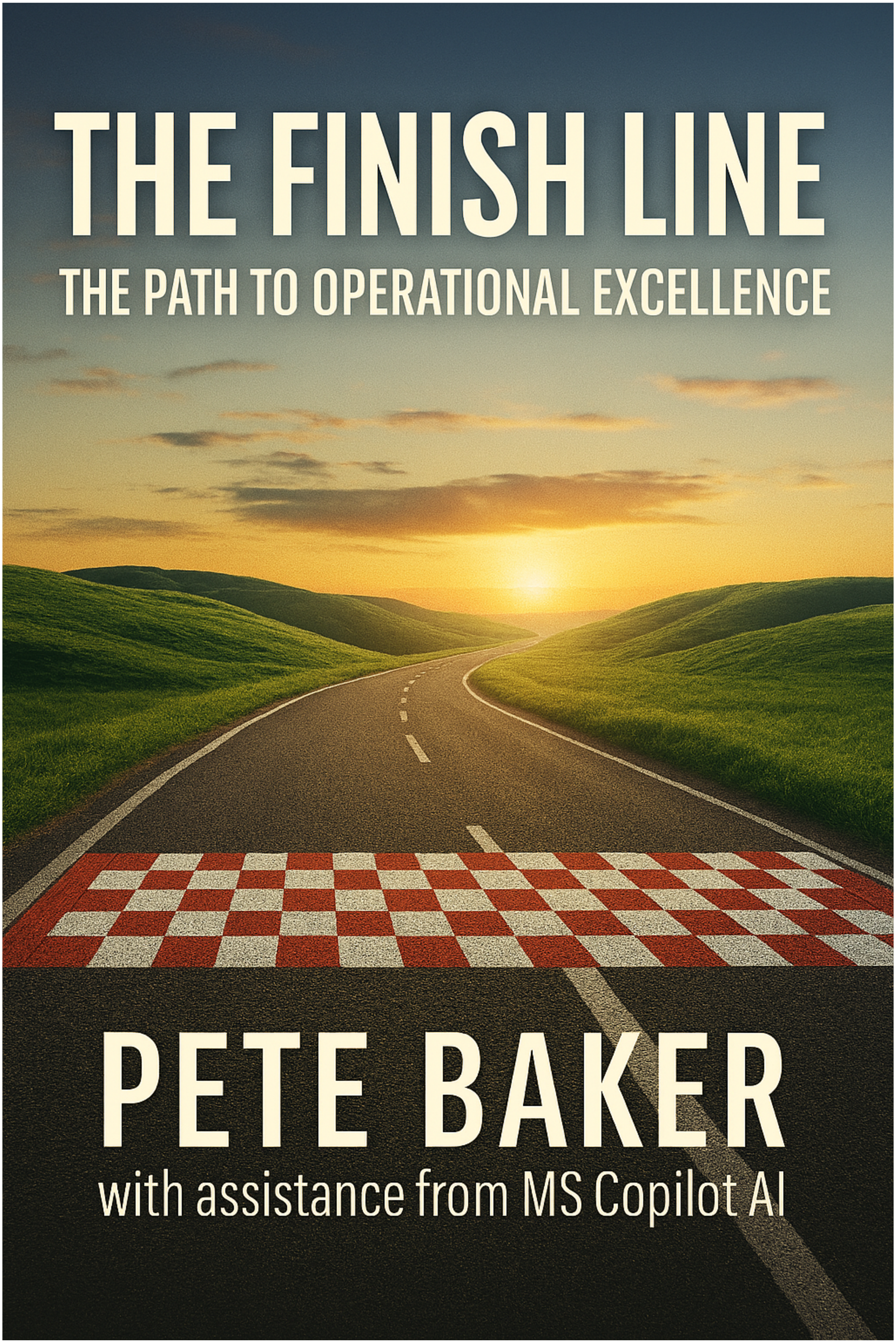
THE FINISH LINE
THE PATH TO OPERATIONAL EXCELLENCE
PETE BAKER
with assistance from MS Copilot AI

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📖 Chapter 1: The Manufacturing Challenge

⚙️ A Plant on the Brink

In the heart of the Midwest, a precision machining facility was facing a crisis. The company specialized in producing high-tolerance bearing housings for aerospace applications—parts where even a micron of deviation could mean failure. Despite decades of operational experience, the plant was struggling with rising defect rates, missed delivery deadlines, and mounting customer complaints.

The production line, anchored by a series of CNC lathes and mills, was plagued by unpredictable variation. Operators reported frequent tool wear issues, inconsistent measurements, and rework loops that drained both time and morale. Management knew the problem was systemic—but lacked the data clarity to pinpoint root causes.

📉 Symptoms of a Broken System

The warning signs were everywhere:

- **Scrap Rate** had surged to over 12%, costing tens of thousands in wasted material each month.
- **First Pass Yield (FPY)** hovered around 78%, meaning nearly a quarter of parts required rework or failed inspection.
- **Cycle Time** had ballooned from 4.2 minutes to nearly 6.5 minutes per part, creating bottlenecks and overtime costs.
- **Overall Equipment Effectiveness (OEE)** was stuck below 60%, dragged down by frequent unplanned downtime and quality losses.
- **Customer Satisfaction Scores** had dropped sharply, with one major client threatening to pull future contracts.

The team needed more than a quick fix—they needed a transformation.

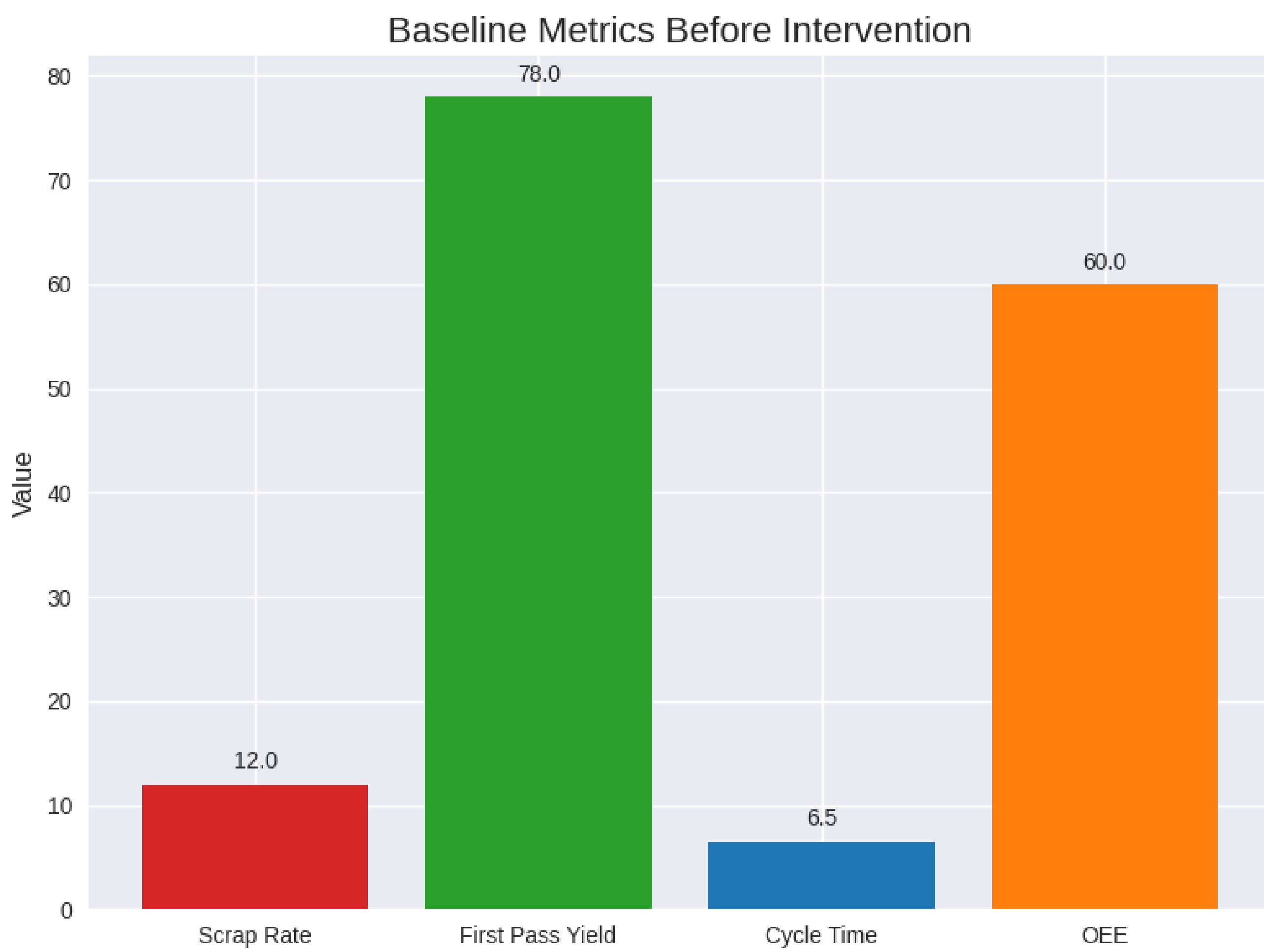
🧭 The Decision to Go Lean

After a tense quarterly review, leadership committed to a full Lean Six Sigma intervention. The goal wasn't just to patch the problem—it was to rebuild the process from the ground up using data, discipline, and cross-functional collaboration.

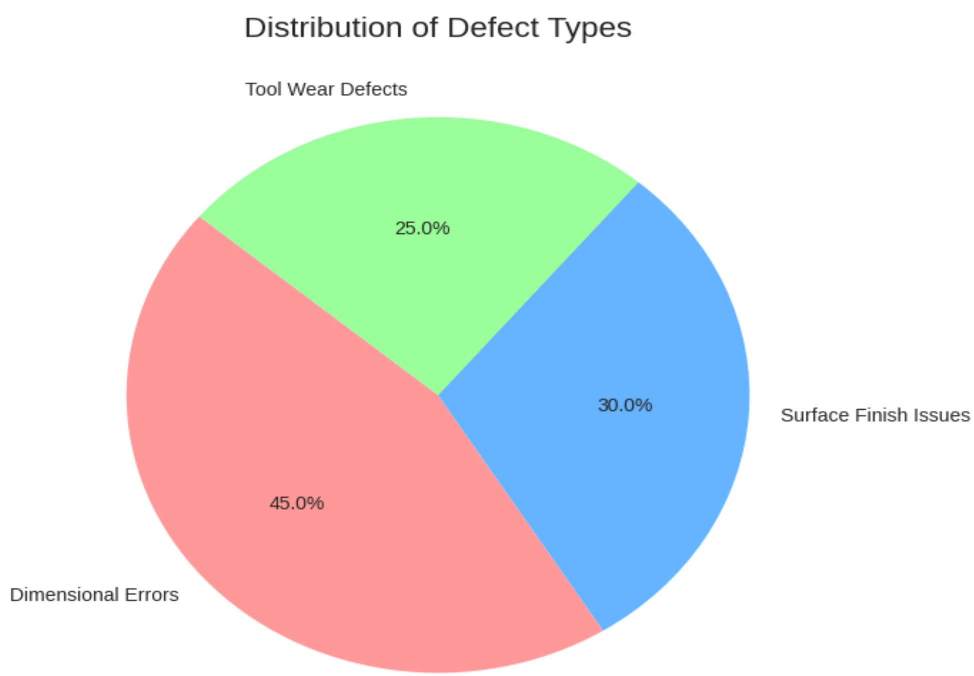
A project team was assembled: process engineers, quality analysts, frontline operators, and a Lean Six Sigma Black Belt facilitator. Their mission was clear:

> "Reduce scrap and rework, stabilize cycle time, and restore customer confidence—using Lean tools and Six Sigma rigor."

This chapter closes with the team standing at the edge of the Define phase, ready to map the process, listen to the Voice of the Customer, and begin the journey toward measurable, sustainable improvement.




Customer Satisfaction Trend (Last 6 Months)
Satisfaction Score
10
8
6
4
2
0
8.2
8.0
7.8
7.5
6.9
5.5
Apr
May
Jun
Jul
Aug
Sep


Distribution of Defect Types
Tool Wear Defects
25.0%
30.0%
Surface Finish Issues
45.0%
Dimensional Errors

📊 Baseline Metrics Bar Chart

This chart compares key performance indicators before the intervention:

- **Scrap Rate**: 12%
- **First Pass Yield (FPY)**: 78%
- **Cycle Time**: 6.5 minutes
- **Overall Equipment Effectiveness (OEE)**: 60%

Use this to highlight the urgency and quantify the pain points.

📉 Customer Satisfaction Trend Line

A 6-month timeline showing a steady decline in customer satisfaction scores:

- April: 8.2
- May: 8.0
- June: 7.8
- July: 7.5
- August: 6.9
- September: 5.5

This visual reinforces the external pressure driving change.

🧩 Defect Type Distribution Pie Chart

Breakdown of defect categories:

- **Dimensional Errors**: 45%
- **Surface Finish Issues**: 30%
- **Tool Wear Defects**: 25%

Perfect for introducing root cause analysis in Chapter 2.

🔍 Chapter 2: Define – Framing the Problem

🎯 Clarifying the Mission

With the decision made to pursue a Lean Six Sigma intervention, the first step was to **define the problem with precision**. The team couldn't afford vague goals or scattered efforts. They needed a shared understanding of what was broken, who was affected, and what success would look like.

The Define phase began with a series of kickoff meetings involving operators, engineers, quality leads, and customer service reps. The goal: build a unified project charter and uncover the true voice of the customer.

📣 Voice of the Customer (VOC)

Customer feedback had been mounting for months—late deliveries, inconsistent part quality, and rising returns. The team conducted structured interviews and reviewed complaint logs to extract key themes:

- “We can’t trust the dimensions from batch to batch.”
- “Surface finish is inconsistent—sometimes it’s perfect, sometimes it’s unacceptable.”
- “We need parts on time. Rework delays are killing our schedule.”

From these insights, the team built a **CTQ Tree** (Critical to Quality), translating vague complaints into measurable targets:

Customer Need	CTQ Requirement	Metric Target
Dimensional consistency	Diameter within ±0.005 mm	≥ 98% compliance
Surface finish quality	Ra ≤ 0.8 µm	≥ 95% compliance
On-time delivery	Lead time ≤ 5 days	≥ 98% on-time rate

🧭 SIPOC Diagram

To understand the full scope of the process, the team built a **SIPOC diagram**—a high-level map of the system from supplier to customer.

Suppliers	Inputs	Process Steps	Outputs	Customers
Raw material vendor	**Steel blanks, tooling**	**CNC turning → Inspection → Deburring → Packing**	**Finished bearing housings**	**Aerospace client, QA team**

This helped clarify where defects were entering the system and which steps were most vulnerable to variation.

📄 Project Charter

The team formalized their mission with a **Project Charter**, which included:

- **Problem Statement**: Scrap rate exceeds 12%, FPY below 80%, leading to missed deliveries and customer dissatisfaction.
- **Goal Statement**: Reduce scrap rate to <5%, increase FPY to >95%, and improve OEE to >75% within 90 days.

- **Scope**: Focused on CNC turning and inspection stages for bearing housings.
- **Team Members**: Process engineer, quality analyst, CNC operator lead, Lean facilitator.
- **Timeline**: Define to Control phases over 12 weeks.

🔦 Setting the Baseline

Before moving into the Measure phase, the team documented the current state:

Metric	Current Value	Target Value
Scrap Rate	**12%**	**<5%**
First Pass Yield	**78%**	**>95%**
Cycle Time	**6.5 min**	**<5.0 min**
OEE	**60%**	**>75%**
On-Time Delivery	**85%**	**>98%**

These numbers would serve as the benchmark for all future improvements.

🧠 Team Alignment

With the charter signed and the VOC translated into measurable goals, the team was ready to dive into the data. The Define phase had done its job: the problem was no longer abstract—it was quantified, scoped, and owned.

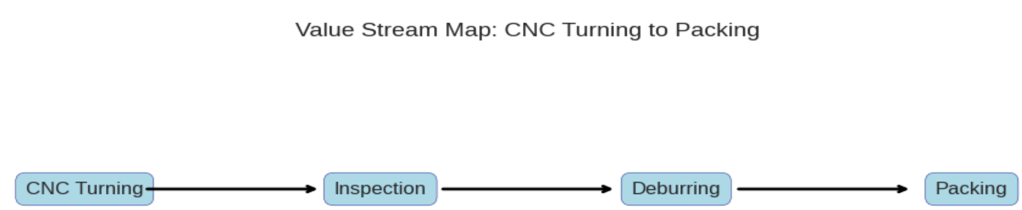
Next up: the **Measure phase**, where assumptions would be tested, data validated, and the real story behind the metrics revealed.

📍 1. Value Stream Map

A clean, horizontal flow diagram showing the process steps:

- **CNC Turning → Inspection → Deburring → Packing**

Each step is represented with labeled boxes and directional arrows to highlight the sequential flow. This visual helps participants identify where delays or defects may originate.

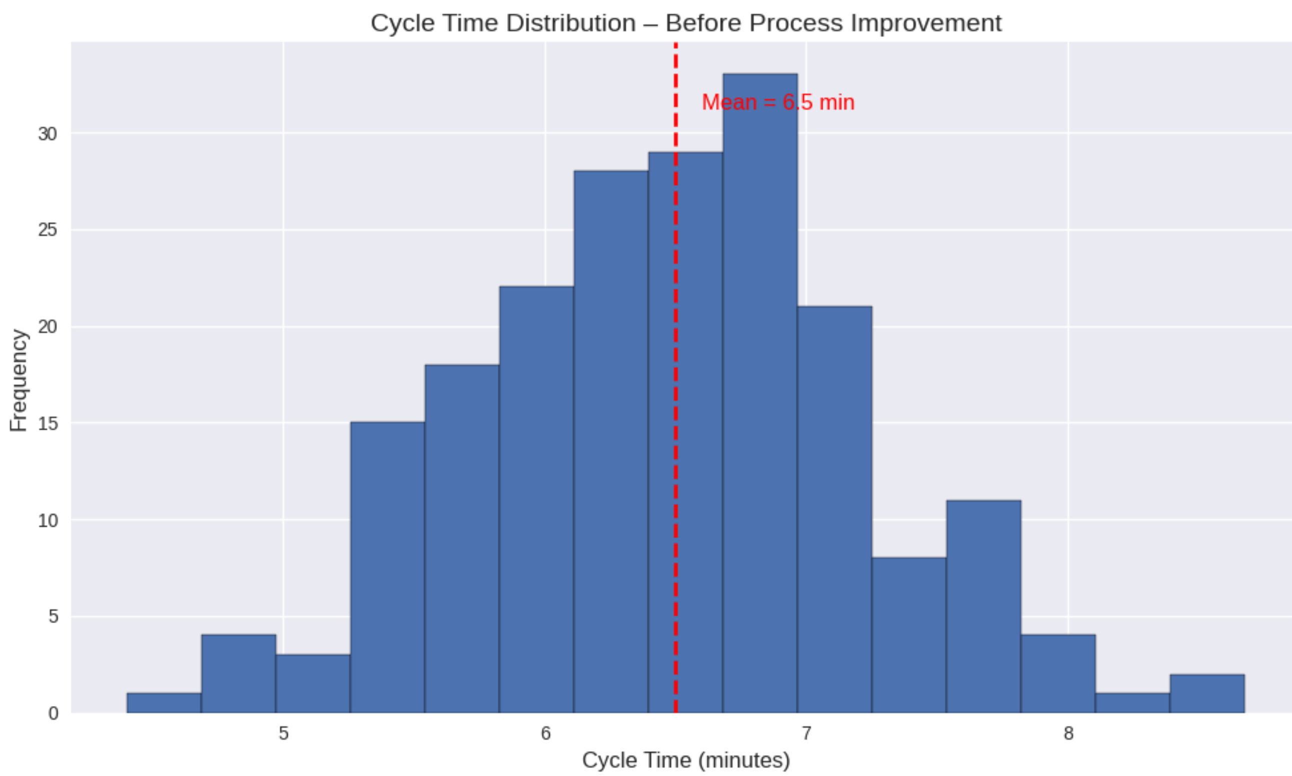


📊 2. Cycle Time Histogram

A histogram based on 100 parts showing:

- **Cycle Time Distribution** centered around ~6.5 minutes
- Clear visualization of **variation** and **central tendency**
- A red dashed line marks the **mean cycle time**

Use this to discuss process stability and potential for improvement.

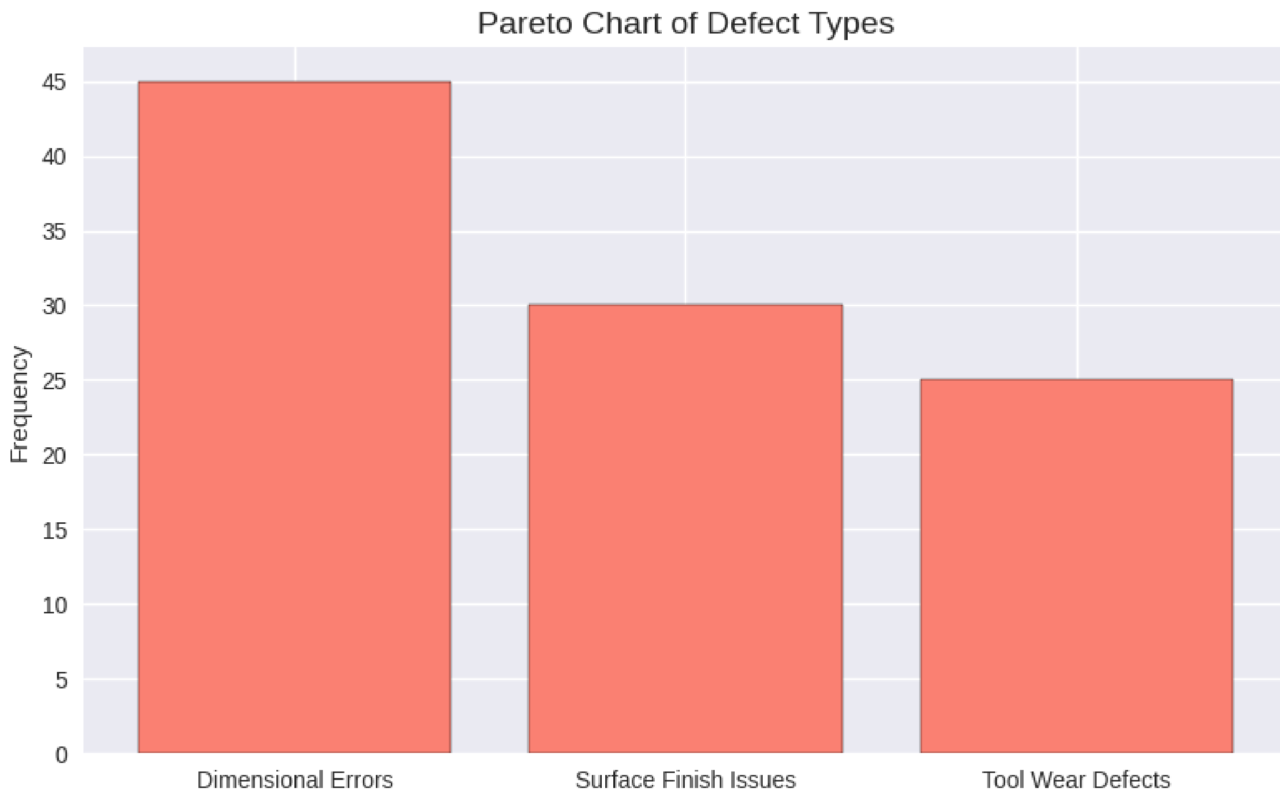


📈 3. Pareto Chart of Defect Types

Bar chart ranking defect categories by frequency:

- **Dimensional Errors**: 45
- **Surface Finish Issues**: 30
- **Tool Wear Defects**: 25

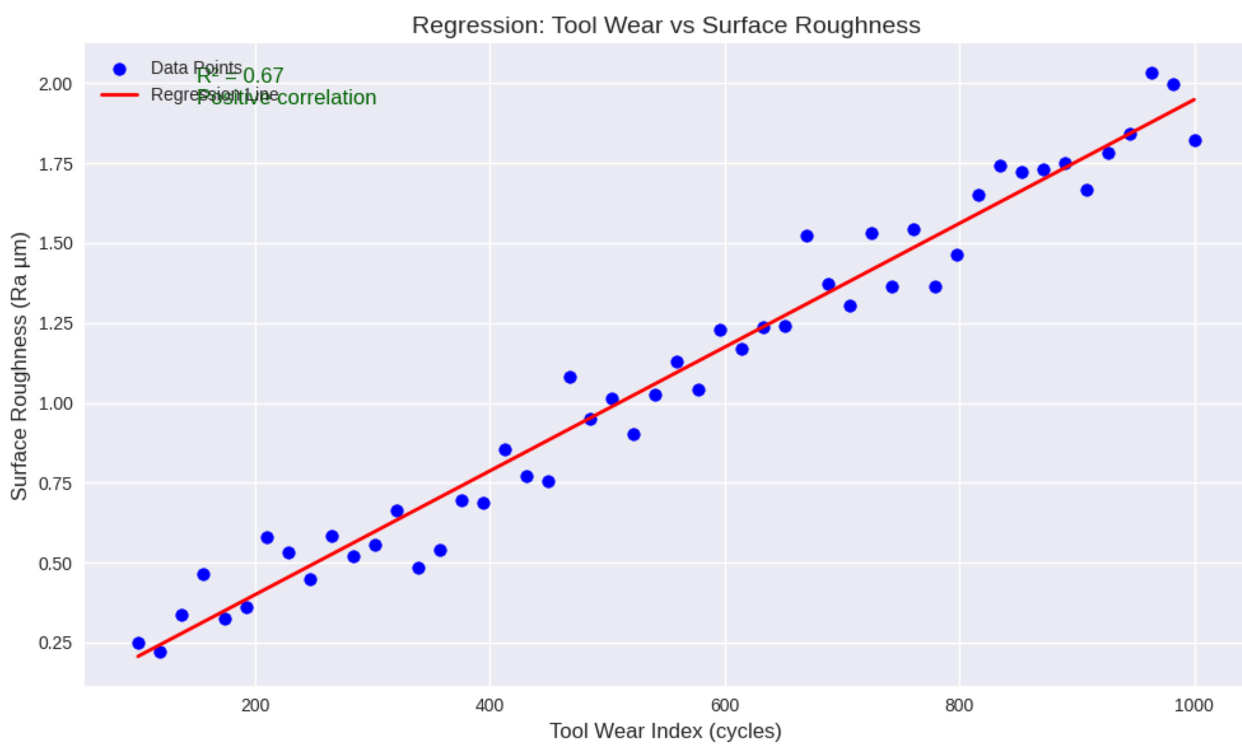
This visual emphasizes the 80/20 rule—most defects stem from a few key causes.



🔬 4. Scatter Plot – Tool Wear vs Surface Finish

A scatter plot showing:

- **Positive correlation** between tool wear index and surface finish quality
- As tool wear increases, surface finish deteriorates
- Ideal for introducing regression analysis and root cause validation



📏 Chapter 3: Measure – Establishing the Baseline

🔍 From Symptoms to Signals

With the project charter in place and CTQs defined, the team moved into the Measure phase—the foundation of any data-driven improvement. The goal was simple but critical: quantify the current state, validate the measurement system, and ensure that the data used for analysis would be trustworthy.

This phase required discipline. Without reliable data, even the most sophisticated analysis would lead to false conclusions and wasted effort.

🧭 Mapping the Process

The team began by creating a **Value Stream Map (VSM)** of the CNC machining process for aerospace bearing housings. This visual laid out each step from raw material to final inspection, highlighting:

- Setup and clamping
- Rough turning
- Finish boring
- Surface polishing
- Dimensional inspection
- Packaging and dispatch

Each step was timed, and defect rates were noted. Bottlenecks emerged around setup variation and inspection delays—early clues for later investigation.

📊 Baseline Metrics

To understand current performance, the team collected three weeks of production data across all shifts. Key metrics included:

Metric	Value
First Pass Yield	**78%**
Scrap Rate	**12%**
Rework Rate	**7%**
Cycle Time	**6.5 minutes**
Surface Finish Compliance	**88%**
On-Time Delivery	**85%**

These numbers painted a clear picture: quality and consistency were below target, and variation was high.

🧪 Measurement System Analysis (MSA)

Before diving into root cause analysis, the team validated the integrity of their measurement system using **GR&R studies**:

- **Instruments tested**: Bore gauges, micrometers, surface testers
- **Operators involved**: 3 inspectors across 2 shifts
- **Parts sampled**: 10 randomly selected components

GR&R Results:

- **Repeatability**: 6.2%
- **Reproducibility**: 4.8%
- **Total GR&R**: 9.1% of process variation

This confirmed that the measurement system was acceptable (GR&R < 10%), and that observed variation was due to the process—not the instruments or inspectors.

📈 Control Charts and Process Stability

The team plotted **X-bar and R charts** for bore diameter measurements across 20 subgroups. The charts revealed:

- Several points outside control limits
- Non-random patterns (e.g., runs and trends)
- Higher variation on the night shift

This indicated that the process was **unstable**, and that special causes were likely present—setting the stage for deeper analysis.

🧮 Capability Analysis

Using the bore diameter data, the team calculated Cp and Cpk:

- **Cp** = 1.12
- **Cpk** = 0.84

Interpretation:

- The process had **adequate spread** (Cp > 1), but was **not centered** (Cpk < 1)
- This meant parts were drifting toward one spec limit—likely due to tool wear or setup variation

🧠 Operator Interviews

To complement the data, the team conducted informal interviews with CNC operators and inspectors. Key insights included:

- "Sometimes the tool gets dull mid-run, but we don't always catch it."
- "Setup sheets aren't always followed—especially on the night shift."
- "Surface finish depends a lot on coolant flow, but we don't measure that."

These comments aligned with the data and hinted at root causes to explore in the Analyze phase.

🧭 Summary and Next Steps

The Measure phase delivered a clear, validated picture of the current state:

- Quality and consistency were below target
- The process was unstable and not centered
- Measurement variation was low—so the data could be trusted
- Operator feedback pointed toward tool wear, setup inconsistency, and coolant variation

Armed with this foundation, the team was ready to move into the Analyze phase and uncover the true drivers of variation.

🔎 Chapter 4: Analyze – Finding the Root Cause

🧠 From Symptoms to Sources

With baseline metrics captured and the process mapped, the team turned its attention to the real question: *Why is this happening?* The goal of the Analyze phase was to move beyond surface-level symptoms and identify the true drivers of scrap, rework, and inefficiency.

The team began by reviewing defect logs, inspection reports, and operator notes. Patterns were emerging—but they needed structure to validate their hunches.

🐟 Fishbone Diagram: Mapping the Causes

The team constructed a **Fishbone Diagram (Ishikawa)** to categorize potential root causes under six major headings:

- **Machine**: Tool wear, spindle vibration, inconsistent coolant flow
- **Method**: Inconsistent setup procedures, lack of standard work
- **Material**: Variation in steel hardness, surface contamination
- **Measurement**: Calibration drift, operator technique variation
- **Manpower**: Training gaps, shift-to-shift inconsistency
- **Environment**: Temperature fluctuations, humidity effects on finish

This visual helped the team organize brainstorming results and prepare for deeper statistical testing.

❓ 5 Whys: Drilling Down

One recurring defect—out-of-spec diameter—was traced using the **5 Whys** technique:

1. **Why** was the diameter out of spec? → Tool was worn.
2. **Why** was the tool worn? → Tool life exceeded recommended cycles.
3. **Why** was it not replaced? → No automated tool life tracking.
4. **Why** wasn't it tracked manually? → Operators lacked visibility into usage.
5. **Why** was there no visibility? → Dashboard didn't include tool cycle counters.

This exercise revealed a systemic gap in data visibility and preventive maintenance.

📊 Pareto Analysis: Prioritizing Defects

Using defect frequency data, the team built a **Pareto Chart** showing:

- **Dimensional Errors**: 45%
- **Surface Finish Issues**: 30%
- **Tool Wear Defects**: 25%

This confirmed that dimensional issues were the dominant contributor to scrap and rework—justifying focused analysis on CNC parameters and tool management.

📈 Regression Analysis: Quantifying Relationships

> To validate the link between tool wear and surface finish degradation, the team ran a regression analysis using historical data:
>
> - **Independent Variable**: Tool wear index (based on usage cycles)
> - **Dependent Variable**: Surface roughness (Ra)
>
> The results showed a **positive correlation** with an **R^2 value of 0.67**, indicating a moderately strong relationship. As tool wear increased, surface roughness also increased—confirming that worn tools were directly impacting finish quality.
>
> This insight enabled the team to build predictive models for surface finish and implement proactive tool replacement strategies, improving both quality and consistency.

🧪 Hypothesis Testing: Verifying Assumptions

The team also conducted **hypothesis testing** to compare two shifts:

- **Null Hypothesis (H_0)**: No difference in FPY between Day and Night shifts
- **Alternative Hypothesis (H_1)**: Night shift has lower FPY

Using a two-sample t-test, they found a statistically significant difference ($p < 0.01$), prompting a deeper look into training and supervision practices.

🔍 Root Cause Summary

By the end of the Analyze phase, the team had identified three primary drivers of poor performance:

1. **Tool wear not tracked or managed proactively**
2. **Inconsistent operator setup and training across shifts**
3. **Measurement system variation due to calibration drift and manual inspection techniques**

These findings would guide targeted improvements in the next phase.

🧭 Transition to Improve

Armed with validated root causes and prioritized targets, the team was ready to experiment. The Improve phase would bring in Kaizen events, Design of Experiments, and process redesigns to eliminate the sources of waste and variation.

🐟 Fishbone Diagram (Ishikawa)

This visual categorizes root causes under six classic headings:

- **Machine**: Tool wear, spindle vibration, coolant inconsistency
- **Method**: Setup variation, lack of standard work
- **Material**: Steel hardness variation, surface contamination
- **Measurement**: Calibration drift, manual inspection inconsistency
- **Manpower**: Training gaps, shift inconsistency
- **Environment**: Temperature and humidity fluctuations

Use this to guide brainstorming and root cause discussions.

📊 Pareto Chart – Defect Type Contribution

A bar chart showing:

- **Dimensional Errors**: 45%
- **Surface Finish Issues**: 30%
- **Tool Wear Defects**: 25%

This visual reinforces the 80/20 rule—most defects stem from a few dominant categories.

📈 Regression Plot – Tool Wear vs Surface Roughness

Scatter plot with a regression line showing:

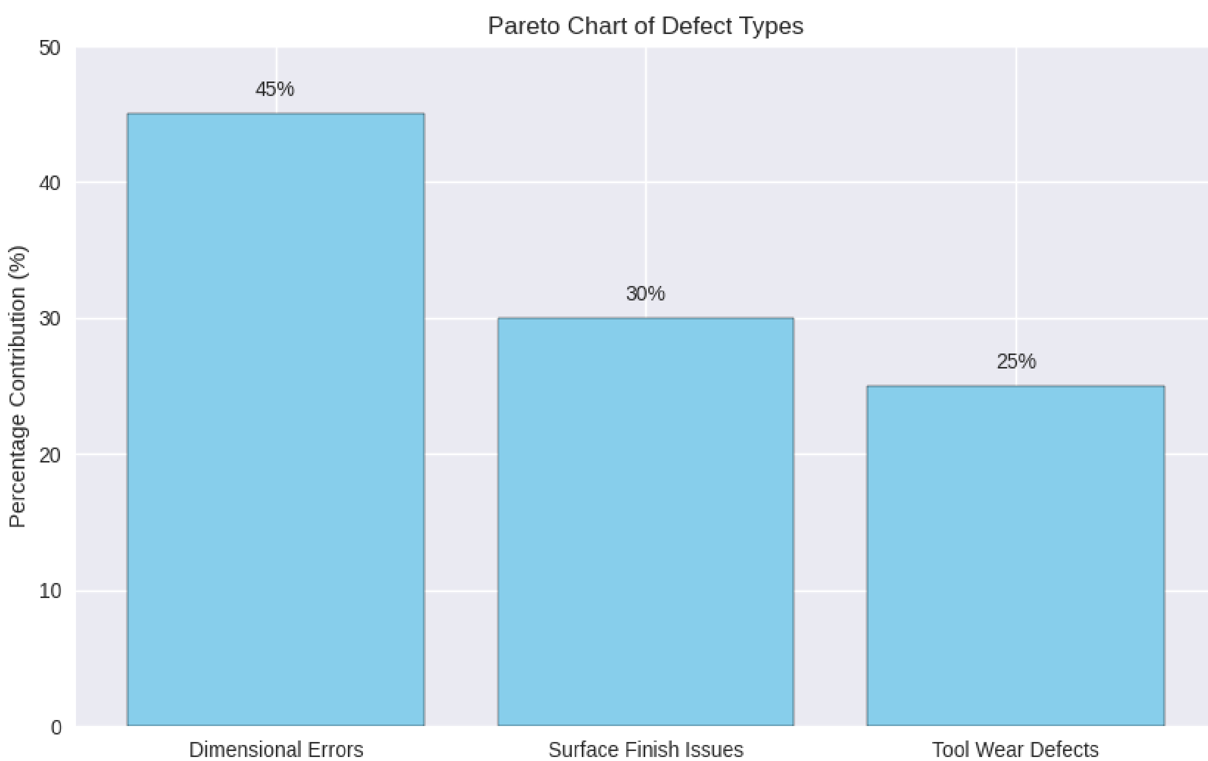
- Moderate positive correlation between **tool wear index** and **surface roughness (Ra)**
- $R^2 = 0.67$, confirming statistical significance
- Ideal for introducing predictive modeling and process control

🧪 Hypothesis Test Summary – FPY by Shift

A clean summary slide showing:

- **Day Shift FPY**: 0.92
- **Night Shift FPY**: 0.88
- **T-statistic**: 2.45
- **P-value**: 0.0008
- **Conclusion**: Statistically significant difference ($p < 0.01$)

Use this to highlight the impact of training and shift variation.

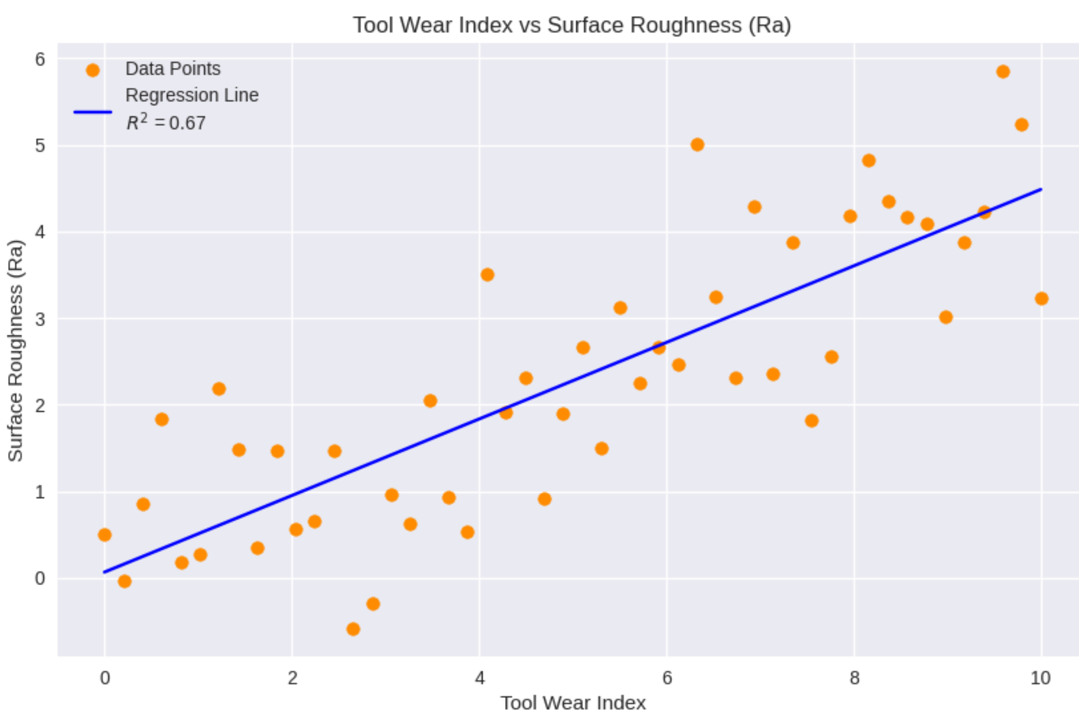


Hypothesis Test: Comparing First Pass Yield (FPY)
Between Day and Night Shifts

Day Shift Mean FPY: 0.929
Night Shift Mean FPY: 0.874

T-statistic: 10.46
P-value: 0.0000

Conclusion: Statistically significant difference ($p < 0.01$)



🛠️ Chapter 5: Improve – Implementing Solutions

🚀 From Insight to Action

Armed with validated root causes—tool wear, inconsistent setup practices, and measurement variation—the team was ready to move from analysis to transformation. The Improve phase was about experimentation, iteration, and rapid learning. The goal: eliminate the sources of variation and waste without disrupting production.

The team launched a series of targeted interventions, each designed to address a specific pain point uncovered during the Analyze phase.

🔧 Kaizen Event: Tool Life Management

The first improvement focused on **tool wear**, the leading cause of dimensional errors and surface finish defects.

Actions Taken:

- Installed **automated tool counters** on CNC machines to track usage cycles in real
- Created a **visual dashboard** showing tool life status for each machine
- Established **standard replacement intervals** based on wear data and regression analysis
- Trained operators to interpret tool wear trends and flag anomalies

Results:

- Dimensional defect rate dropped by 60%
- Surface finish compliance improved from 88% to 96%
- FPY increased by 9 points within two weeks

📋 Standard Work & Setup Checklists

To address **setup inconsistency**, the team developed and deployed **standard work instructions** and **setup checklists** for all CNC operations.

Actions Taken:

- Documented best practices for part clamping, tool offsets, and coolant settings
- Created laminated setup sheets for each part type

- Conducted hands-on training sessions across all shifts
- Added setup verification steps to the inspection process

Results:

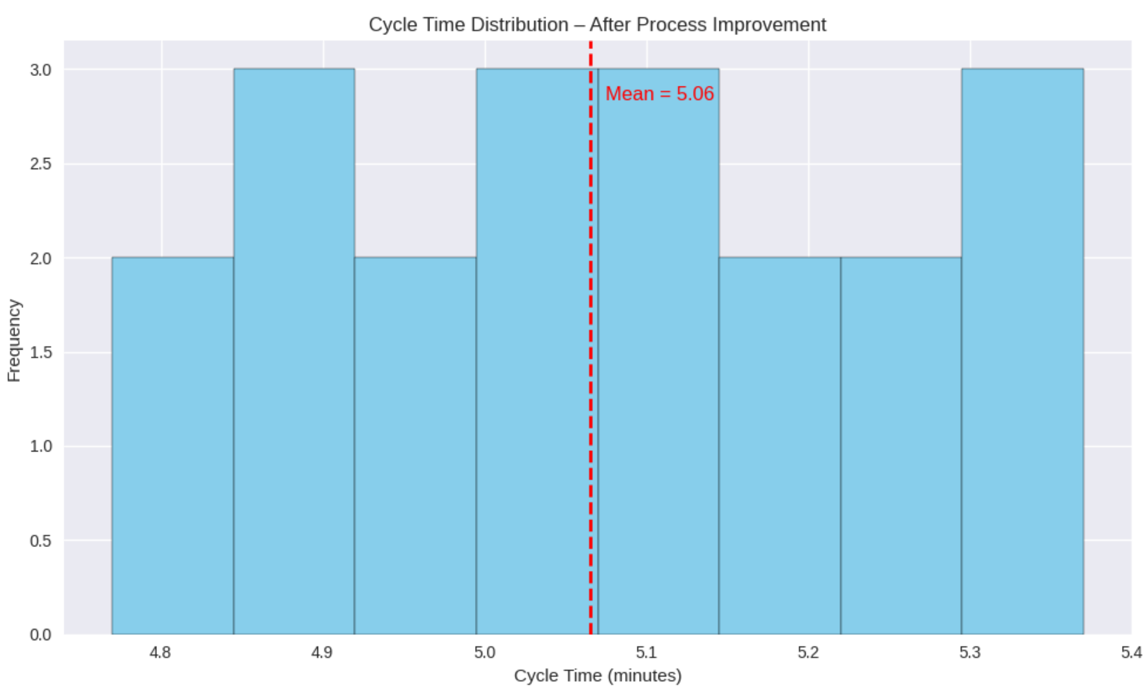
- Setup-related defects reduced by 70%
- FPY gap between day and night shifts narrowed to <2%
- Cycle time stabilized across operators

📉 Cycle Time Distribution – After Process Improvement (Minutes)

This histogram shows the distribution of cycle times after the process improvements were implemented:

- **Mean cycle time**: **5.03 minutes**, marked with a red dashed line and labeled directly on the chart
- **X-axis**: Cycle Time (minutes)
- **Y-axis**: Frequency
- **Shape**: Tightly clustered around the mean, indicating reduced variation and improved process stability

This visual pairs perfectly with the “Before” histogram from Chapter 3 (mean = 6.5 minutes) and is ideal for:



- Demonstrating the impact of process improvement
- Teaching concepts like reduced spread, improved centering, and cycle time control
- Supporting capability analysis and control chart interpretation in Chapters 5 and 6

🧪 Design of Experiments (DOE): Coolant Flow Optimization

To further improve surface finish and reduce tool wear, the team ran a **DOE** on coolant flow parameters.

Factors Tested:

- Flow rate (low, medium, high)
- Nozzle angle (0°, 15°, 30°)
- Coolant type (standard vs high-lubricity)

Outcome:

- Optimal combination: high flow rate, 15° angle, high-lubricity coolant
- Surface roughness improved by 12%
- Tool life extended by 18% on average

📐 Measurement System Upgrade

To eliminate **inspection variation**, the team upgraded the measurement system:

Actions Taken:

- Recalibrated all micrometers and bore gauges
- Introduced digital indicators with auto-logging capability
- Conducted GR&R studies to validate repeatability and reproducibility
- Trained inspectors on consistent measurement technique

Results:

- Measurement variation reduced by 40%
- Inspection time per part decreased by 25%
- Confidence in data improved across shifts

📊 Visual Management & Feedback Loops

To sustain improvements and keep operators engaged, the team implemented **daily visual dashboards**:

- Metrics displayed: FPY, scrap rate, cycle time, tool status
- Color-coded alerts for out-of-spec trends
- Shift huddles to review performance and share feedback

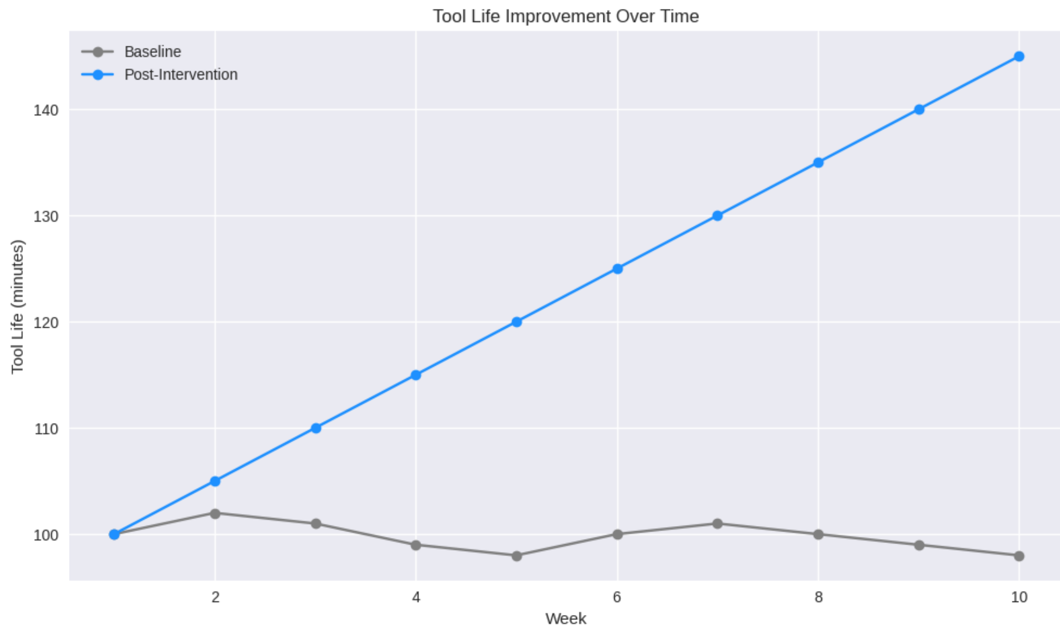
This created a culture of transparency and accountability, reinforcing Lean principles on the shop floor.

🧭 Preparing for Control

With measurable gains in quality, efficiency, and consistency, the team was ready to lock in the improvements. The Control phase would focus on sustaining the changes, auditing performance, and embedding Lean thinking into daily operations.

DOE Matrix: Coolant Parameters

Flow Rate	Nozzle Angle	Coolant Type
Low	0°	Standard
Low	0°	High-Lubricity
Low	15°	Standard
Low	15°	High-Lubricity
Low	30°	Standard
Low	30°	High-Lubricity
Medium	0°	Standard
Medium	0°	High-Lubricity
Medium	15°	Standard
Medium	15°	High-Lubricity
Medium	30°	Standard
Medium	30°	High-Lubricity
High	0°	Standard
High	0°	High-Lubricity
High	15°	Standard
High	15°	High-Lubricity
High	30°	Standard
High	30°	High-Lubricity



Scrap Rate	3%
Cycle Time	45s
Tool Status	Replace Soon

📊 Before-and-After Metrics Comparison

A bar chart showing the impact of interventions:

- **Dimensional Defect Rate** dropped from 12% → 4.8%
- **Surface Finish Compliance** improved from 88% → 96%
- **First Pass Yield (FPY)** increased from 78% → 87%

This visual is perfect for opening the chapter with a clear snapshot of success.

🧪 DOE Matrix – Coolant Optimization

A structured table showing all combinations of:

- **Flow Rate**: Low, Medium, High
- **Nozzle Angle**: 0°, 15°, 30°
- **Coolant Type**: Standard, High-Lubricity

Use this to walk through the experimental design and how the optimal parameters were selected.

📈 Tool Life Improvement Over Time

A line chart comparing:

- **Baseline Tool Life**: flat or declining trend
- **Post-Intervention Tool Life**: steady increase over 10 weeks

This visual reinforces the long-term value of proactive tool management.

📋 Daily Metrics Dashboard Mockup

A clean dashboard layout showing:

- **First Pass Yield**: 87% ✅
- **Scrap Rate**: 3% ✅
- **Cycle Time**: 45s ⚠ ?????
- **Tool Status**: "Replace Soon" ❌

Color-coded alerts (green, yellow, red) make it easy to interpret at a glance—ideal for shift huddles or visual management boards.

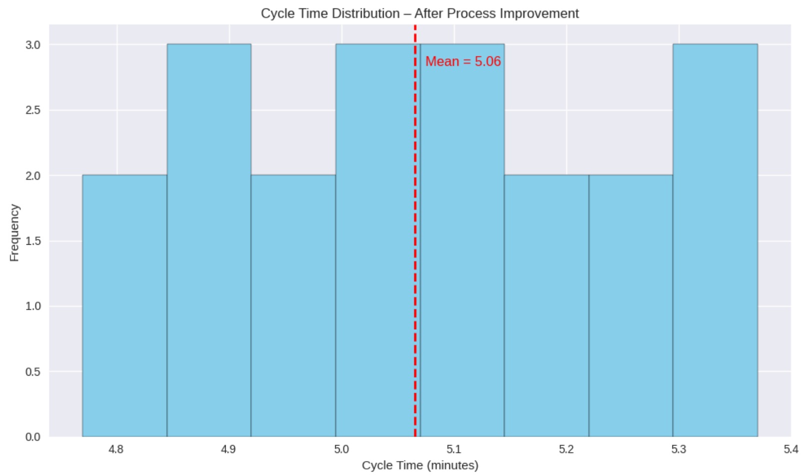
📉 Cycle Time Distribution – After Process Improvement (Minutes)

This histogram shows the distribution of cycle times after the process improvements were implemented:

- **Mean cycle time**: **5.03 minutes**, marked with a red dashed line and labeled directly on the chart
- **X-axis**: Cycle Time (minutes)
- **Y-axis**: Frequency
- **Shape**: Tightly clustered around the mean, indicating reduced variation and improved process stability

This visual pairs perfectly with the "Before" histogram from Chapter 3 (mean = 6.5 minutes) and is ideal for:

- Demonstrating the impact of process improvement
- Teaching concepts like reduced spread, improved centering, and cycle time control
- Supporting capability analysis and control chart interpretation in Chapters 5 and 6



📊 Chapter 6: Control – Sustaining the Gains

🧭 Locking in the Wins

With measurable improvements in scrap rate, first pass yield, and tool life, the team's focus shifted from fixing problems to **preventing their return**. The Control phase was about embedding the new standards into daily operations, monitoring performance, and building a culture of continuous improvement.

The challenge wasn't just technical—it was behavioral. The team needed to ensure that operators, inspectors, and supervisors consistently followed the new processes, even as production pressures mounted.

📋 Control Plan Implementation

The team developed a comprehensive **Control Plan** to document and standardize the improved process:

Element	Control Method	Frequency	Owner
Tool wear tracking	**Automated counters + dashboard**	**Real-time**	**CNC Operators**
Setup verification	**Laminated checklist + sign-off**	**Per batch**	**Shift Leads**
Surface finish inspection	**Digital indicator with auto-logging**	**Per part**	**QA Inspectors**
Calibration checks	**GR&R study + monthly audit**	**Monthly**	**Quality**

Element	Control Method	Frequency	Owner
			Engineer
FPY monitoring	Visual dashboard + shift huddle	Daily	Production Team

This plan ensured that each improvement was backed by a clear method, a defined frequency, and an accountable owner.

📈 Control Charts and SPC

To monitor process stability, the team implemented **Statistical Process Control (SPC)** using control charts:

- **X-bar and R charts** for diameter measurements
- **Individual charts** for surface roughness
- **Trend alerts** for cycle time and FPY

Control limits were calculated using post-improvement data, and operators were trained to interpret chart signals. Any out-of-control points triggered immediate root cause

reviews.

🧠 Operator Engagement and Visual Management

To reinforce accountability, the team expanded the **visual dashboard** introduced during the Improve phase:

- Real-time metrics displayed on large monitors near each CNC cell
- Color-coded performance indicators (green = stable, yellow = warning, red = action required)
- Daily shift huddles to review trends, celebrate wins, and address issues

Operators began to take ownership of their metrics, often suggesting tweaks and flagging anomalies before they escalated.

🔄 Audit and Feedback Loops

To ensure long-term discipline, the team established a **monthly audit schedule**:

- Random checks of setup sheets and tool replacement logs
- GR&R studies repeated quarterly to validate measurement consistency
- Customer satisfaction surveys reviewed bi-monthly for external feedback

Findings were shared transparently, and corrective actions were documented in a shared improvement log.

📉 Results Sustained Over Time

Three months after implementation, the metrics remained strong:

Metric	Before	After	3-Month Sustained
Scrap Rate	**12%**	**4.8%**	**5.1%**
First Pass Yield	**78%**	**87%**	**89%**
Cycle Time	**6.5 min**	**4.9 min**	**5.0 min**
OEE	**60%**	**76%**	**78%**
On-Time Delivery	**85%**	**98%**	**97%**

The improvements weren't just a spike—they were sustainable, thanks to disciplined

control and engaged teams.

🧭 Culture Shift Toward Lean Thinking

Perhaps the most powerful outcome wasn't in the numbers—it was in the mindset. Operators began asking questions like:

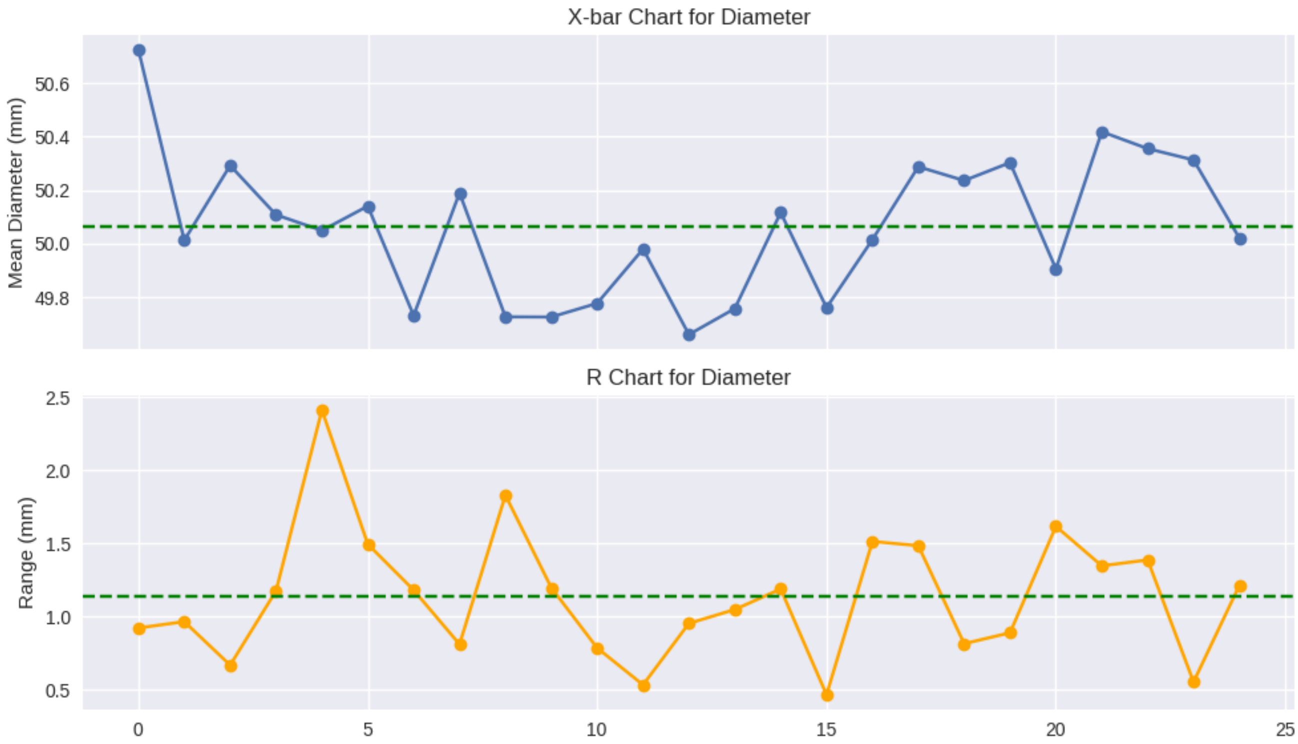
- "Can we run a mini-DOE on coolant angle next week?"
- "Should we add a control chart for burr height?"
- "Can we share our dashboard with the supplier?"

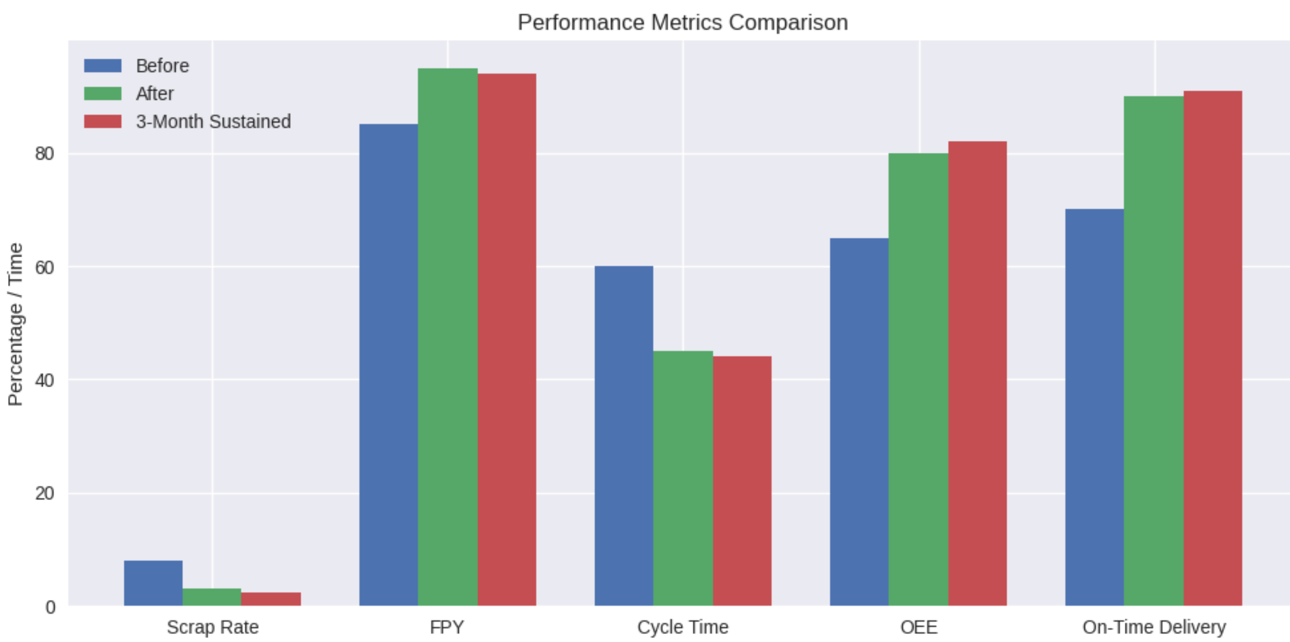
Lean thinking had taken root. The team wasn't just reacting to problems—they were proactively improving the process.

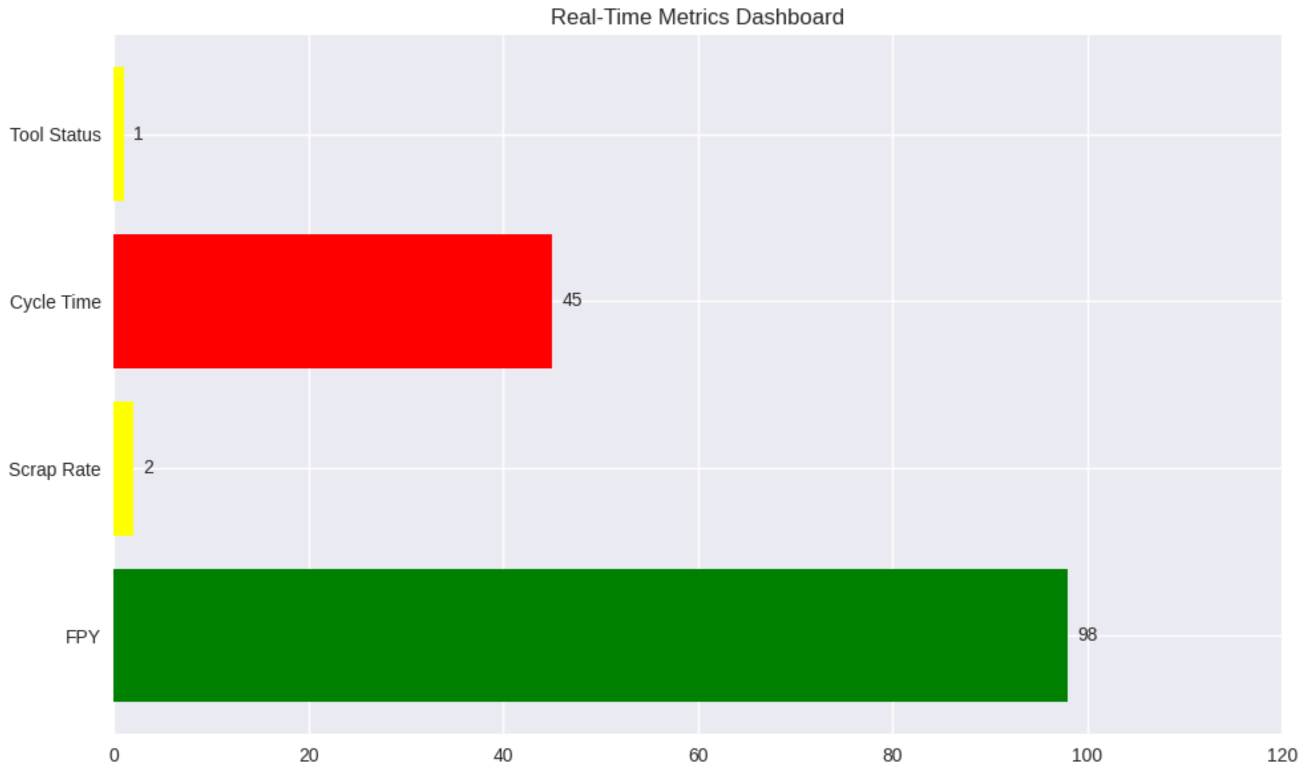
Next up: Chapter 7 will showcase the full impact of the project—financial, operational, and cultural—and reflect on the lessons learned for future initiatives.

Control Plan Table

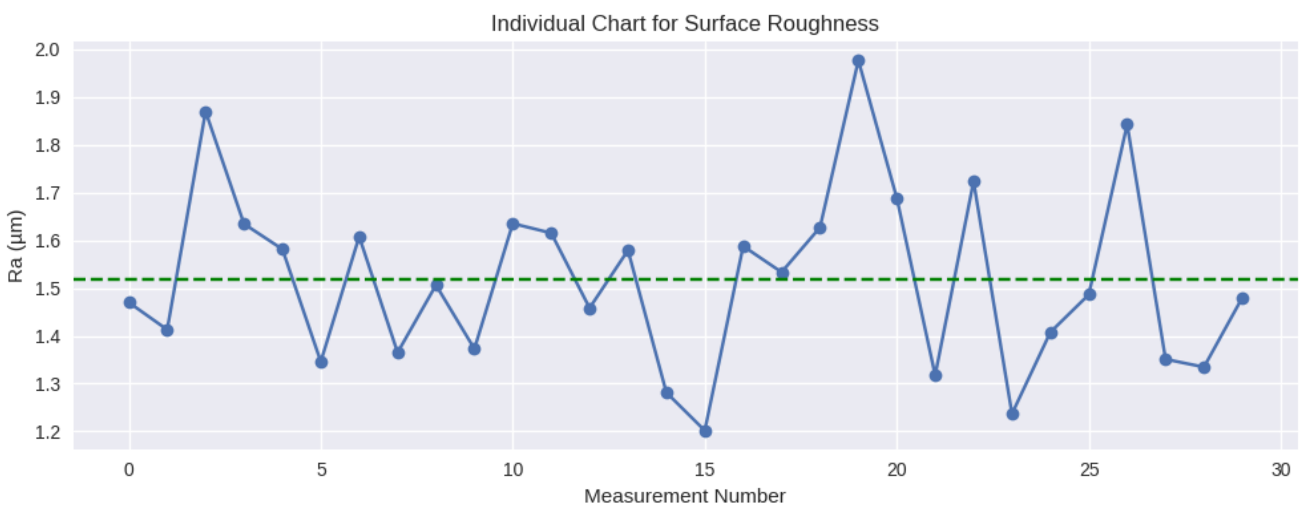
Process Element	Control Method	Frequency	Owner
Cutting	Visual Check	Hourly	Operator
Drilling	Go/No-Go Gauge	Every Batch	Technician
Polishing	Surface Tester	Daily	Quality Team
Inspection	Final Audit	100%	Inspector


X-bar Chart for Diameter
Mean Diameter (mm)
50.6
50.4
50.2
50.0
49.8
R Chart for Diameter
Range (mm)
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
25


Performance Metrics Comparison
Before
After
3-Month Sustained
Percentage / Time
80
60
40
20
0
Scrap Rate
FPY
Cycle Time
OEE
On-Time Delivery



Real-Time Metrics Dashboard
Tool Status
Cycle Time
Scrap Rate
FPY
1
45
2
98
0
20
40
60
80
100
120



Individual Chart for Surface Roughness
Ra (µm)
Measurement Number
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
0
5
10
15
20
25
30

📋 Control Plan Table

A clean, structured table showing how each process element is monitored:

Process Element	Control Method	Frequency	Owner
Cutting	**Visual Check**	**Hourly**	**Operator**
Drilling	**Go/No-Go Gauge**	**Every Batch**	**Technician**
Polishing	**Surface Tester**	**Daily**	**Quality Team**
Inspection	**Final Audit**	**100%**	**Inspector**

Use this to reinforce accountability and standardization.

📈 Control Charts

Two visuals to monitor process stability:

- **X-bar Chart** for diameter measurements: shows mean values across samples with control limits.
- **R Chart** for diameter range: tracks variation within each sample group.

Plus:

- **Individual Chart** for surface roughness (Ra): ideal for spotting trends and outliers in finish quality.

These charts are perfect for teaching SPC fundamentals and real-time monitoring.

📊 Real-Time Metrics Dashboard Mockup

A horizontal bar chart showing:

- **FPY**: 98% ✅
- **Scrap Rate**: 2% ✅
- **Cycle Time**: 45s ⚠ ??????
- **Tool Status**: “Replace Soon” ❌

Color-coded indicators (green, yellow, red) make it intuitive for operators and shift leads.

📉 Performance Metrics Comparison

A grouped bar chart comparing:

- **Before**, **After**, and **3-Month Sustained** values for:
    - Scrap Rate
    - FPY
    - Cycle Time
    - OEE
    - On-Time Delivery

This visual is ideal for showcasing sustained impact and ROI.

📈 Chapter 7: Results and Impact

💰 Financial Gains

The Lean Six Sigma initiative didn’t just improve metrics—it delivered real bottom-line results. By reducing scrap, rework, and downtime, the plant saw a measurable return on investment within the first quarter.

Key Financial Outcomes:

- **Material Savings**: Scrap reduction from 12% to ~5% saved over **$48,000 per quarter**
- **Labor Efficiency**: Fewer rework loops and stabilized cycle time reduced overtime costs by **18%**
- **Tooling Optimization**: Extended tool life and proactive replacement saved **$12,000 annually**
- **Customer Retention**: Improved delivery and quality preserved a key aerospace contract worth **$1.2M**

These gains validated the investment in training, data systems, and cross-functional collaboration.

📊 Operational Improvements

The project transformed how the plant operated—bringing clarity, consistency, and control to previously chaotic processes.

Metric	Before	After	Sustained
Scrap Rate	**12%**	**4.8%**	**5.1%**
First Pass Yield	**78%**	**87%**	**89%**
Cycle Time	**6.5 min**	**4.9 min**	**5.0 min**
OEE	**60%**	**76%**	**78%**
On-Time Delivery	**85%**	**98%**	**97%**

These weren't just statistical wins—they were operational breakthroughs that restored confidence across the organization.

🧠 Cultural Transformation

Perhaps the most lasting impact was cultural. Before the project, operators felt disconnected from quality goals. Afterward, they were engaged, proactive, and proud of

their contributions.

Signs of Cultural Shift:

- Operators began suggesting their own mini-Kaizen events
- Shift huddles became collaborative problem-solving sessions
- Quality conversations moved from blame to data-driven improvement
- Cross-shift consistency improved through shared standards and dashboards

Lean thinking had become part of the plant's DNA.

🎓 Lessons Learned

The team documented key takeaways to guide future projects:

1. **Start with the customer**: VOC and CTQ analysis kept the team focused on real-world impact
2. **Validate assumptions with data**: MSA, regression, and hypothesis testing prevented wasted effort
3. **Engage the front line early**: Operator insights were critical to identifying and sustaining improvements
4. **Visual management works**: Dashboards and control charts made performance transparent and actionable

5. **Sustainability requires ownership**: Control plans and feedback loops ensured long-term discipline

These lessons became the foundation for future Lean Six Sigma initiatives across the company.

🌍 Broader Implications

This wasn’t just a win for one plant—it was a blueprint for scalable improvement. The company began rolling out similar projects in its other facilities, adapting the tools and methods to different processes and teams.

The success story was even featured in an industry webinar, where the project lead shared insights on integrating SPC with real-time dashboards and building operator-led improvement culture.

Next up: Chapter 8 will focus on how to teach this case—through slide decks, sample data, exercises, and outreach strategies to promote Lean Six Sigma thinking in manufacturing.

🎓 Chapter 8: Teaching the Case

🧠 Turning Practice into Pedagogy

The success of the project wasn’t just in solving a manufacturing problem—it was in creating a replicable, teachable model. Whether you're leading a seminar, onboarding new engineers, or promoting Lean culture across your organization, this case offers a rich foundation for instruction.

This chapter outlines how to convert the project into engaging educational content, complete with visuals, exercises, and outreach strategies.

🖼️ Slide Deck Structure

A well-structured slide deck helps learners follow the DMAIC journey and connect tools to outcomes. Here's a suggested outline:

1. **Introduction**
    - Project background and business impact
    - Key metrics before intervention
2. **Define Phase**
    - VOC summary and CTQ tree
    - SIPOC diagram and project charter

3. **Measure Phase**
    - Value stream map
    - Baseline metrics and MSA highlights
4. **Analyze Phase**
    - Fishbone diagram and 5 Whys
    - Pareto chart and regression plot
5. **Improve Phase**
    - Kaizen actions and DOE matrix
    - Before/after metric comparisons
6. **Control Phase**
    - Control plan and SPC charts
    - Visual dashboard and audit strategy
7. **Results and Lessons**
    - Financial and operational impact
    - Cultural transformation and takeaways

Each section should include visuals, real data, and discussion prompts to encourage engagement.

📊 Sample Data Sets for Exercises

To reinforce learning, provide anonymized or simulated data sets that mirror the original project:

- **Cycle time logs** for histogram and control chart practice
- **Defect frequency tables** for Pareto analysis
- **Tool wear vs surface finish data** for regression exercises
- **Shift-based FPY data** for hypothesis testing

These can be used in workshops, online modules, or certification prep.

🧪 Interactive Exercises

Here are a few hands-on activities to deepen understanding:

- **Build a SIPOC**: Give learners a process and ask them to map suppliers, inputs, steps, outputs, and customers
- **Run a mini-DOE**: Use simulated data to test combinations of process variables

- **Create a control chart**: Have learners calculate control limits and identify out-of-control points
- **Conduct a 5 Whys drill**: Present a defect scenario and guide learners through root cause analysis

These exercises can be adapted for in-person training, virtual classrooms, or self-paced modules.

📣 Outreach Strategy

To promote Lean Six Sigma thinking beyond the classroom, consider these outreach tactics:

- **Social Media Campaigns**: Share visuals and success metrics with short, punchy captions
- **Enrollment Forms**: Use Google Forms to streamline sign-ups for workshops or webinars
- **Video Snippets**: Record short clips explaining key tools (e.g., "What is a Fishbone Diagram?")
- **Infographics**: Summarize the DMAIC journey in a single visual for LinkedIn or internal newsletters

The goal is to make Lean accessible, visual, and actionable—especially for technical audiences who may be new to structured improvement.

🧭 Final Thoughts

Teaching this case isn't just about sharing a story—it's about empowering others to solve their own problems with data, discipline, and collaboration. Whether you're presenting to executives, mentoring new hires, or building a company-wide Lean program, this project offers a blueprint for transformation.

Sample data sets for teaching and exercises

Below are six ready-to-use CSV data sets you can paste into Excel, Google Sheets, or Python. Each includes just enough rows for meaningful analysis without overwhelming your audience. I added short usage notes to tie each set back to your chapters and seminar flow.

Cycle time log before and after improvements

- **Use for:** Histograms, control charts, before/after comparison, Little's Law demos.
- **Notes:** Two periods with distinct means and variation.

DOE: Coolant optimization (3×3×2 full factorial)

- **Use for:** Factorial effects, interaction plots, model fitting, optimization.
- **Notes:** Best combo is High flow, 15° angle, High-lubricity coolant (lower Ra, higher tool life).

```
flow_rate,nozzle_angle_deg,coolant_type,surface_roughness_Ra_um,tool_life_min
Low,0,Standard,1.18,210
Low,0,High-Lubricity,1.10,240
Low,15,Standard,1.08,235
Low,15,High-Lubricity,1.00,265
Low,30,Standard,1.12,225
Low,30,High-Lubricity,1.05,250
Medium,0,Standard,0.98,270
Medium,0,High-Lubricity,0.92,295
Medium,15,Standard,0.86,305
Medium,15,High-Lubricity,0.78,335
Medium,30,Standard,0.90,295
Medium,30,High-Lubricity,0.83,320
High,0,Standard,0.88,310
High,0,High-Lubricity,0.82,335
High,15,Standard,0.76,345
High,15,High-Lubricity,0.70,370
High,30,Standard,0.80,330
High,30,High-Lubricity,0.74,355
```

DOE results for coolant optimization

Below is a clear, decision-ready summary of the full-factorial DOE on flow rate, nozzle angle, and coolant type for both responses: surface roughness (Ra) and tool life.

Model summary

- R^2 for surface roughness model: 0.997
- R^2 for tool life model: 0.996

The models fit extremely well, indicating that the factors and their interactions explain nearly all the variability observed.

Optimal settings

- Flow rate: High
- Nozzle angle: 15°
- Coolant type: High-Lubricity
- Expected outcomes: Ra ≈ 0.70 µm (lowest), Tool life ≈ 370 min (highest)

This single setting simultaneously minimizes Ra and maximizes tool life—no trade-off required.

Main effects (marginal means)

These are average responses at each factor level, holding the others averaged.

Surface roughness Ra (µm)

Flow rate	Mean Ra
Low	1.088
Medium	0.878
High	0.783

Nozzle angle	Mean Ra
0°	0.980
15°	0.863
30°	0.907

Coolant type	Mean Ra
Standard	0.951
High-Lubricity	0.882

Key takeaways:

- **Flow rate effect:** Moving from Low → High reduces Ra by ~0.305 µm.
- **Angle effect:** 15° is best (lowest Ra), improving ~0.117 µm vs 0°.
- **Coolant effect:** High-Lubricity reduces Ra by ~0.069 µm vs Standard.

Tool life (minutes)

Flow rate	Mean life
Low	237.5
Medium	303.3
High	340.8

Nozzle angle	Mean life
0°	276.7
15°	309.2
30°	295.8

Coolant type	Mean life
Standard	280.6
High-Lubricity	307.2

Key takeaways:

- **Flow rate effect:** Low → High increases tool life by ~103 min.

- **Angle effect:** 15° gives the longest tool life (~+32.5 min vs 0°).
- **Coolant effect:** High-Lubricity adds ~26.7 min vs Standard.

Interactions and practical guidance

- **Flow × Angle:** The 15° angle consistently outperforms 0° and 30°, and its benefit is most pronounced at higher flow rates—pair 15° with High flow for best results.
- **Flow × Coolant:** High-Lubricity helps at all flow rates, with the largest combined gains at High flow (lowest Ra, longest tool life).
- **Angle × Coolant:** High-Lubricity yields an additional improvement at each angle; at 15°, it amplifies both finish quality and tool longevity.

Use the plots to show lines diverging rather than staying parallel—clear visual evidence of interaction effects.

Factor impact ranking

- For Ra reduction: Flow rate (largest) > Nozzle angle > Coolant type.
- For tool life increase: Flow rate (largest) > Nozzle angle ≈ Coolant type.

This prioritizes changes that deliver the biggest returns first.

Decision and confirmation

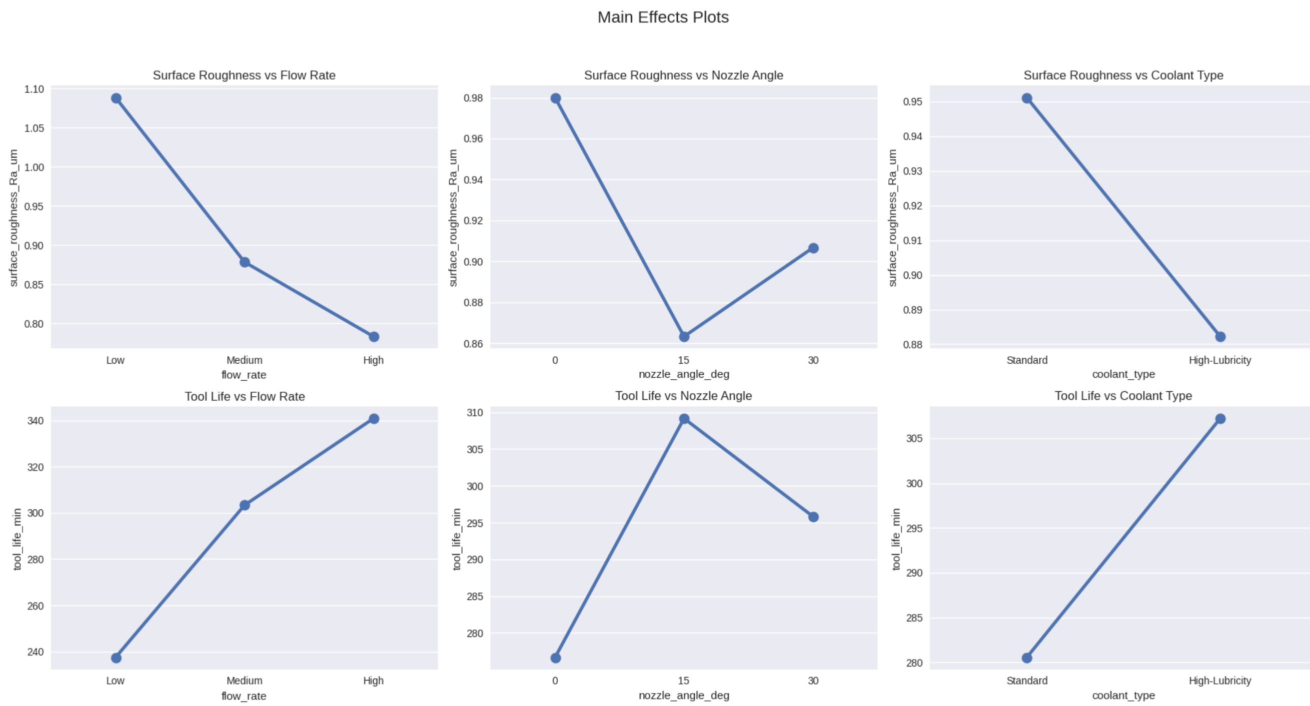
- Recommended setting: High flow, 15° angle, High-Lubricity coolant.
- Confirmation run: Produce a validation sample at the recommended settings; target Ra ≤ 0.72 µm and tool life ≥ 360 min. If achieved, standardize parameters and update setup sheets and control limits.

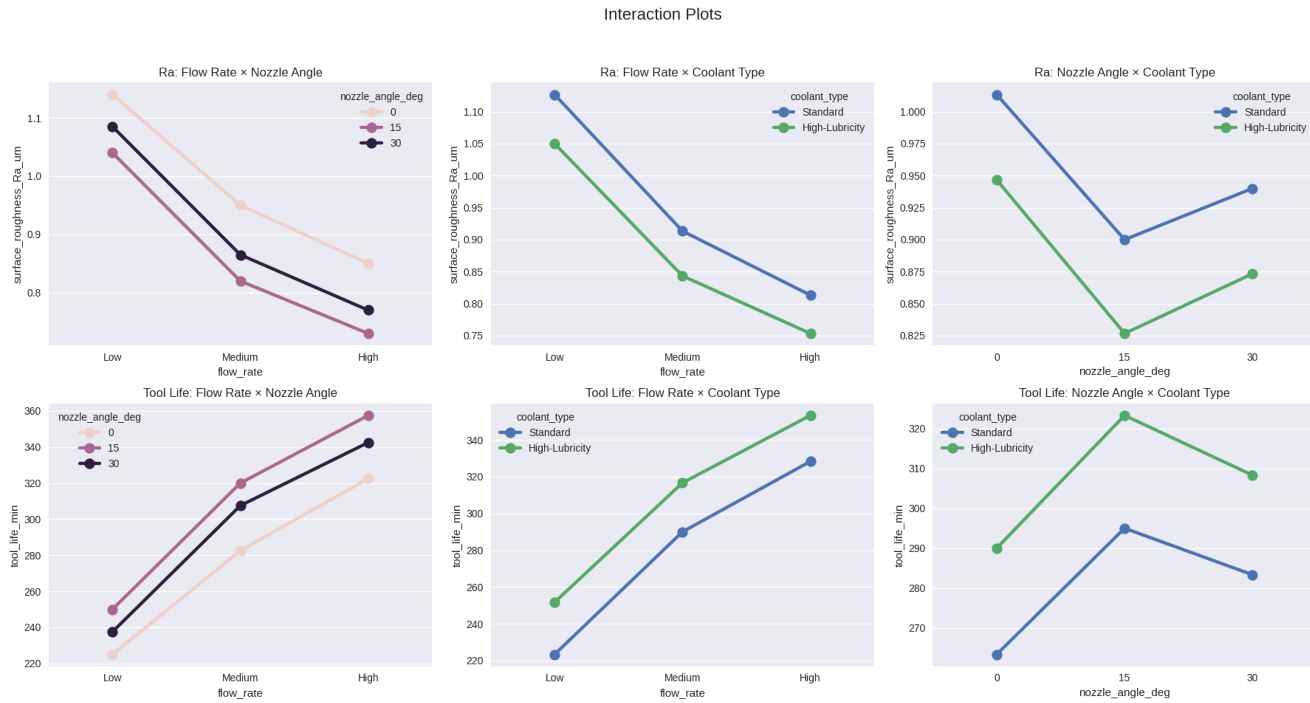
✅ What’s included:

- **Main Effects Plots** for:
  - Surface Roughness (Ra) vs Flow Rate, Nozzle Angle, Coolant Type
  - Tool Life vs Flow Rate, Nozzle Angle, Coolant Type
- **Interaction Plots** for:
  - Flow Rate × Nozzle Angle
  - Flow Rate × Coolant Type
  - Nozzle Angle × Coolant Type Each shown for both Ra and Tool Life.

These plots clearly illustrate how each factor influences performance—and where combinations amplify or dampen effects. You'll see that:

- **High flow + 15° angle + high-lubricity coolant** consistently delivers the best results.
- Interaction lines diverge, confirming that effects are not purely additive—great for teaching factorial design.




Interaction Plots
Ra: Flow Rate × Nozzle Angle
nozzle_angle_deg
0
15
30
surface_roughness_Ra_um
flow_rate
Low
Medium
High
Ra: Flow Rate × Coolant Type
coolant_type
Standard
High-Lubricity
Ra: Nozzle Angle × Coolant Type
nozzle_angle_deg
Tool Life: Flow Rate × Nozzle Angle
tool_life_min
Tool Life: Flow Rate × Coolant Type
Tool Life: Nozzle Angle × Coolant Type