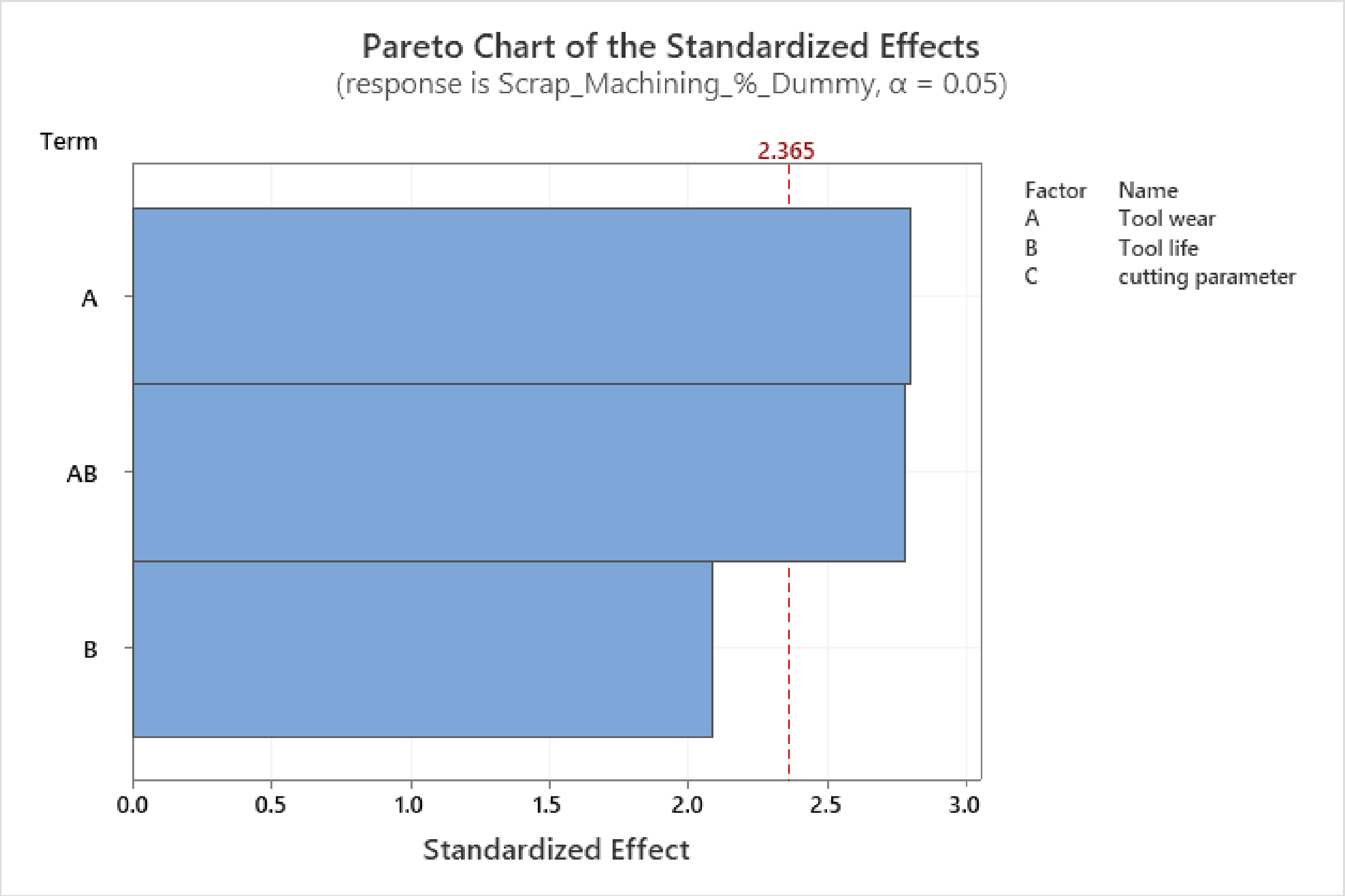
Analysis of Variance

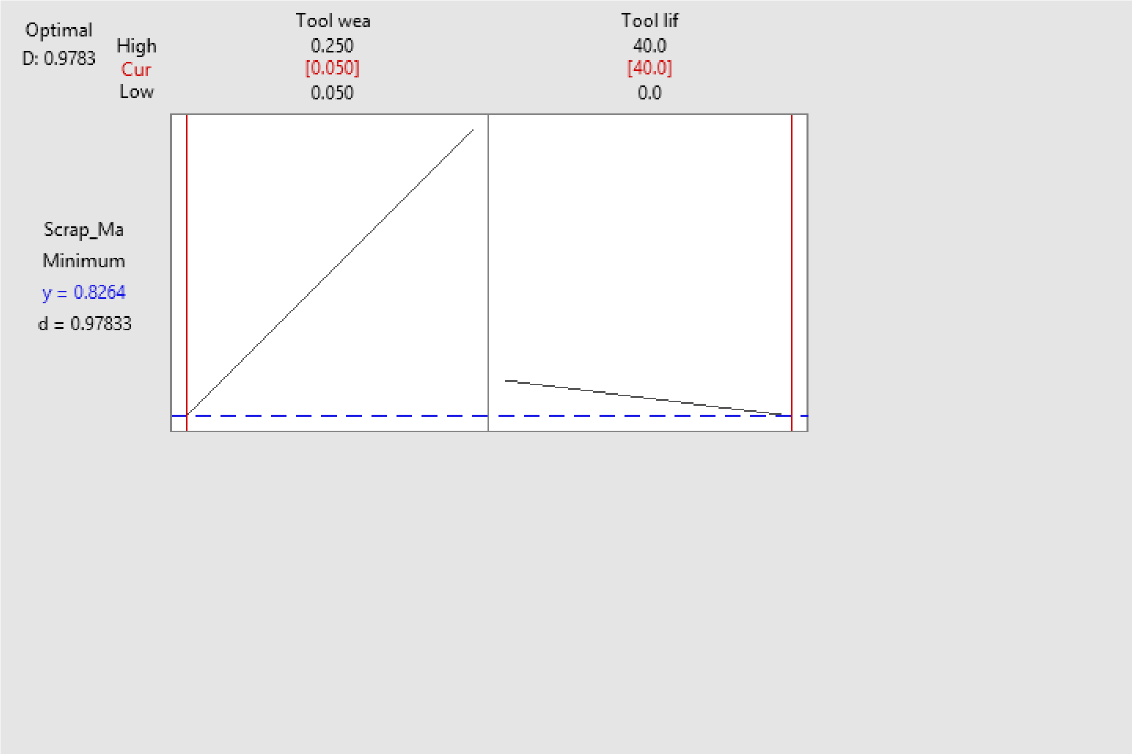
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	1473.50	491.166	6.63	0.019
Linear	2	900.59	450.293	6.08	0.030
Tool wear	1	579.02	579.020	7.81	0.027
Tool life	1	321.56	321.565	4.34	0.076
2-Way Interactions	1	572.91	572.911	7.73	0.027
Tool wear*Tool life	1	572.91	572.911	7.73	0.027



The regression model is statistically significant ($p < 0.05$). Both **Tool wear** and **its interaction with Tool life** significantly impact scrap machining %.

Improve





The Pareto chart shows that **Tool wear (A)** and the **interaction of Tool wear & Tool life (AB)** significantly affect scrap machining %, while Tool life (B) alone has a minor impact.

The optimization plot indicates that **minimum scrap (≈0.83%)** is achieved at **low Tool wear (0.05)** and **high Tool life (40.0)**. The high desirability value (**D = 0.9783**) confirms that these settings provide the **optimal and statistically reliable process condition**.

Improve

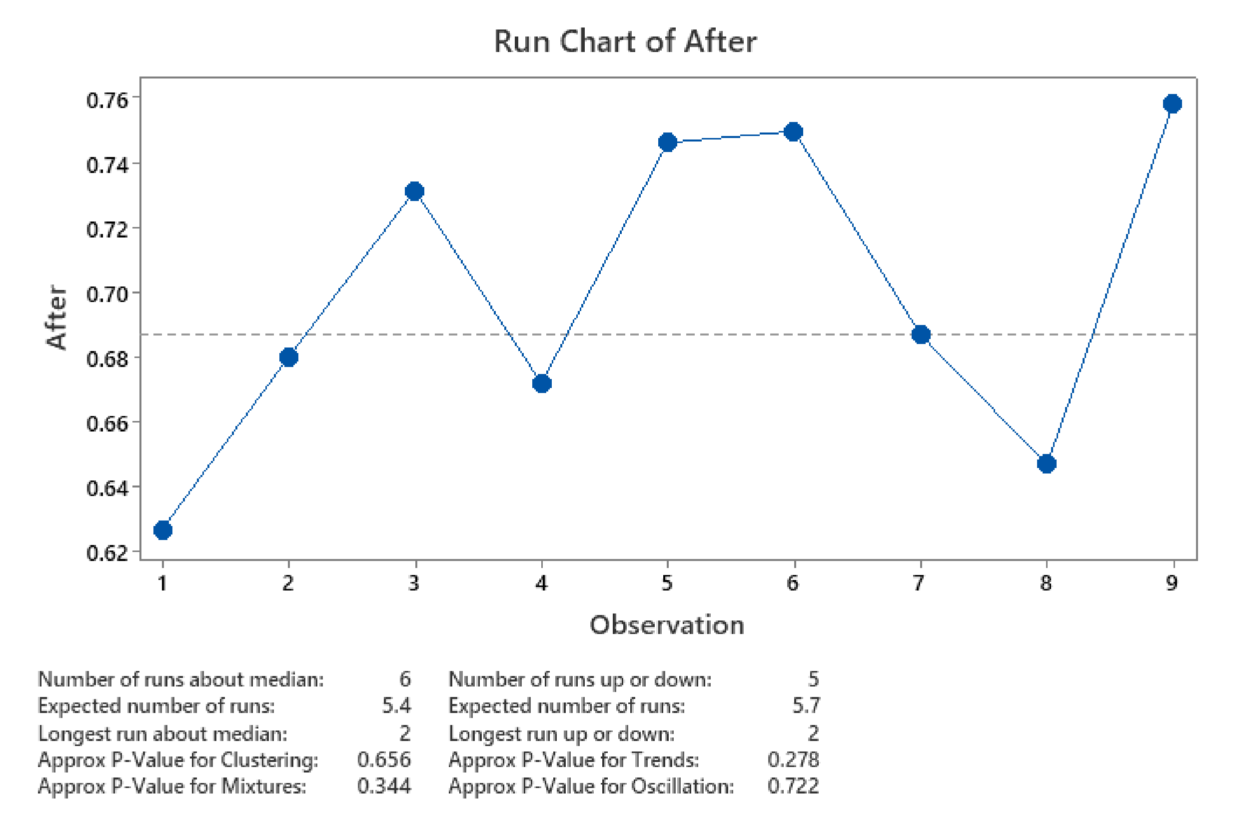
Inference :

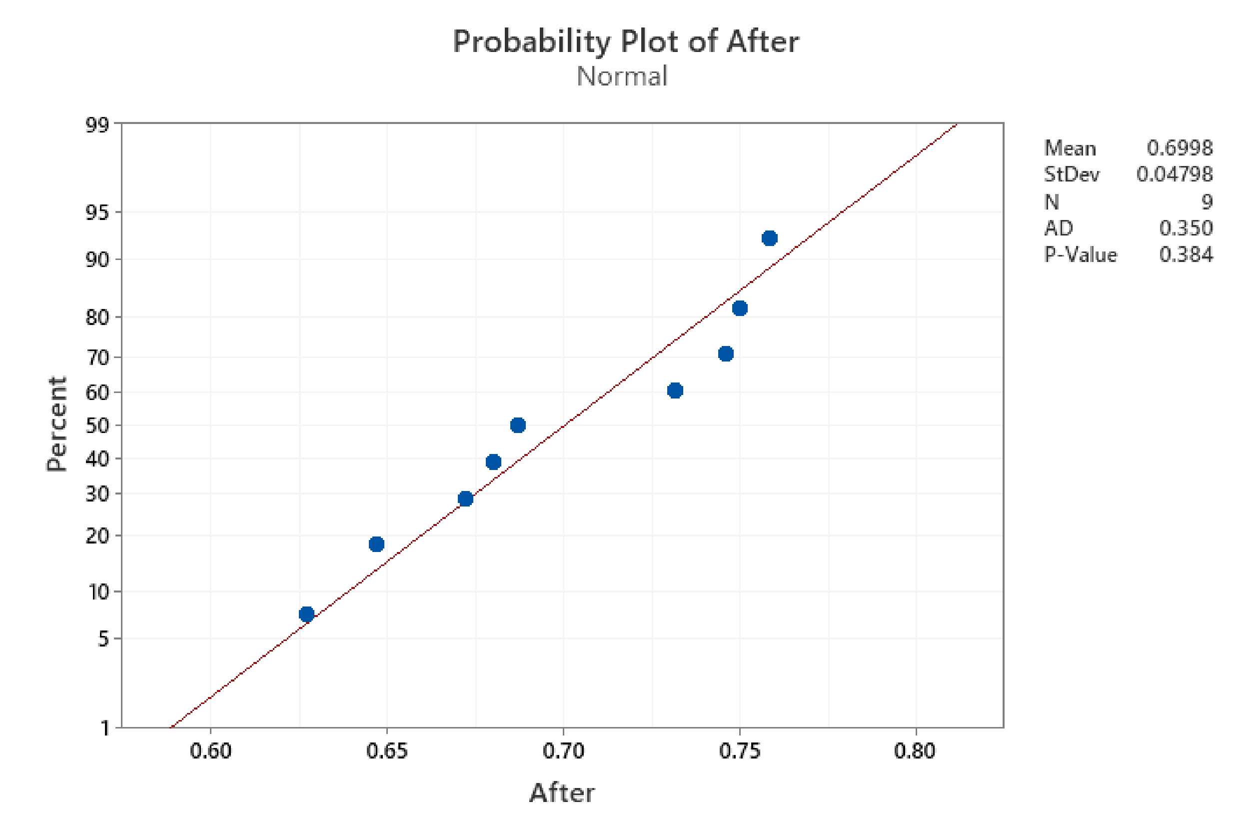
8 step validation

- Overall Model and individual p value is less than 0.05
- VIF is also less than 5
- R-Sq Adj is above 85 %
- Residual analysis - Normality plot shows data is normally distributed, equal variance shows the random behaviour, Residual observation order run chart is OK and Histogram does not shows any outlies

- Since it is passing all the step regression equation is valid and XXX are critical input.

Improve – Run chart and Normality Test (After Improvement)





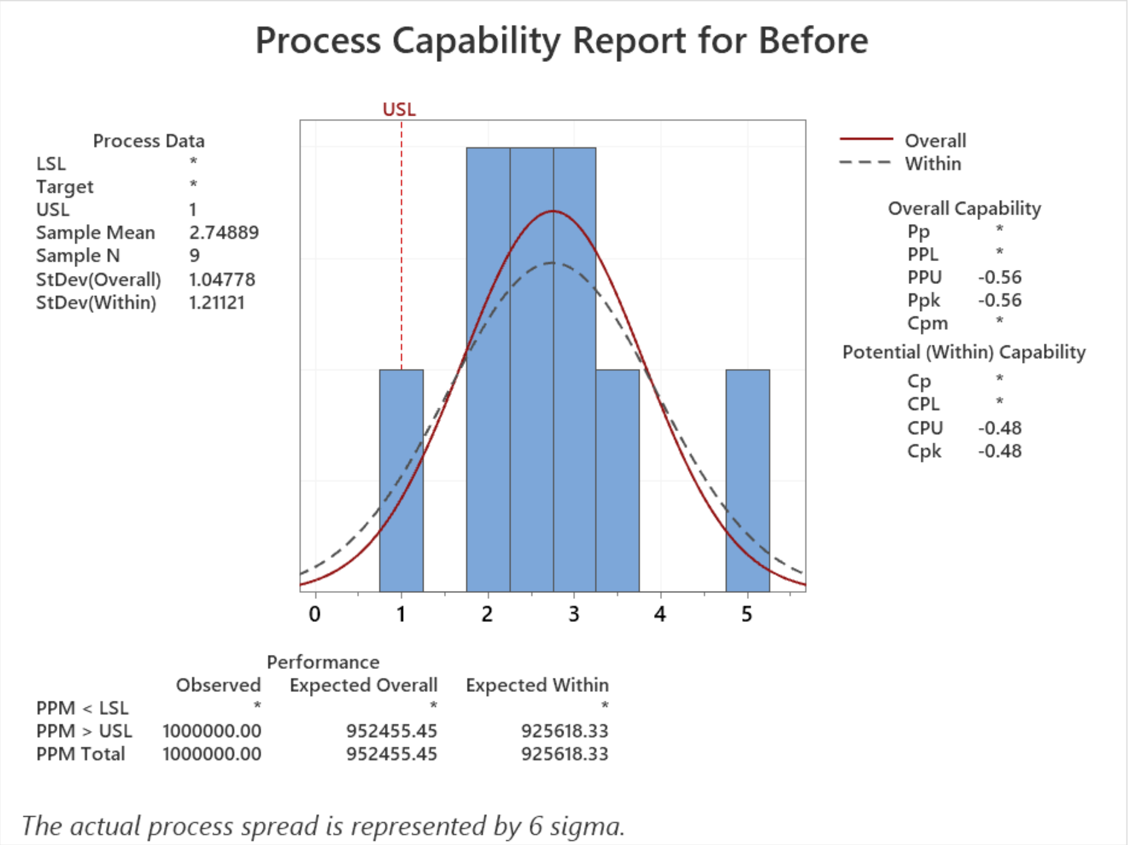
Inference:

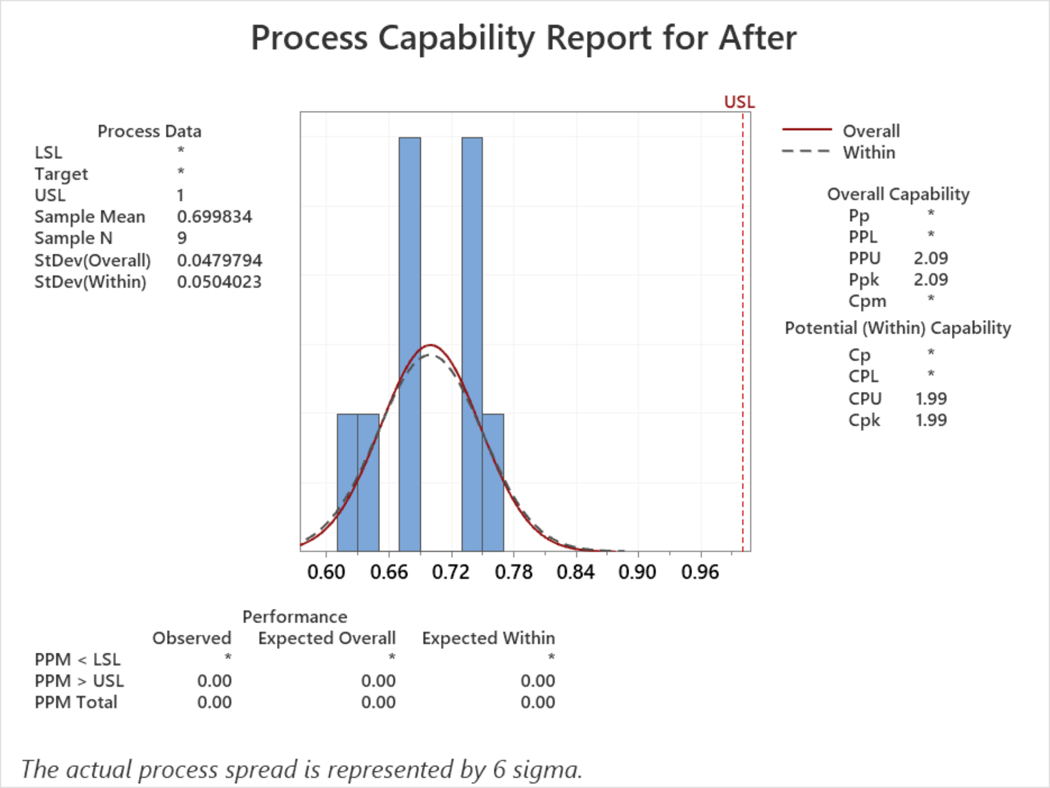
- Run chart – process is stable there is no special causes in the process (p value > 0.05)

Inference:

- Normality test – Data are normally distributed

Improve – Process capability – Before & After Improvement





Inference :

- Before Cpk < After Cpk, which shows process is much more capable after improvement
- There is less variability in system since stdev reduced after improvement
- After improvement the data are normally distributed near the target within specified limit

Improve –After Improvement (Statistical validation for Improvement – Hypothesis Testing)

Two-Sample T-Test and CI: Before, After

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Before	9	2.75	1.05	0.35
After	9	0.6998	0.0480	0.016

Estimation for Difference

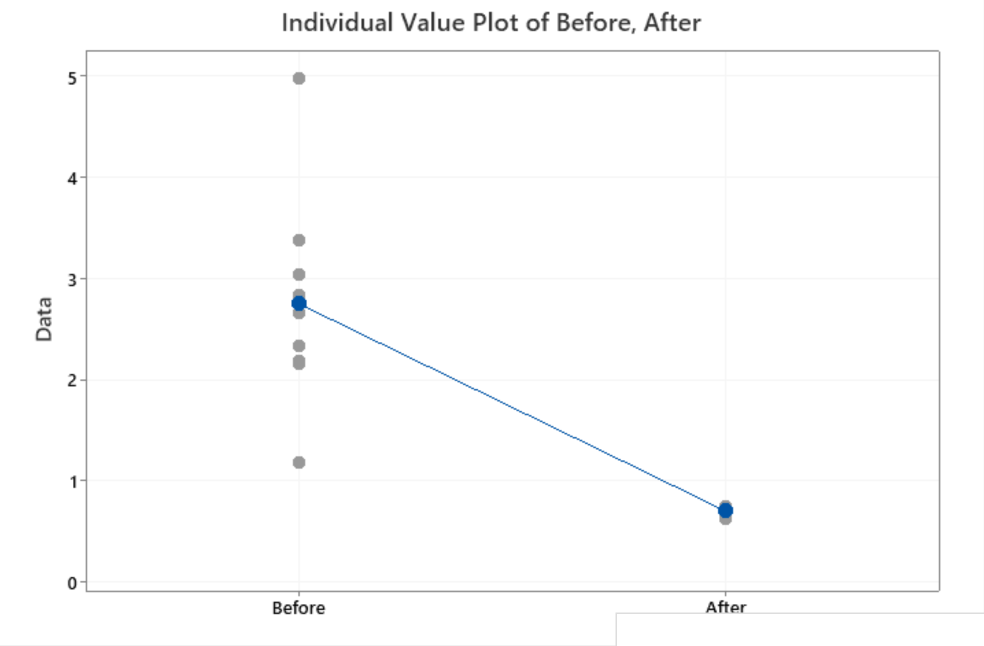
Difference	95% CI for Difference
2.049	(1.243, 2.855)

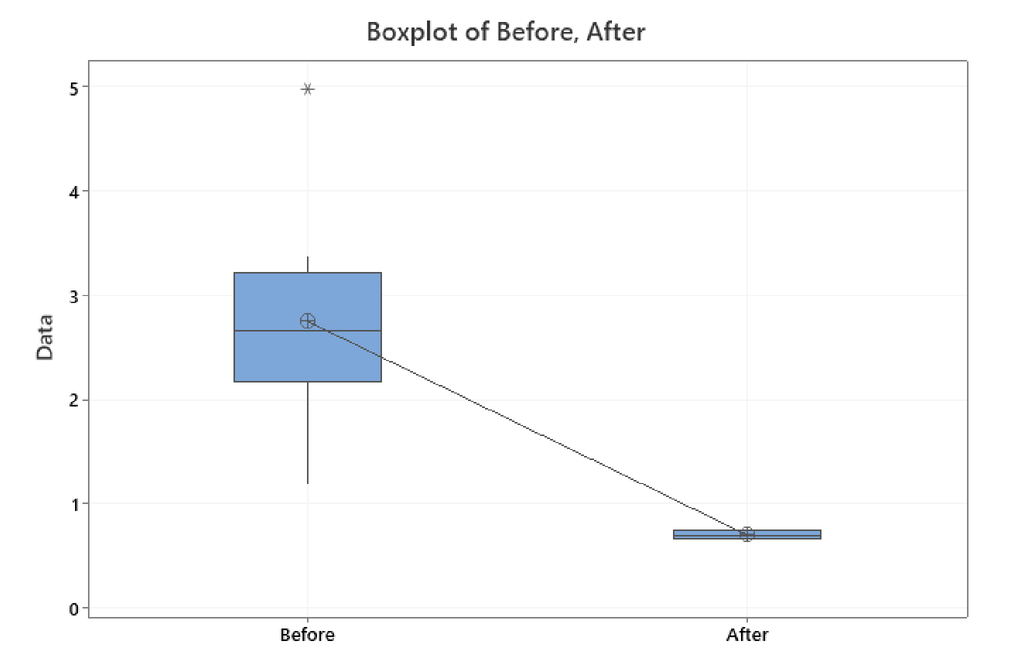
Test

Null hypothesis H_0: $\mu_1 - \mu_2 = 0$

Alternative hypothesis H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
5.86	8	0.000





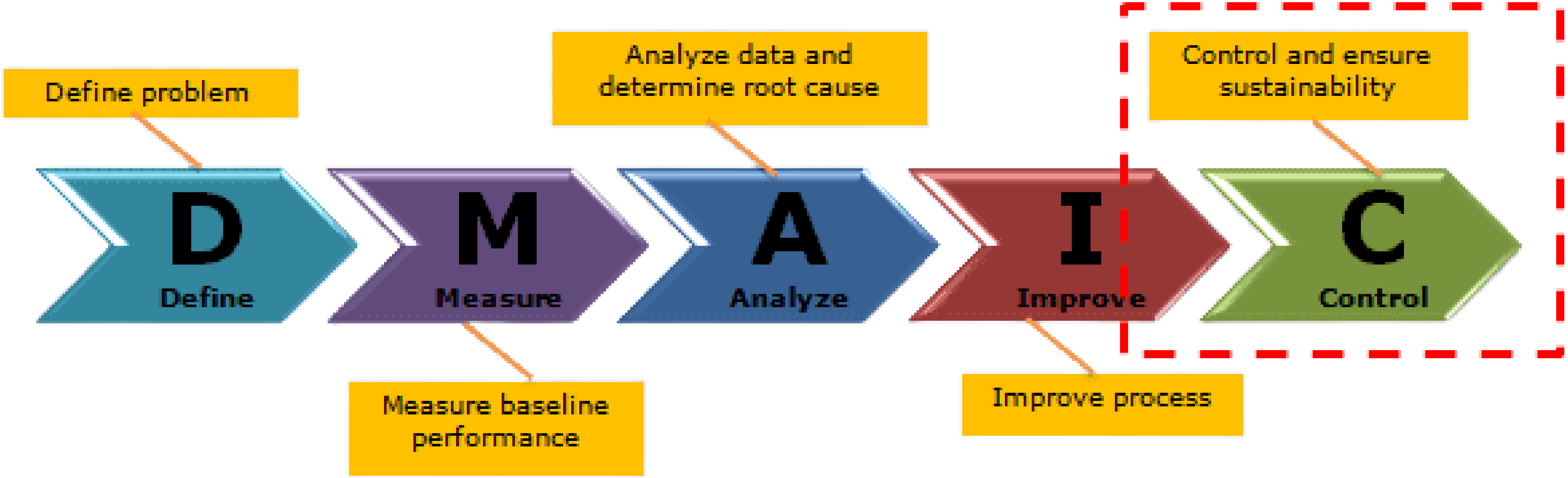
Inference:

- Since P value is less than 0.05, there is enough evidence to reject the null hypothesis and we can conclude that the difference between the population means is statistically significant.
- It is also visible from the individual value plot & box plot, there is clear difference in mean after improvement which is closer to required % scrap

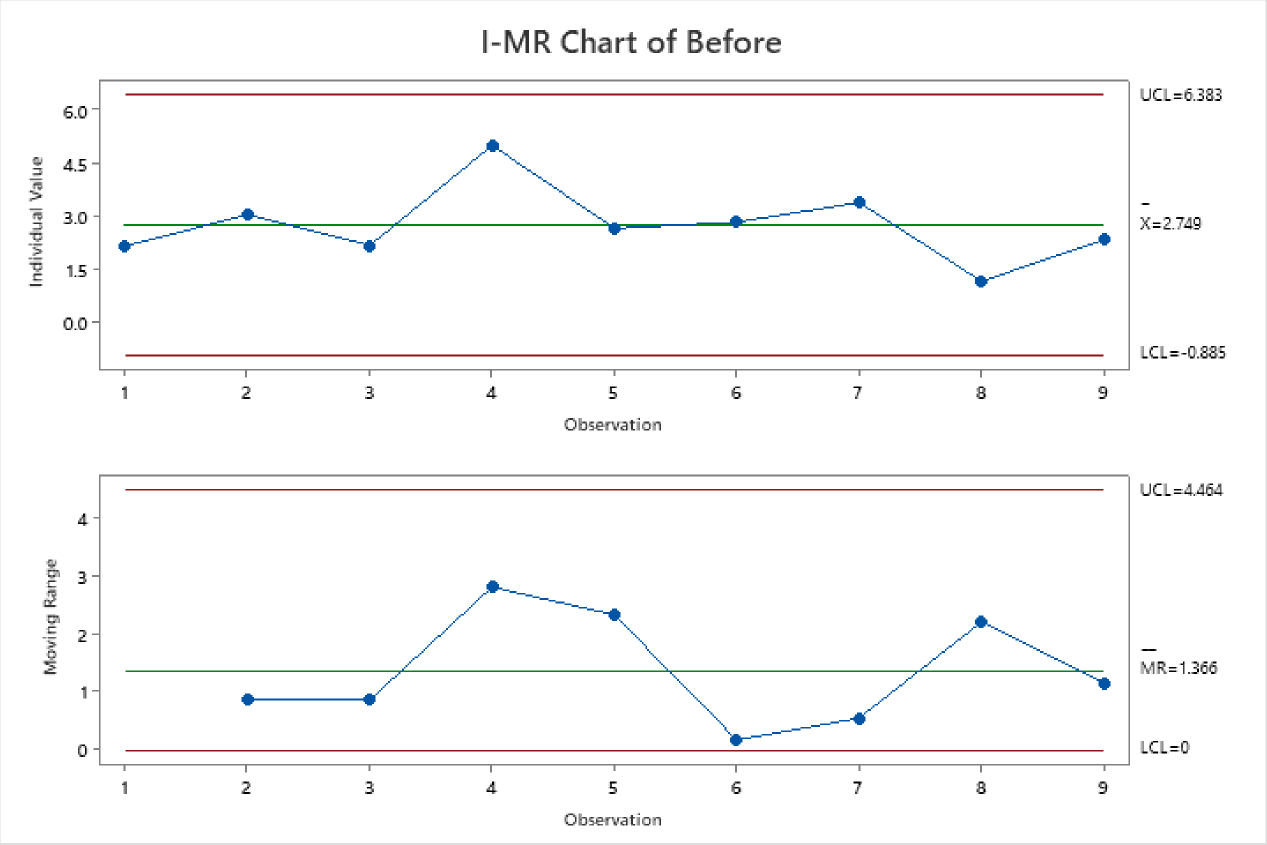
FMEA

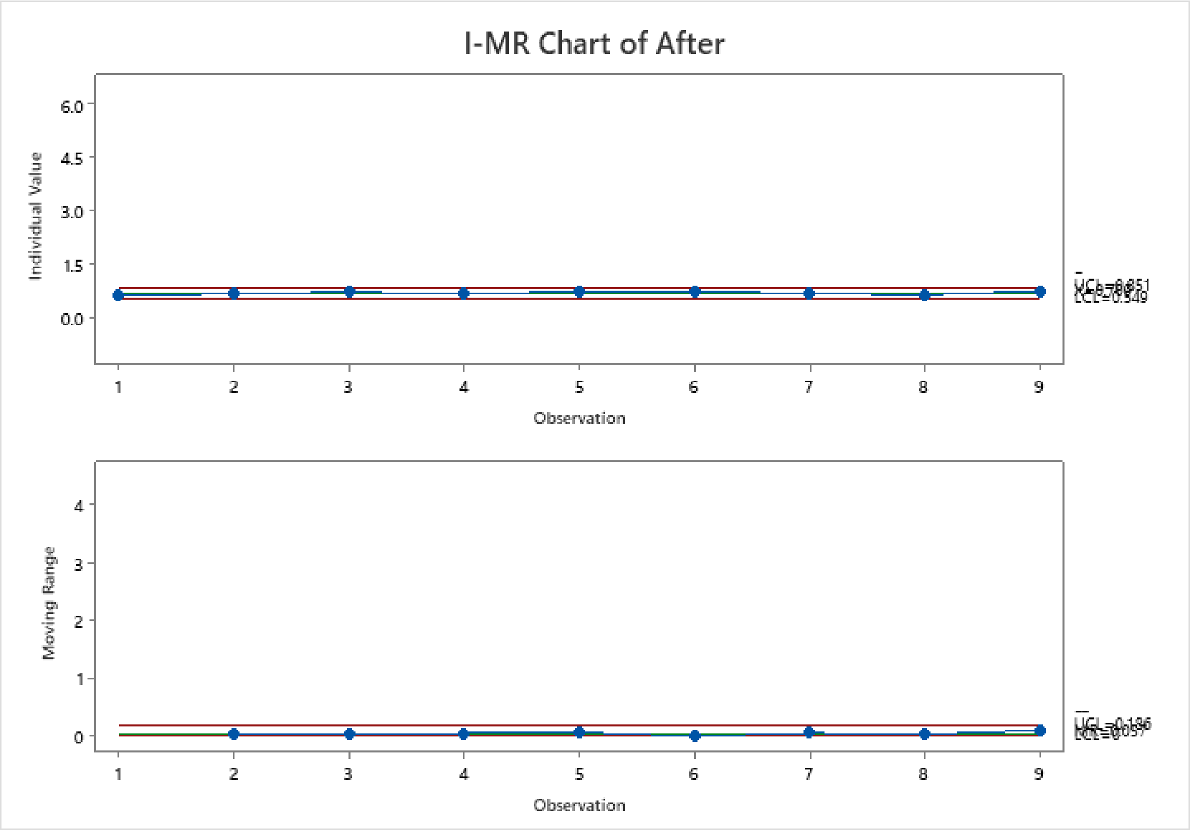
Process Step	Function / Requirement	Potential Failure Mode	Potential Effects	S	Potential Causes / Mechanisms	O	Current Controls (Prev/Det)	D	RPN	Recommended Actions (acceptance criteria)	Owner	Target	Residual S	Residual O
Program load (DNC)	Correct recipe & locked parameters	Wrong program/params loaded or drift from recipe	OOT dims, scrap spike	9	Wrong file, manual edits, legacy offsets	5	Paper signoff; 1st-off check	6	270	DNC checksum & read-only CTQ params; auto-compare to golden; override timer ≤5 min with alarm	Mfg Eng	Week 1	9	2
Tool management	Hold VB below limit	Tool wear limit exceeded (VB)	Finish fail, burrs	8	Extended run, hard material, no early signal	6	Visual checks; periodic VB measure	6	288	PLC interlock at VB 0.10/0.15 mm; life counter tie-off; Andon	Ops / Maint	Week 2	8	2
Tool life control	Replace at/before limit	Tool life overrun	Chatter, OOT dims	7	Counter not reset; takt pressure	5	Manual log; shift review	7	245	Hard stop at +5% life; auto reset; reason code required to extend	Ops	Week 2	7	2
Tooling kitting	Correct insert/holder used	Wrong tool / insert grade	Rapid wear, surface finish fail	8	Kit mix-up, look-alike	3	Traveler check	6	144	Barcode/QR tool ID; presetters; poka-yoke nests	Tool Crib	Week 3	8	1
Machine health	Maintain geometry	Calibration drift after crash	OOT features	7	Crash, thermal drift	3	Monthly ballbar	7	147	Crash event → lock & re-cal; release only after report pass	Maint / QA	Immediate	7	2
Vibration control	Keep RMS ≤ spec	High vibration not acted	SF fail, burrs	6	Unbalance, bearing wear	4	Periodic check	6	144	Online sensor with email/andon at ≥4.5 mm/s; PM ticket auto-create	Maintenance	Week 4	6	2
Coolant control	Maintain concentration /pH	Coolant out of range	Wear ↑, heat, scrap	6	Doser fail, evaporation	5	Manual titration	5	150	Daily refractometer + auto-doser; SPC log; alarm bands	Ops / Chem	Week 2	6	2
CMM program	Verify datum/logic	CMM program mismatch	False scrap / escapes	6	Rev not updated	3	Programmer review	5	90	Simulation + PPAP/FAI signoff; GRR spot check on CTQs	CMM Prog	Week 2	6	1
MSA – VB	Reliable wear reading	High %GRR on VB	Wrong decisions	6	Method variation	4	Ad-hoc checks	6	144	GRR ≤10%, work instruction, refs; re-cal monthly	QA	Week 3	6	2
Skills & SOP	Follow new OCAP	Training gaps / non-adherence	Drifts reappear	7	New limits not learned	5	Toolbox talk	5	175	Cert check-off; job aids at machine; LPA daily	Supervisor / HR	Week 2	7	2

CONTROL PHASE



Improve (Statistical validation for Improvement – I-MR Chart)





Inference:

- As seen in control chart, before improvement mean was high and there was high variability in the **Scrap reduction** and after improvement, it has achieved to target the Scrap reduction
- There is a significant reduction in Scrap reduction

Control Plan

Control Plan (Machining – Aerospace Components)

A. Characteristics & Controls

#	Process Step / CTQ	Characteristic (X or Y)	Target / Spec (after DOE)	How to Measure (Gage)	Sampling / Frequency	Control Method	Owner	Reaction / OCAP (triggered when…)
1	Final Part Quality	**Y: % Scrap_Machining**	**Target ≤ 1.0%** (alarm > 2.0% shift avg)	MES rejection log; confirmed by QA	**Every lot + hourly roll-up**	**p-chart** (by hour & shift); Pareto by defect	Supervisor / QA	If hour p-point above UCL or 2 consecutive > target → stop line, quarantine WIP, start short-term corrective action (STCA), notify ME & QA, run root-cause checklist.
2	Tooling – Finishing Ops	**X1: Tool_Wear_VB_mm**	**VB ≤ 0.10 mm (finish)**; **≤ 0.15 mm (rough)**	Microscope or on-machine probe; calibrated edge-wear gage	At setup, then **every 30 min** or **every N parts** (e.g., 20)	**I-MR chart** per tool family; tool-life counter	Operator / ME	If VB > limit or 2 point up-trend → change tool, verify part on next piece, log in tooling card; if repeat on same op → ME reviews feeds/speeds & cooling immediately.
3	Tool Usage	**X2: Tool_Life_Overrun_%**	**≤ 5%** beyond recommended life	PLC life counter; MES tool table	Real-time; audit **each change**	**Andon alarm** at 3%; hard interlock at 5%	Operator / Maintenance	≥5% blocks cycle start; replace tool; investigate reason (stock variance, coolant, parameter drift). Supervisor sign-off required to override.
4	CNC Parameters	**X3: CutParam_Dev_%** (feed/speed/DOC deviation)	**±2%** vs. locked recipe (no manual overrides >102%)	CNC log vs. golden recipe; DNC compare	**100% electronic**; audit **per shift**	**SPC checks** on deviation; **override logs**	ME / Supervisor	Any override >102% for >5 min or recipe mismatch → revert to standard, run 1st-off inspection, log deviation; repeat in shift → lock program & escalate to PE.
5	Machine Health	Vibration_RMS_mm_s (leading indicator)	**≤ 4.5 mm/s RMS**	Vibration sensor	**Weekly** (or online)	**Trend chart**	Maintenance	>4.5 or 20% jump week-over-week → PM task & rebalance check.
6	Calibration	Calibration_Error_µm	Per OEM spec; **ballbar ≤ 10 µm** critical axes	Laser/ballbar report	**Monthly** + after crash	Pass/Fail + trend	Maintenance / Metrology	Fail → lock machine for critical features; re-calibrate before release.
7	Inspection Program	CMM_Prog_ErrorRate_%	**= 0** (no program-related NCRs)	NCR tracking	**Per NCR**; weekly review	**u-chart** (if needed)	QA / CMM Prog	Any program-related NCR → MRB, immediate program review, simulation, and GRR spot-check on feature.

Control Plan

B. Standardization & Mistake-Proofing

- **Recipe lock-down (DNC):** Only approved NC programs; checksum compare at load; **read-only** parameters for CTQs.
- **Override governance:** Max override 102% with **time-based alarm**; auto-revert after 5 minutes.
- **Tool-life interlocks:** PLC blocks cycle start if **Tool_Life_Overrun_% > 5%**.
- **Visual controls:** Tool wear limits posted at machine; green/yellow/red wear cards.
- **Poka-Yoke:** Tool ID scanner ties the correct insert grade/geometry to the operation; wrong tool ID prevents cycle.

C. Measurement System Assurance (MSA)

- **Gauge R&R** for **Tool_Wear_VB_mm** and CMM features (target **%GRR < 10%**; accept ≤ 20%).
- **Microscope/edge gage calibration:** monthly; use **certified artifacts**.
- **CMM verification:** daily artifact check (ring gauge / step gage), monthly full verification.

D. Preventive Maintenance (PM) & Specials

- **Coolant health:** concentration & pH spec; test **daily**; alarm if out of range → adjust & log.
- **Spindle & axis health:** online vibration trending; **weekly** review; action at thresholds (see table).
- **Tooling PM:** standardized regrind/replacement intervals aligned with VB limits; supplier COA for edge prep.

Control Plan

E. Layered Process Audits (LPA)

- **Daily (Supervisor, 5 min):** recipe lock verified, overrides = 0, tool-life counter OK, wear check stickers current.
- **Weekly (ME/QA):** SPC charts current (I-MR for VB, p-chart for scrap), top 3 defects Pareto, DOE settings still in control.
- **Monthly (Manager):** audit adherence, training matrix, CAPA closure status.

F. Reaction Plan (OCAP – one page posted at machine)

1. **Contain:** stop line if Y or X beyond limit; segregate WIP/FG since last good check.
2. **Verify measurement:** quick re-check with a second gage/operator.
3. **Corrective action by trigger:**
    1. **VB over limit** → change tool → verify 1st-off, log cause.
    2. **Tool life overrun** → replace & reset life; review counter setup; check cycle counts.
    3. **Parameter deviation** → reload golden recipe; lock overrides; run 1st-off.
4. **Escalate:** if repeated within shift → notify PE + Maintenance; raise **deviation ticket** in MES.
5. **Document:** record root cause, parts at risk, disposition, and preventive change (parameter, PM, training).

G. Documentation & Change Control

- **SOPs updated** with DOE-optimized settings & limits; revision controlled.
- **ECN/ECR process** for any parameter/tooling change; verification run + capability check (Cpk ≥ 1.33 for CTQs).
- **Training & certification:** Operators re-certified on new limits; refresh every 6 months or after changes.

Conclusion

Results after improvement

- **Project has achieved its intended results after improving thickness by identifying the variation cause and reducing scrap rate.**