Reduction of Delamination in Composite Rocket Motor Casing

Harish GS

ROADMAP

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

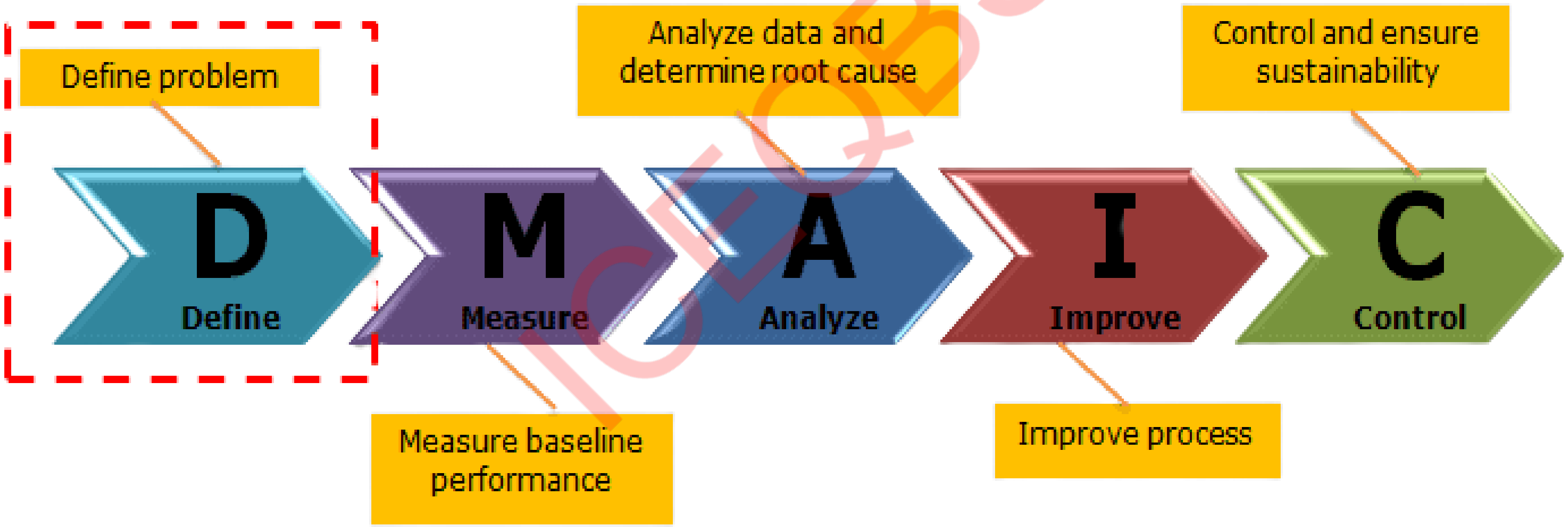
OVERVIEW

Background

Delamination in filament-wound composite rocket motor casings has become a critical quality and reliability concern due to high variability in Interlaminar Shear Strength (ILSS). Over the past nine months, this variability has led to increased scrap and rework, extended production cycle times, and a higher risk of failure during proof pressure testing, directly impacting manufacturing efficiency and mission reliability.

The current state results in significant cost losses from rejected casings, additional inspection and rework efforts, and delayed deliveries. By reducing ILSS variability through optimization of the filament winding process, the project is expected to lower delamination defects by at least 50%, stabilize production output, and improve first-pass yield.

DEFINE PHASE

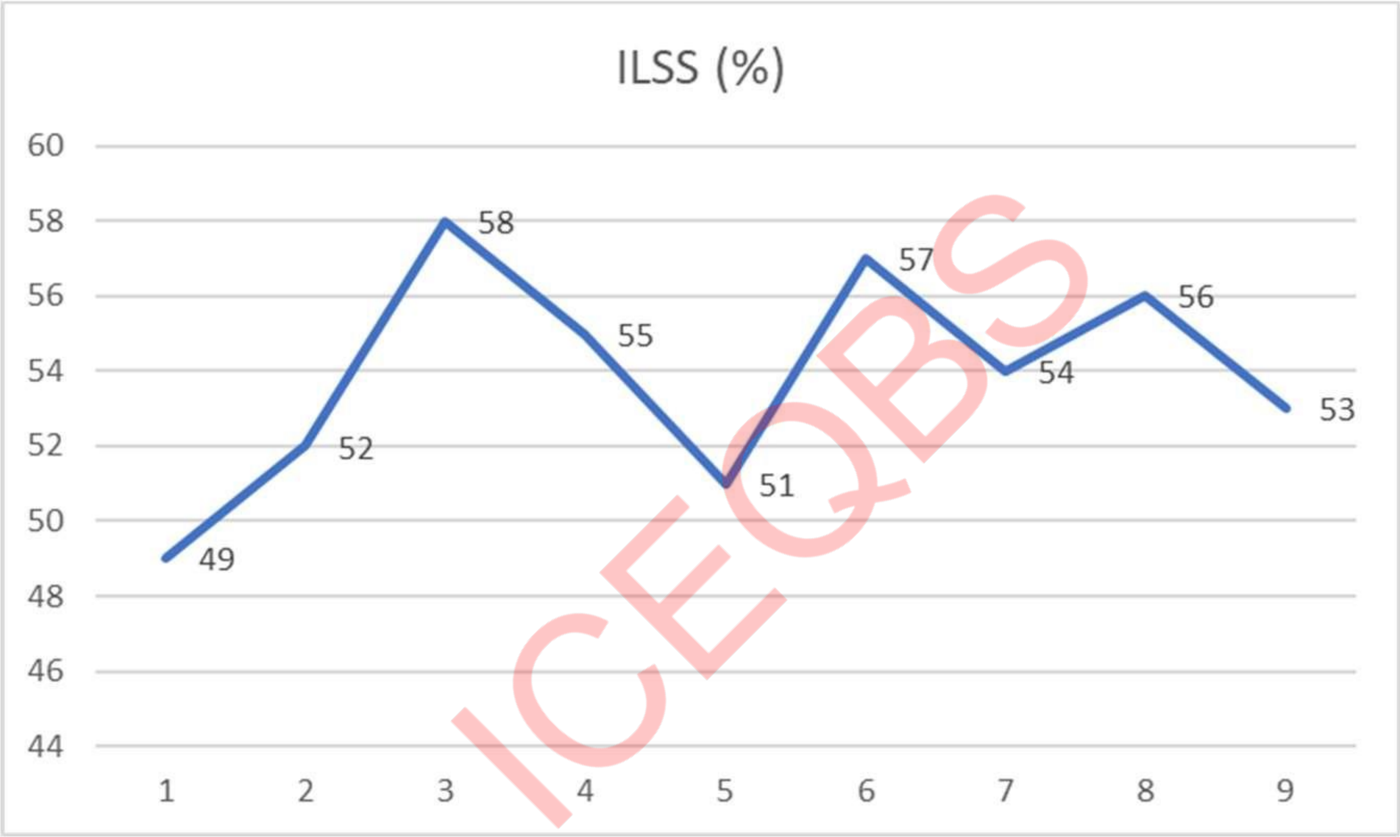


VOC & CTQ

CTQ Tree :

Voice of customer	Critical to X	Primary Metric for improvement
No delamination in the composite casing	CTC – Fiber tension control	**Primary Metric -** Y = Interlaminar Shear Strength (ILSS) **Secondary Metric -** Delamination defect rate (%)

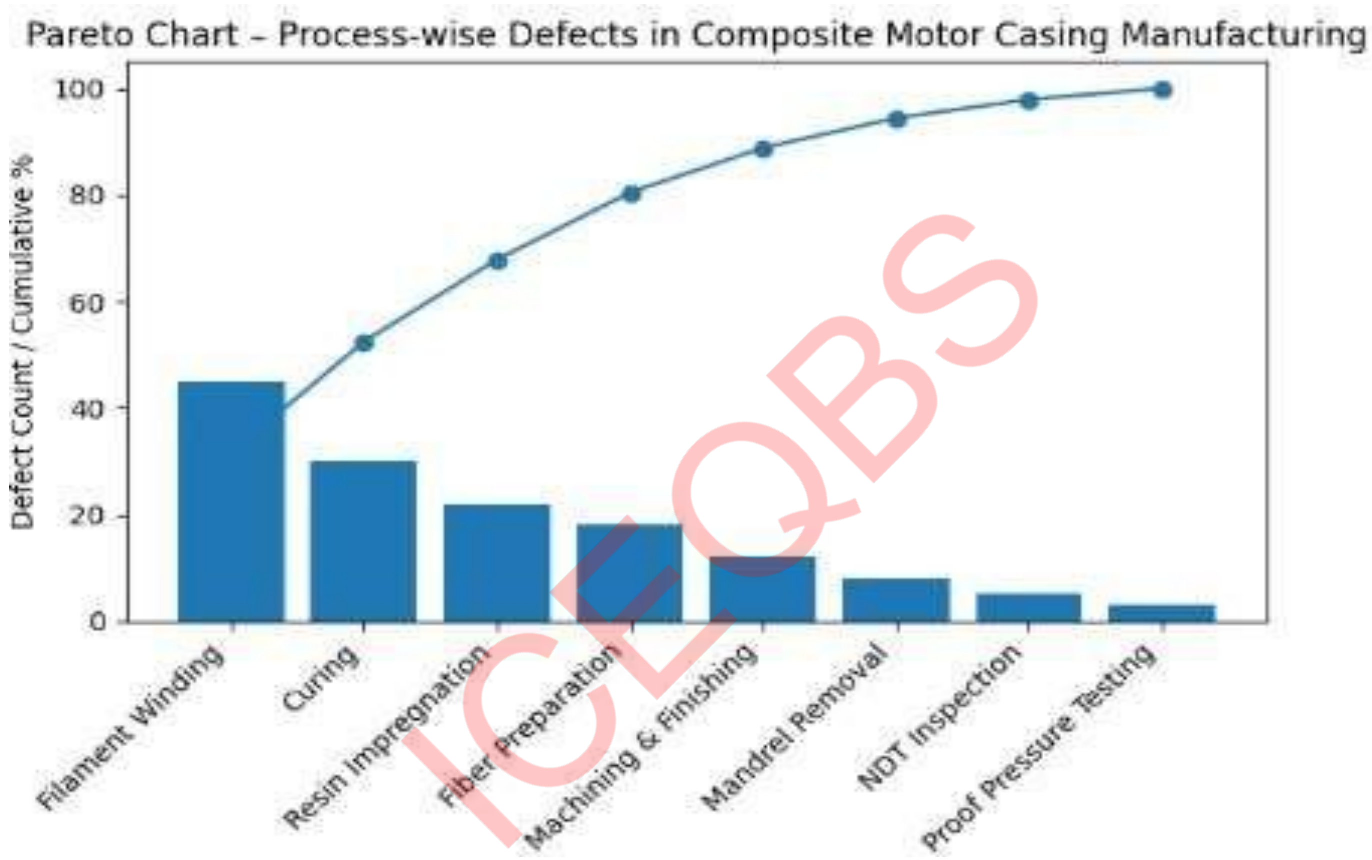
Baseline Performance of Primary Metric (9 months data as Line chart)



Inference :

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

Pareto chart



Inference :

- Filament Winding contributes substantially for the scrap and included in the scope of the project

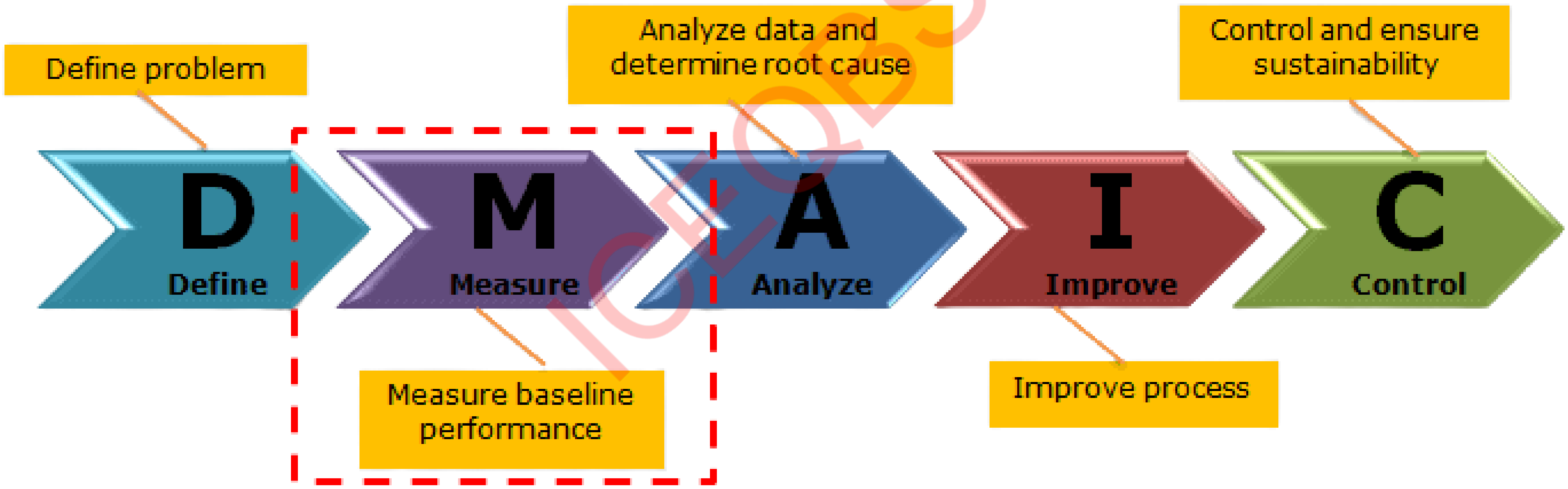
Project Charter

Project Title:	Reduction of Delamination in Composite Rocket Motor Casing – Filament Winding Process
Project Leader	**Project Team Members:**
Harish	Quality Engineer NDT Engineer Production Supervisor
Champion/Sponsors:	**Key Stake Holders**
Head – Composite Manufacturing	
Problem Statement:	**Goal Statement:**
Over the last 9 months, the Interlaminar Shear Strength (ILSS) of composite rocket motor casings manufactured through the filament winding process has shown high variability, with an average of 54% and a standard deviation of 3%.	Reduce variability in ILSS by improving the filament winding process such that: Standard deviation of ILSS is reduced from 3% to ≤ 1.5% Average ILSS is maintained at ≥ 65% Delamination defect rate is reduced by at least 50% within 6 months of project initiation.
Secondary Metric	**Assumptions Made:**
Productivity	ILSS measurement and testing methods are accurate, repeatable, and consistently applied.

Project Charter

Tangible and Intangible Benefits:	Risk to Success:
Reduction in scrap and rework costs by **₹15–20 lakhs per year** (dummy data). Improved first-pass yield and reduced production cycle time.	Variability in raw material properties or supplier inconsistency affecting ILSS. Inadequate adherence to optimized winding and curing parameters on the shop floor.
In Scope:	**Out of Scope:**
Filament winding process parameters (fiber tension, winding angle) Operator practices during winding Environmental conditions during winding	Raw material supplier changes Curing and autoclave process Design changes to casing geometry
Signatories:	**Project Timeline:**
Head – Composite Manufacturing	6 months

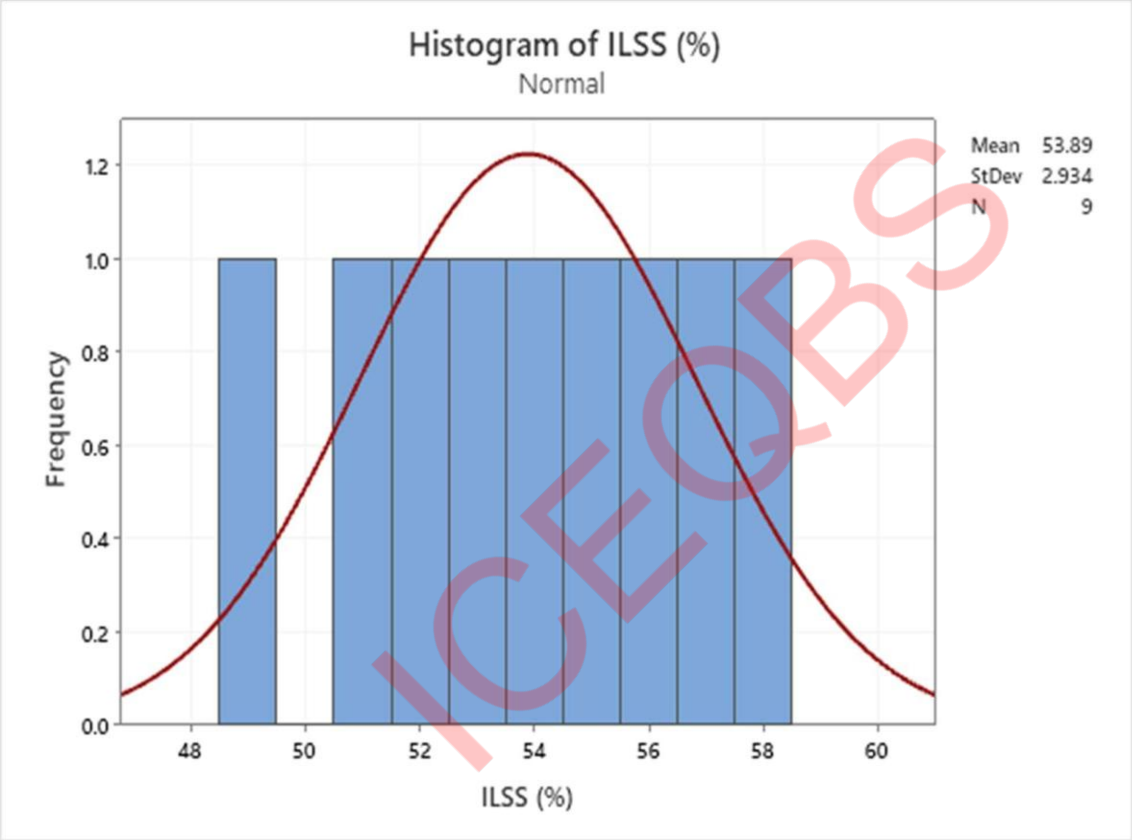
MEASURE PHASE



SIPOC

Suppliers	Inputs	Process (High Level)	Outputs	Customers
Fiber supplier	Carbon/Glass fiber tows	1. Receive and verify fibers	Wound composite casing	Curing / Autoclave team
Resin supplier	Resin system	2. Prepare fibers for winding	Uniform fiber layup	Quality / NDT department
Material stores	Release agents	3. Set winding parameters	Required thickness	Machining & finishing team
Maintenance team	Calibrated winding machine	4. Filament winding operation	No delamination	Proof pressure testing team
Production planning	Process specifications	5. In-process inspection	Acceptable ILSS	Rocket motor assembly customer

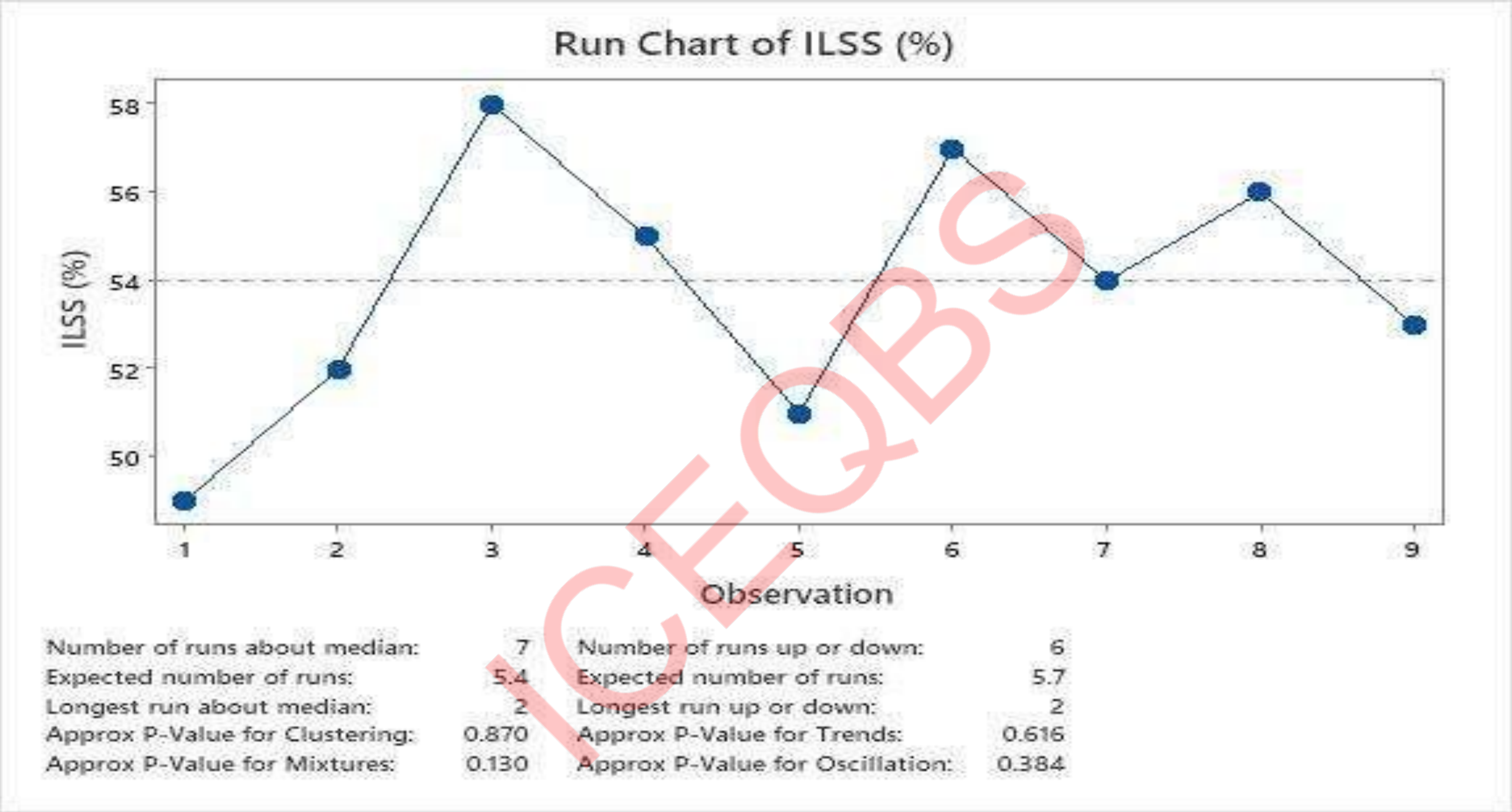
Data collection – Histogram (Before improvement)



Inference :

- Data is normally distributed over the mean

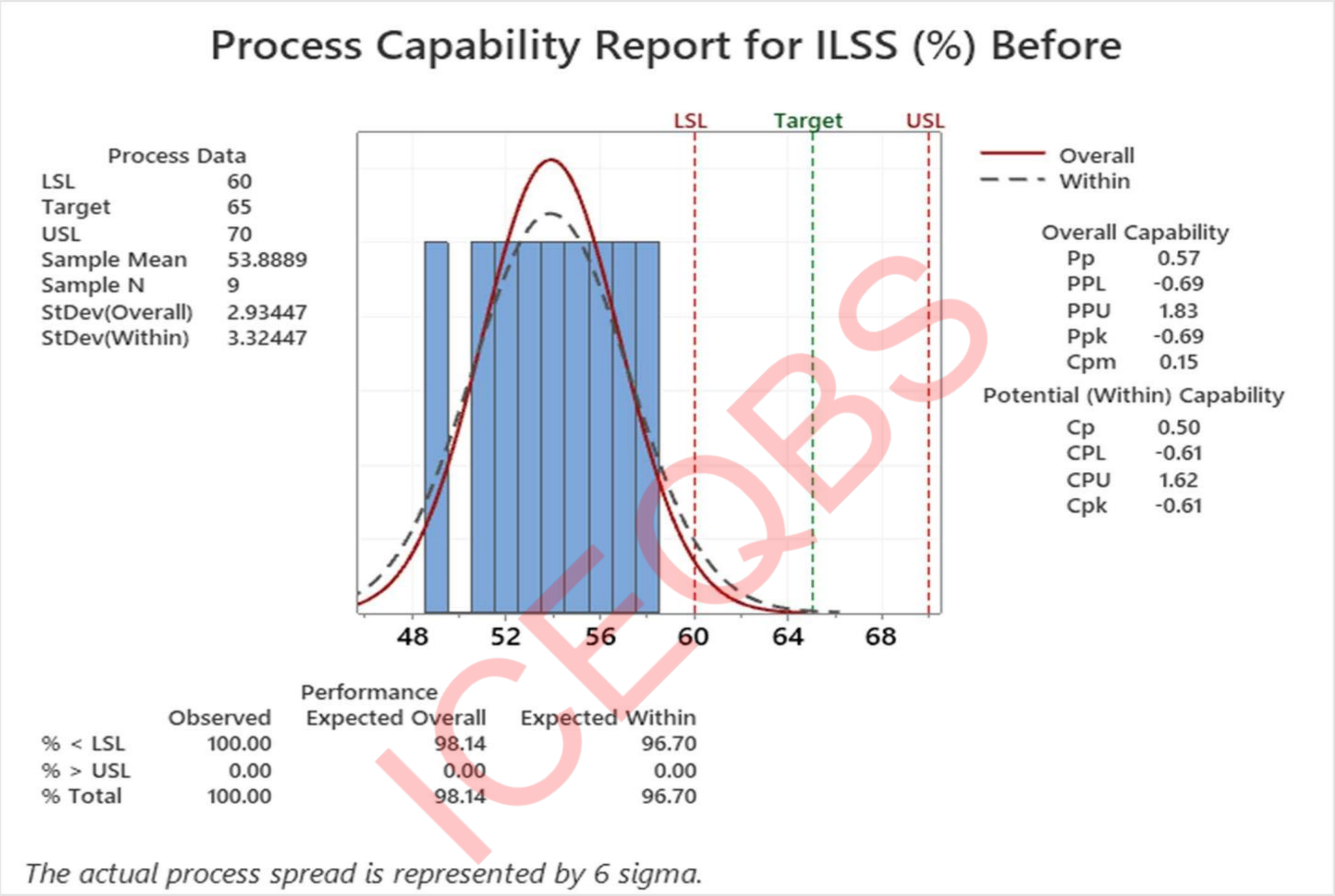
Data collection – Run Chart (Before improvement)



Inference :

Since all P values are greater than 0.05, no special causes are detected

Data collection – Normality plot (Before improvement)



Inference :

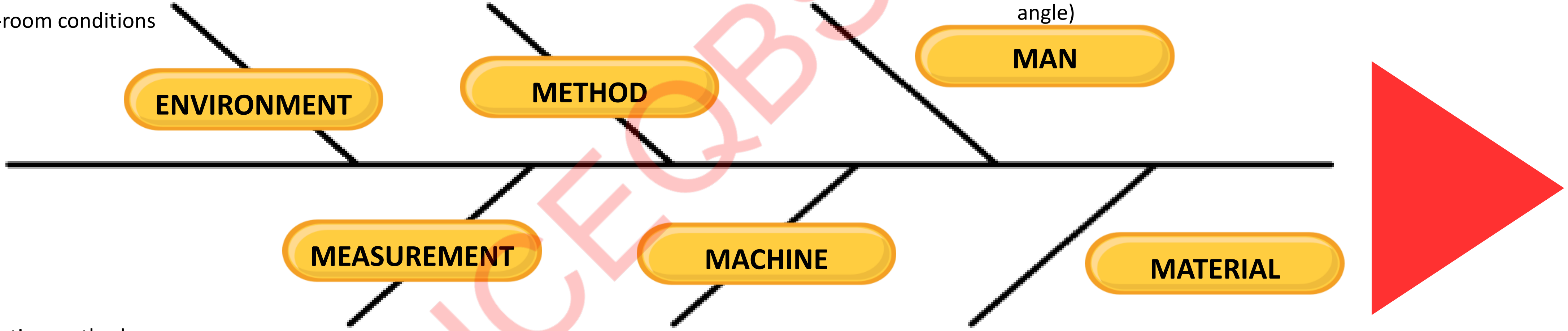
- The ILSS process is incapable and poorly centered, with the mean below the LSL and negative Cpk, resulting in a high risk of delamination and requiring immediate process improvement.

Fish Bone Diagram

- High humidity affecting resin curing
- Temperature fluctuations in winding area
- Dust or foreign particle contamination
- Poor ventilation
- Uncontrolled clean-room conditions

- Incorrect winding angle programming
- Non-optimized winding sequence
- Improper resin impregnation method
- Inadequate compaction during winding
- Lack of standardized process parameters

- Inadequate operator training
- Improper fiber handling techniques
- Non-adherence to standard operating procedures
- Fatigue due to long winding shifts
- Lack of awareness of CTQ parameters (fiber tension, angle)



- Inaccurate ILSS testing method
- Poor repeatability of test results
- Insufficient sample size for analysis
- Calibration errors in testing equipment
- Delayed feedback from inspection results

- Inconsistent fiber tension control system
- Poor calibration of winding machine
- Worn-out rollers or guides
- Malfunctioning resin delivery system
- Vibration or mechanical instability during winding

- Variation in fiber tow quality
- Resin viscosity variation
- Moisture absorption in fibers
- Expired or improperly stored resin
- Contaminated fibers or resin

Fish Bone Diagram

Common Causes

- Inadequate operator training
- Non-adherence to standard operating procedures
- Variation in Fiber tow quality
- Resin viscosity variation
- Incorrect winding angle programming
- Non-optimized winding sequence
- Inadequate compaction during winding
- Poor repeatability of ILSS testing
- Temperature fluctuations in winding area
- High humidity in winding area

Special Causes

- Malfunctioning Fiber tension control system
- Poor calibration of winding machine
- Worn-out rollers or guides
- Expired or contaminated resin
- Moisture absorption in Fibers
- Resin delivery system failure
- Vibration or mechanical instability during winding
- Calibration error in testing equipment
- Dust or foreign particle contamination

Sudden environmental control failure

3M Analysis for Waste

MUDA

1. Rework due to delamination defects
2. Scrap of wound casings failing ILSS requirements
3. Excess resin usage during winding

Mura

1. Variation in fiber tension between batches
2. Fluctuating winding speed across shifts
3. Inconsistent environmental conditions (temperature/humidity)

Muri

1. Variation in fiber tension between batches
2. Fluctuating winding speed across shifts
3. Inconsistent environmental conditions (temperature/humidity)

8 Wastes Analysis

Defects	• Delamination detected during NDT • Casing rejection due to low ILSS
Overproduction	• Winding extra casings to compensate for expected rejection • Producing casings before downstream processes are ready
Waiting	• Idle winding machine due to resin preparation delay • Waiting for mandrel availability
Non-Utilized Talent	• Skilled operators used only for manual monitoring • Engineers not involved in parameter optimization
Transportation	• Moving wound casings multiple times before curing • Unnecessary transfer of fibers between storage locations
Inventory	• Excess fiber tows stored near winding area • WIP casings waiting for curing or inspection
Motion	• Operators repeatedly adjusting tension manually • Frequent walking to fetch tools or consumables
Overprocessing	• Additional inspections due to poor first-time quality • Extra resin application to compensate for poor impregnation

Action Plan for Low Hanging Fruits

Special Causes (sudden failures / abnormalities)

Issue Identified	Lean Tool Used	Action Plan	Owner	Timeline
Fiber tension system malfunction	TPM	Immediate calibration and preventive maintenance checklist	Maintenance	1 week
Worn-out rollers / guides	TPM	Replace worn components and define replacement frequency	Maintenance	2 weeks
Resin contamination / expiry	Visual Management	Color-coded resin labelling and FIFO storage	Stores	1 week
Environmental control failure	5S + Poka- Yoke	Install humidity/temperature alarms	Facilities	2 weeks
Testing equipment calibration error	Standard Work	Monthly calibration SOP and audit	Quality	1 week

Action Plan for Low Hanging Fruits

Category	Issue	Lean Tool	Action
Muda	Rework due to delamination	First Time Right	Standardize winding parameters
Muda	Excess resin usage	Standard Work	Resin quantity limits per layer
Mura	Fiber tension variation	SPC	Control charts for tension
Mura	Shift-to-shift variability	Work Standardization	Shift handover checklist
Muri	Operator fatigue	Line Balancing	One operator per machine
Muri	Machine overloading	TPM	Define max duty cycle

Action Plan for Low Hanging Fruits

Waste Type	Issue	Lean Tool	Improvement Action
Defects	Delamination	Poka-Yoke	Auto tension alarms
Overproduction	Extra casings	Pull System	Produce as per downstream demand
Waiting	Mandrel delay	Kanban	Mandrel availability signalling
Talent	Underused skills	Kaizen	Operator suggestion program
Transportation	Excess handling	Layout Improvement	Point-of-use storage
Inventory	Excess fiber stock	FIFO	Visual inventory limits
Motion	Excess walking	5S	Tool shadow boards
Extra Processing	Repeat inspections	Standard Work	In-process quality checks

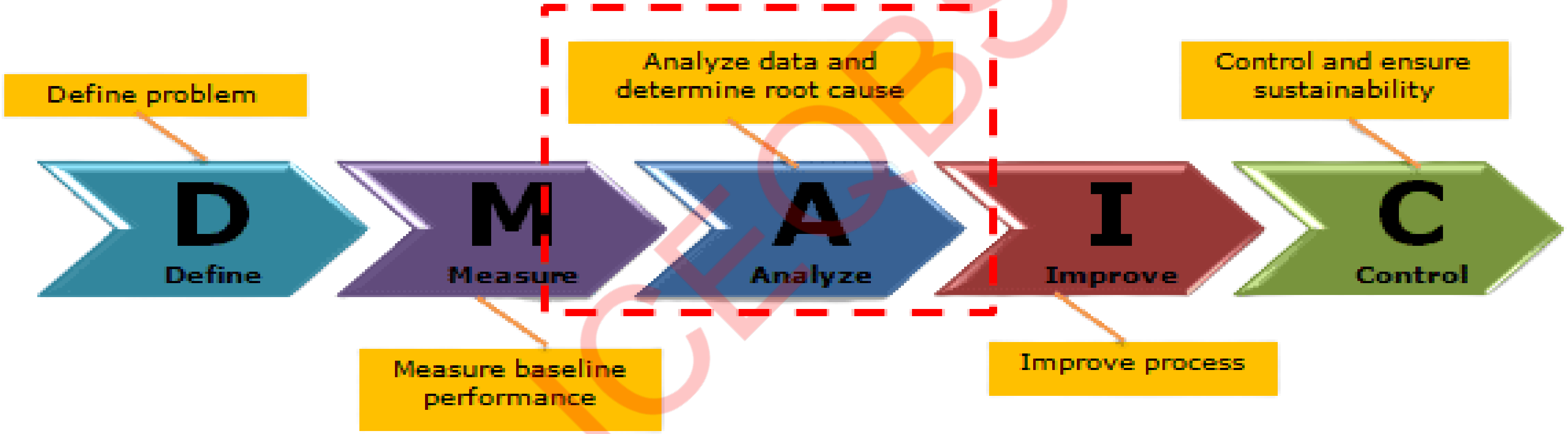
Top 12 Prioritized Root Causes (Based on Net Score)

Rank	Input (X)
1	Process parameter adherence
2	Inadequate compaction
3	Winding angle variation
4	Machine calibration drift
5	Fiber tension variation
6	Resin viscosity variation
7	Fiber moisture content
8	Resin impregnation rate
9	Layup sequence variation
10	Tooling surface condition
11	Operator skill variation
12	Environmental humidity

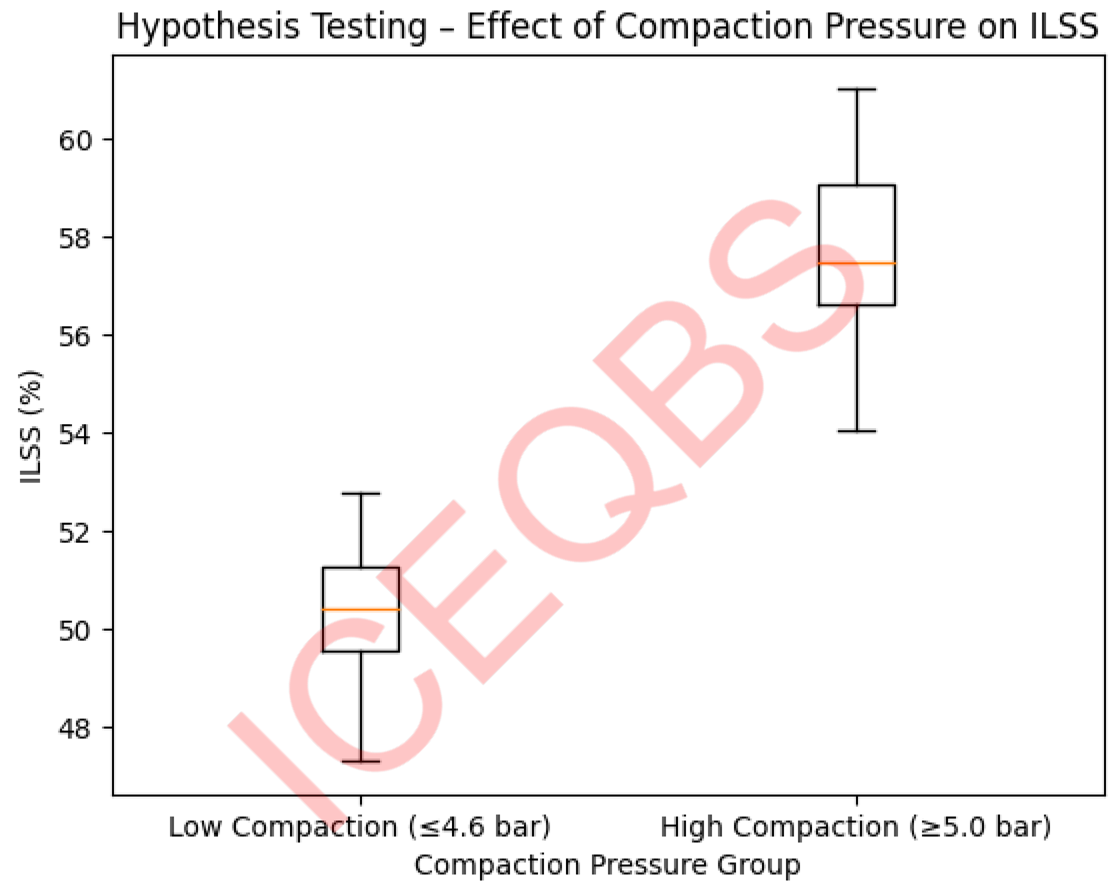
Data Collection Plan

S No	Input (X)	Data Type	Operatio nal Definition	Measurement Method / Tool	Location	Frequency / Sample Size
1	Process parameter adherence	Discrete (%)	% compliance to Defined Limits	Process audit checklist	Winding station	Every batch
2	Compaction pressure	Continuo us	Pressure applied during winding	Pressure sensor	Winding head	Every casing
3	Winding angle variation	Continuo us (°)	Deviation from target angle	Machine encoder	Winding machine	Every casing
4	Machine calibration drift	Continuo us	Deviation from baseline	Calibration records	Winding machine	Weekly
5	Fiber tension variation	Continuo us (N)	Average and range of tension	Load cell sensor	Winding head	Every casing
6	Resin viscosity	Continuo us (cP)	Viscosity at winding temperature	Viscometer	Resin prep area	Every batch
7	Fiber moisture content	Continuo us (%)	Moisture In fiber tows	Moisture analyzer	Fiber storage	Daily
8	Resin impregnatio n rate	Continuo us	Resin flow rate	Flow meter	Resin delivery system	Every casing
9	Layup sequence adherence	Discrete (Yes/No)	Correct sequence followed	SOP checklist	Winding station	Every casing
10	Tooling surface condition	Discrete (1–5)	Visual condition rating	Visual inspection	Mandrel/tool ing	Every batch
11	Operator skill level	Discrete	Certification/ experience	Training records	Production	Monthly
12	Environme	Continuo	Humidity	Hygrometer	Winding area	Hourly

ANALYSE PHASE



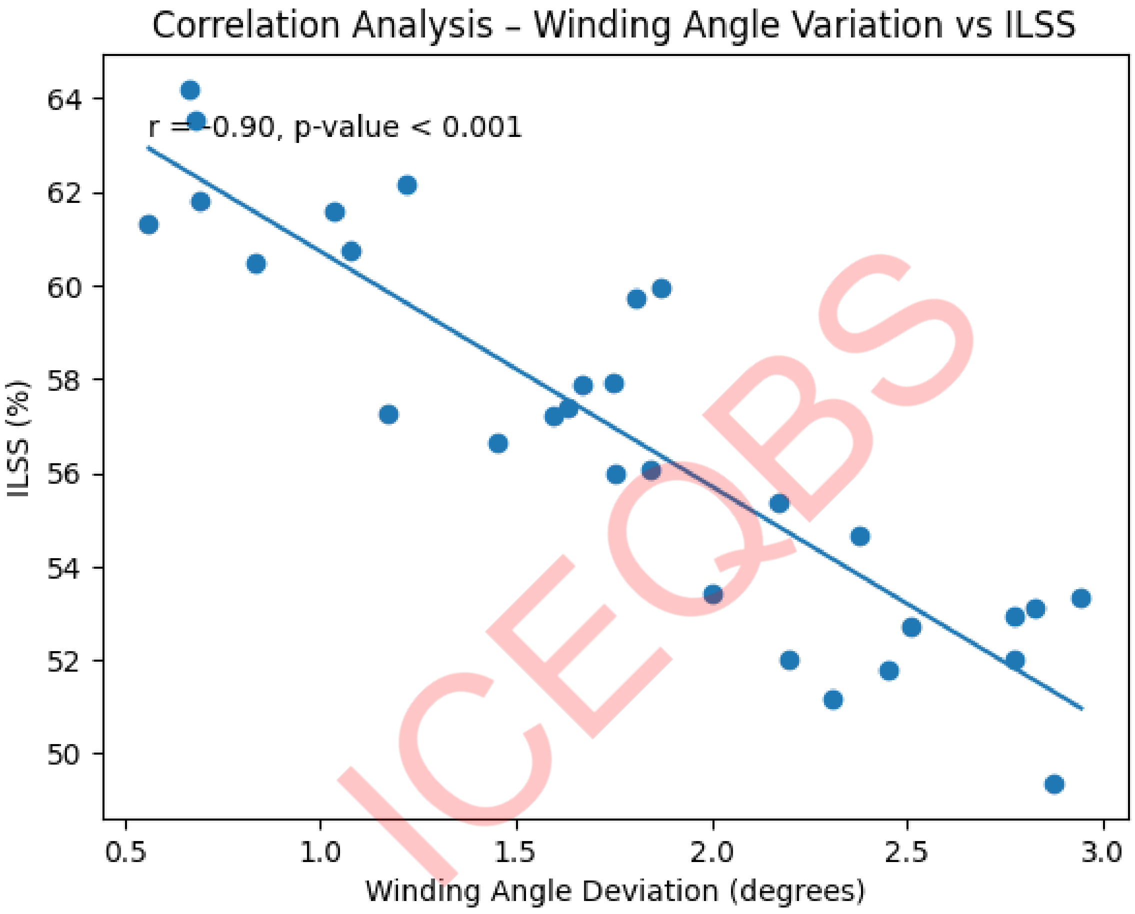
Analyse – Hypothesis testing



Inference :

- Since **p-value < 0.001**, the null hypothesis is rejected, confirming that inadequate compaction pressure is a critical root cause affecting ILSS

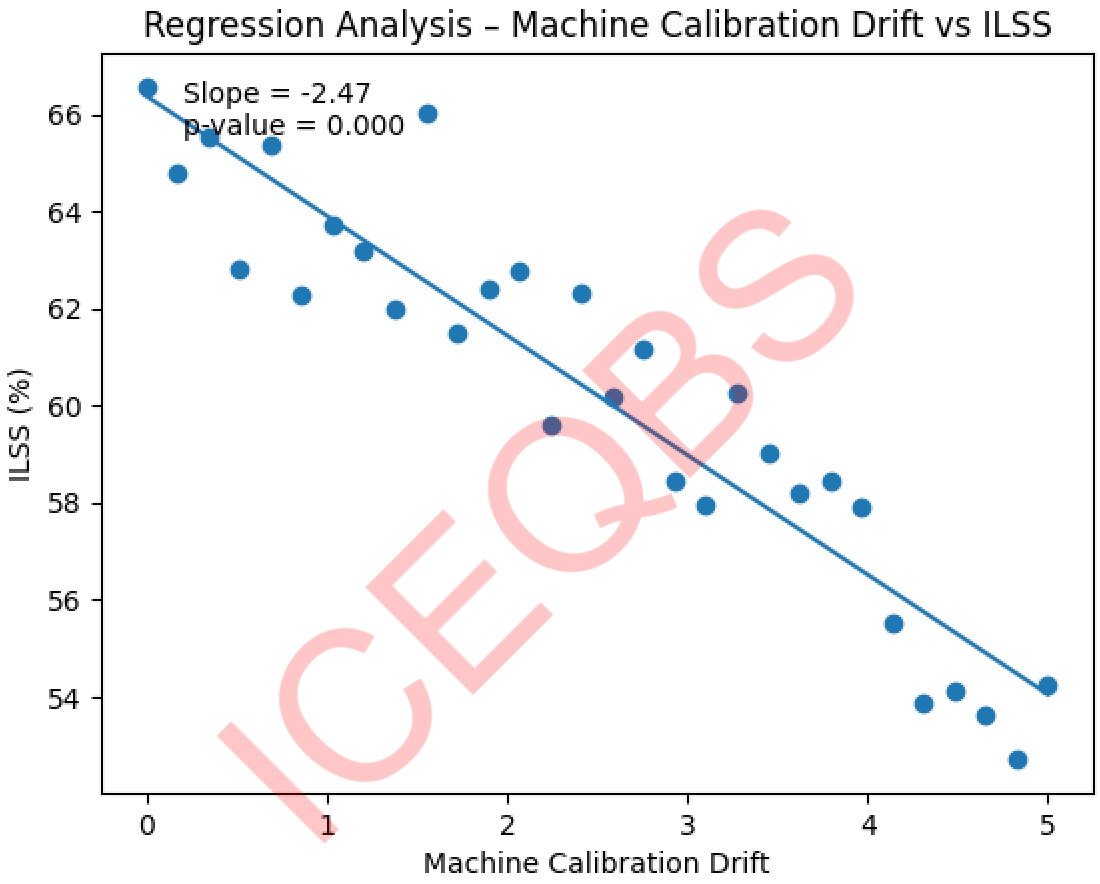
Analyse – Hypothesis testing



Inference :

- Since p-value < 0.001 and r ≈ –0.78 (strong negative correlation), the null hypothesis is rejected, confirming winding angle variation as a critical root cause affecting ILSS.

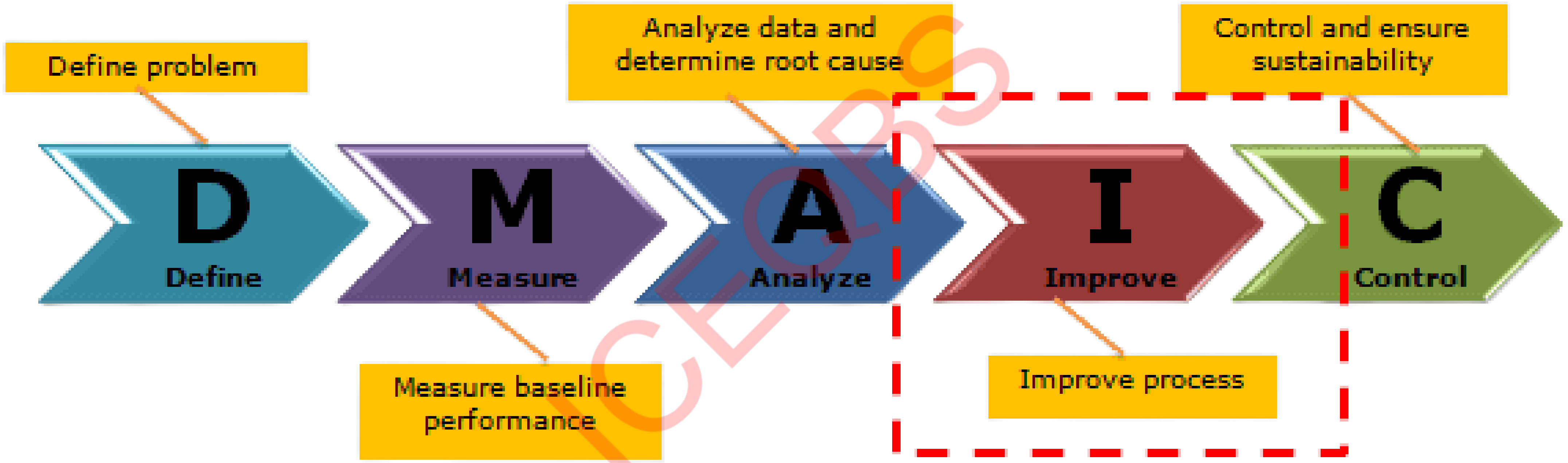
Analyse – Hypothesis testing



Inference :

Since the regression slope is negative and **p-value < 0.003**, the null hypothesis is rejected, confirming machine calibration drift as a critical root cause affecting ILSS.

IMPROVE PHASE



Improve Design of Experiment

Critical Root Cause	Improvement Action	Lean / Six Sigma Tool	Target / Standard	Owner	Timeline
Inadequate compaction	Define optimal compaction pressure window	DOE / SPC	5.0–5.4 bar	Process Engineer	3 weeks
	Install pressure sensors with alarms	Poka-Yoke	Auto alert at ±5%	Maintenance	2 weeks
Winding angle variation	Lock winding angle program	Standard Work	±0.5° max	Maintenance	1 week
	Real-time angle monitoring	SPC	Control chart online	Quality	2 weeks
Machine calibration drift	Implement weekly calibration checklist	TPM	Zero drift beyond 1%	Maintenance	1 week
	Visual calibration status tagging	Visual Management	Green/Red tags	Quality	1 week
Fiber tension variation	Auto-tension control system	Poka-Yoke	48–52 N	Engineering	3 weeks
Resin viscosity variation	Control resin temperature	Process Control	500–550 cP	Process Engineer	2 weeks
	Pre-use viscosity verification	Standard Work	Mandatory check	Quality	1 week
Fiber moisture content	Dry fiber storage cabinets	Environmental Control	<0.3% moisture	Stores	3 weeks
Resin impregnation rate	Optimize flow rate via DOE	DOE	100–105 ml/min	Process Engineer	3 weeks
	Flow meters with alarms	Poka-Yoke	±5 ml/min	Maintenance	2 weeks

Improve

Method

μ_1: population mean of ILSS (%) Before
μ_2: population mean of ILSS (%) After
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
ILSS (%) Before	9	53.89	2.93	0.98
ILSS (%) After	9	66.000	0.596	0.20

Estimation for Difference

Difference	95% CI for Difference
-12.111	(-14.413, -9.809)

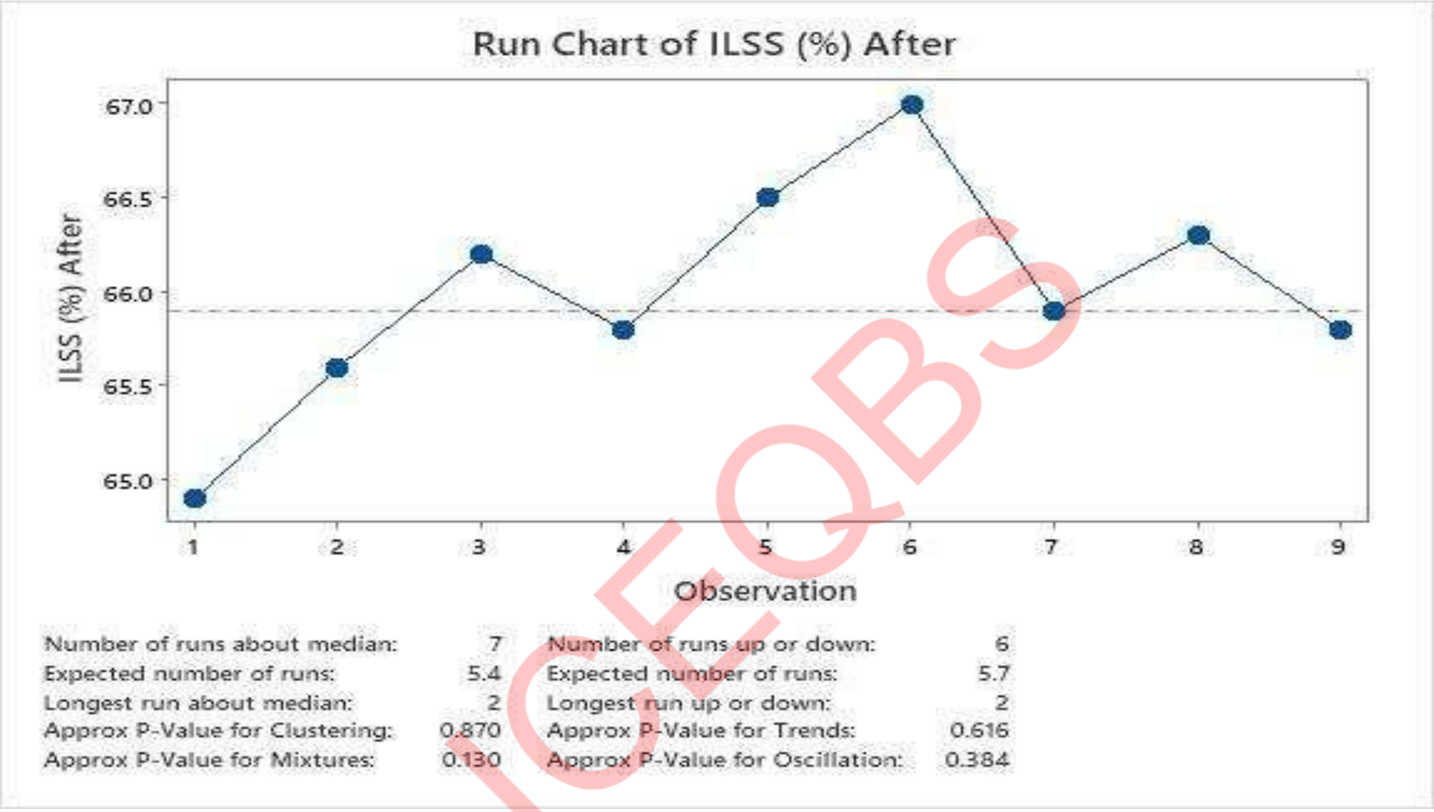
Test

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

T-Value	DF	P-Value
-12.13	8	0.000

Since P value is less than 0.05, a statistically significant difference in observed between before and after performance.

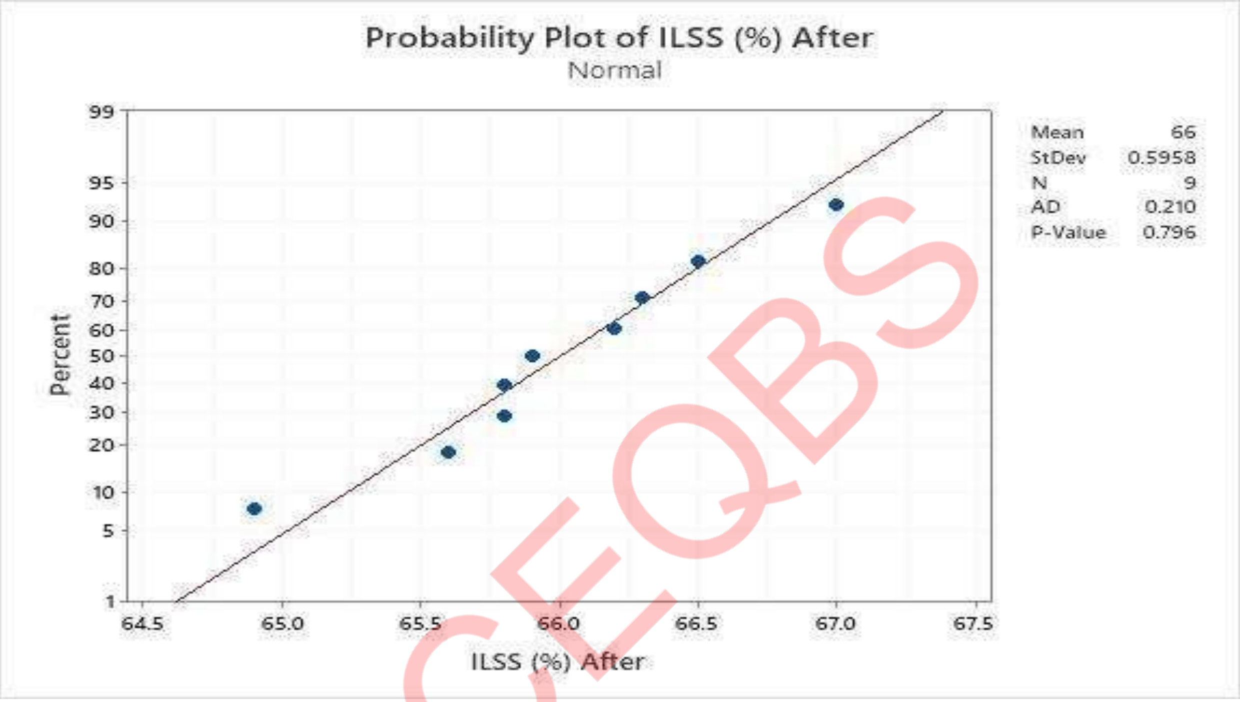
Improve – Run chart and Normality Test (After Improvement)



Inference:

- Since All P values are greater than 0.05, no special causes are detected

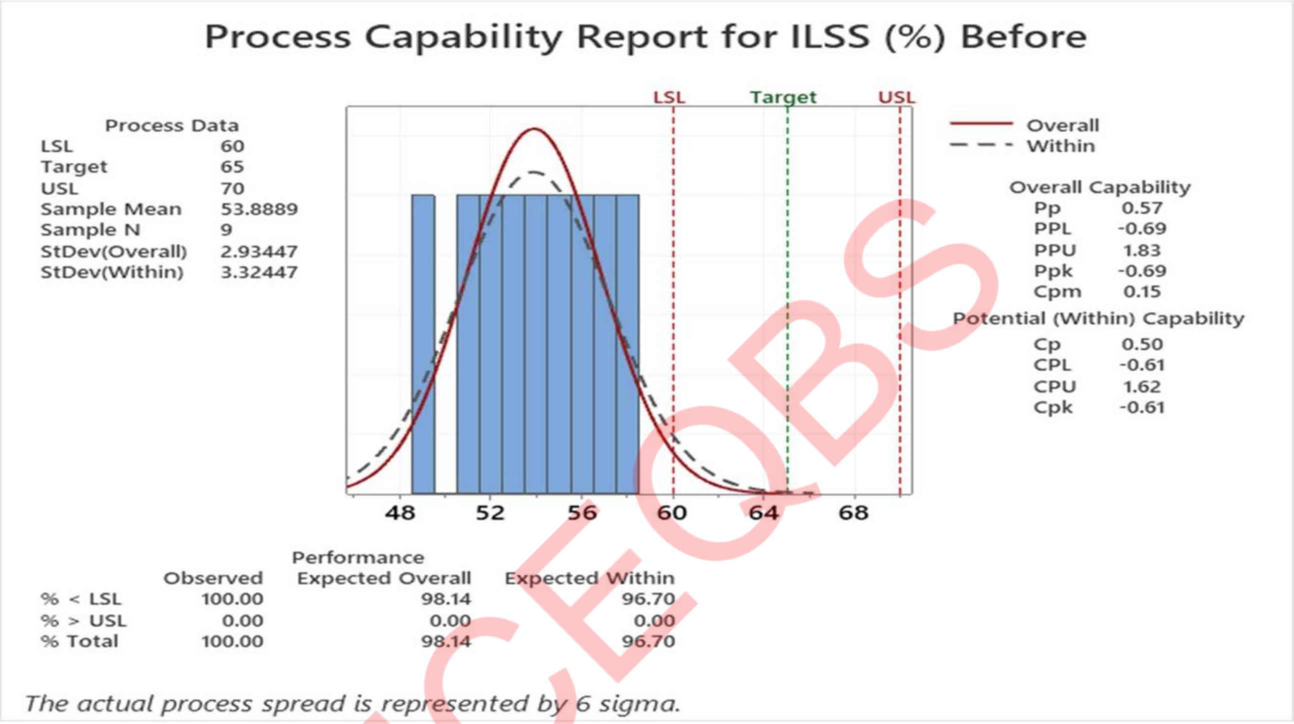
Improve – Run chart and Normality Test (After Improvement)



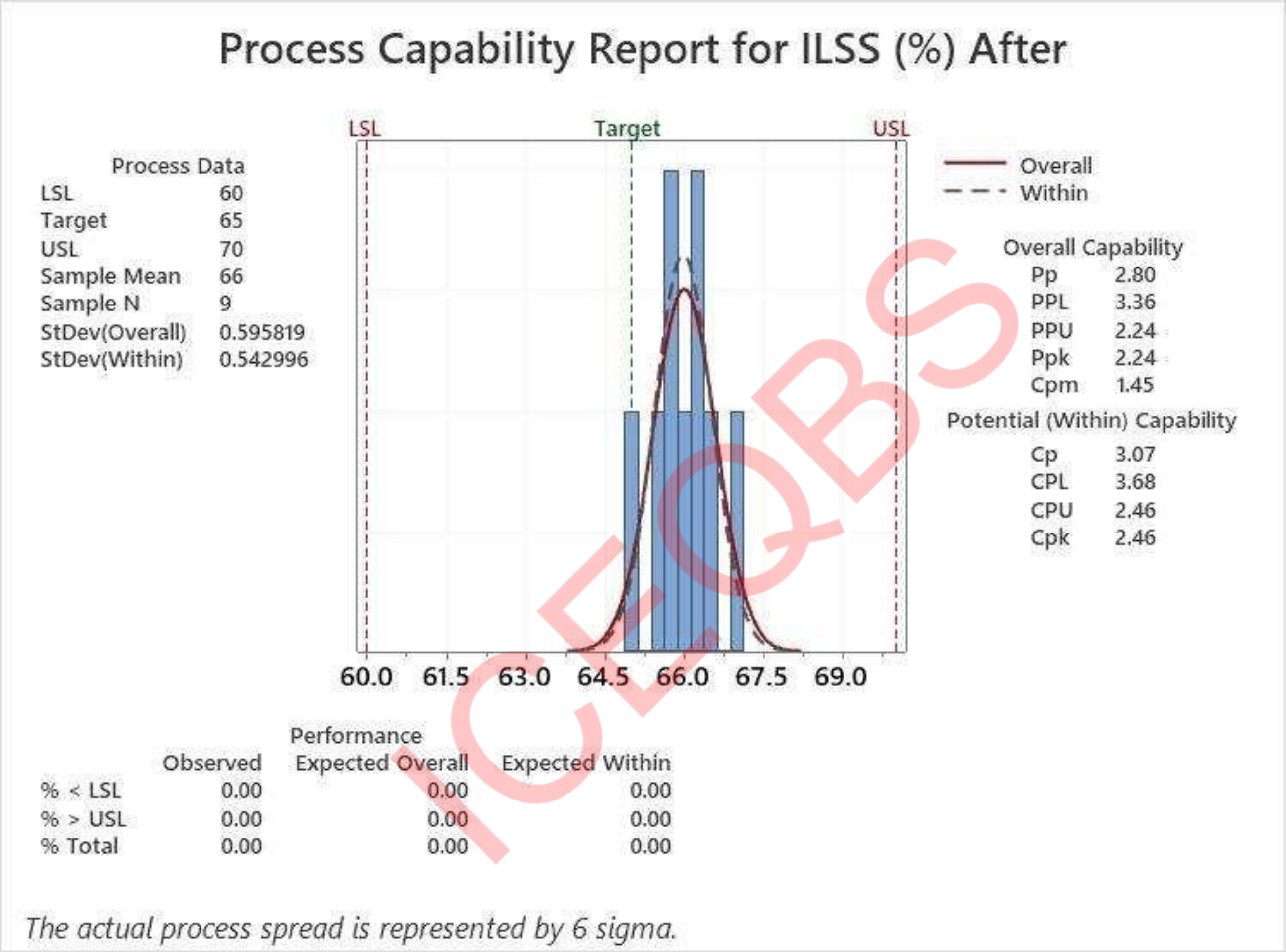
Inference:

Since All P values are greater than 0.05, Data is normally distributed.

Improve – Process capability – Before & After Improvement



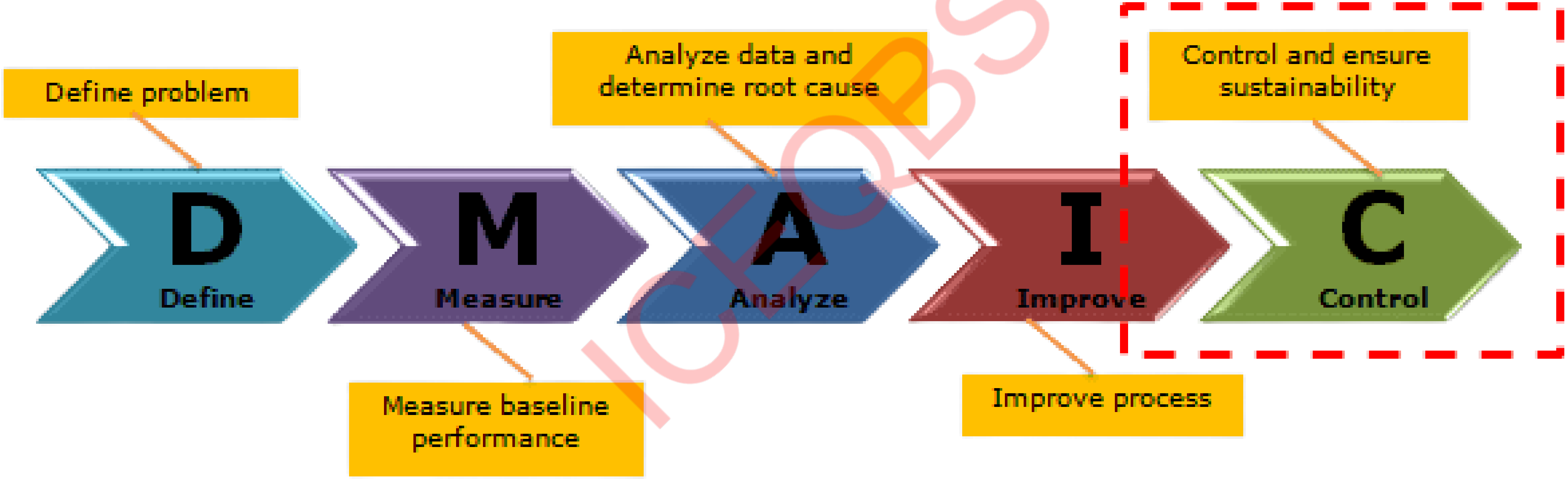
Improve – Process capability – Before & After Improvement



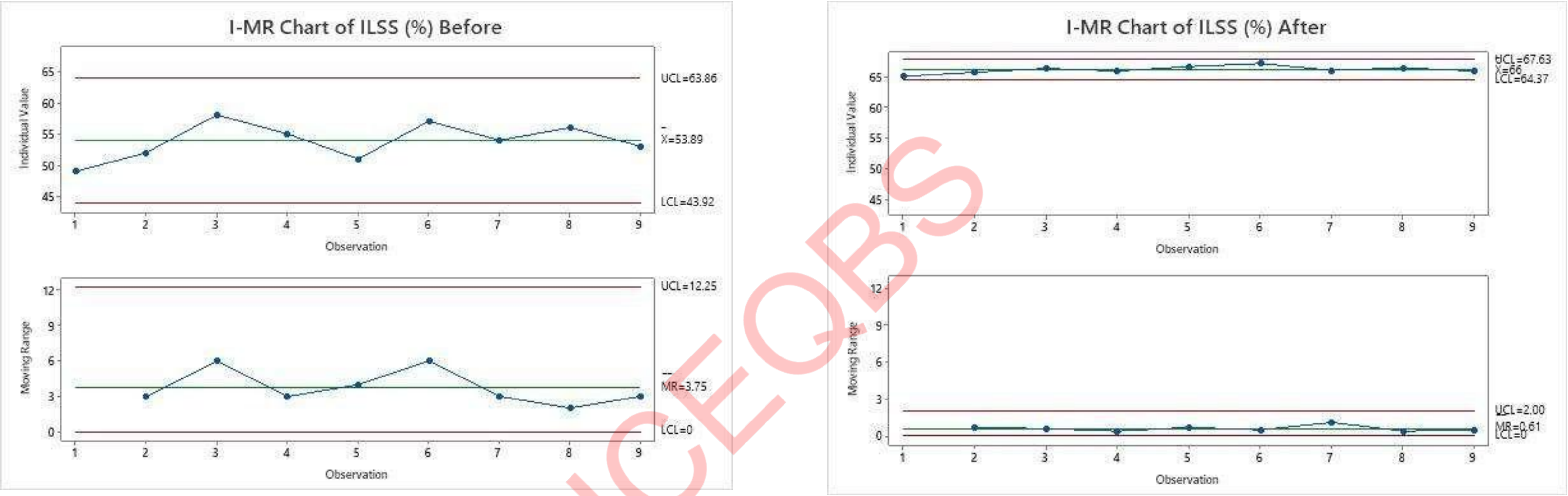
Inference :

- Since Cp is 3.07 Cpk is 2.46 the process meets six sigma capability requirements

CONTROL PHASE



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



Inference:

- The I-MR charts show that after improvement the ILSS process is stable with reduced variation and all points within control limits, indicating effective and sustained process control compared to the unstable "before" state.

Control Plan

Critical Root Cause	5S Mechanisms	Poka-Yoke Mechanisms	Sustaining Benefits
Inadequate compaction	Visual pressure setting chart at machine Dedicated location for pressure tools Standard setup checklist	Pressure sensor interlock Alarm for pressure deviation	Consistent compaction pressure Reduced ILSS variability Lower delamination defects
Winding angle variation	SOP displayed at machine Standardized program naming Removal of obsolete programs	Program lock for winding angle Auto-stop on angle deviation	Uniform fiber orientation Improved structural integrity Reduced rework
Machine calibration drift	Calibration status tags (Red/Green) Visible calibration schedule board Organized calibration tools	Machine start-up lock if calibration overdue Auto notification on drift	Stable machine performance Repeatable process output Improved measurement accuracy
Fiber tension variation	Color-coded tension settings Dedicated tension setup checklist Organized guides and rollers	Auto-tension control system Machine lockout for out-of-range tension	Controlled laminate quality Improved ILSS Reduced operator dependency
Fiber moisture content	Sealed fiber storage cabinets FIFO labelling of fiber spools Visual humidity indicators	Humidity sensor alarms Mandatory moisture check before loading	Reduced moisture-induced defects Improved bonding quality Long-term process stability

Control Plan

Root Cause / Process Step	Potential Failure Mode	Potential Effect of Failure	Potential Cause	S	O	D	RPN	Recommended Preventive Action	Responsible
Inadequate compaction	Compaction pressure set incorrectly	Low ILSS, delamination	Sensor not calibrated, wrong setup	9	4	4	144	Periodic sensor calibration Pressure interlock before start	Maintenance
	Pressure alarm bypassed	Undetected low pressure	Operator override	8	3	5	120	Password-protected alarm bypass Audit trail	Quality

Control Plan

Winding angle variation	Wrong winding program selected	Fiber misalignment, strength loss	Program confusion	9	3	3	81	Program lock & naming standard	Maintenance
	Angle feedback sensor failure	Angle deviation not detected	Sensor wear	8	3	4	96	Preventive sensor replacement plan	Maintenance
Machine calibration drift	Overdue calibration	Process instability	Missed schedule	8	4	4	128	Start-up lock if calibration expired	Quality
	Calibration done incorrectly	False sense of control	Inadequate skill	7	3	5	105	Certified calibration personnel only	Quality
Fiber tension variation	Tension out of range	Poor compaction, delamination	Auto-tension malfunction	9	3	4	108	Redundant tension monitoring	Engineering
	Wrong tension setting used	Variability across batches	Manual error	8	4	3	96	Pre-run tension checklist	Production
Fiber moisture content	Moist fiber used in winding	Poor bonding, delamination	Storage door left open	9	3	4	108	Humidity alarm & auto alert	Stores
	Moisture test skipped	Undetected defect	Time pressure	8	3	5	120	Mandatory moisture check in system	Quality

Control Plan

Critical Root Cause	Process Step	Control Parameter (X)	Specification / Target	Monitoring Method	Frequency	Reaction Plan	Responsibility
Inadequate compaction	Filament winding	Compaction pressure (bar)	5.0 – 5.4 bar	Pressure sensor + SPC chart	Every casing	Stop machine, reset pressure, re-verify previous part	Production / Maintenance
Winding angle variation	Filament winding	Winding angle deviation (°)	±0.5°	Machine encoder + control chart	Every casing	Auto-stop, reload correct program, inspect last part	Maintenance / Quality

Control Plan

Machine calibration drift	Equipment setup	Calibration status	Within calibration validity	Calibration tag & checklist	Weekly	Lock machine, recalibrate, QA approval required	Maintenance / Quality
Fiber tension variation	Fiber feeding	Fiber tension (N)	48 – 52 N	Auto-tension system + SPC	Every casing	Stop winding, correct tension, segregate affected parts	Production
Fiber moisture content	Material handling	Fiber moisture (%)	≤ 0.3%	Moisture analyzer	Daily / Before use	Reject fiber lot, dry or replace material	Stores / Quality

Conclusion

Results after improvement

- This project successfully reduced ILSS variability by addressing critical process drivers, eliminated delamination risks, and established robust controls to ensure consistent structural integrity and long-term process stability