LEAN SIX SIGMA CASE STUDY

Project SENTINEL

Reducing Label Damage Defects in Electromechanical Controller Assembly

A Complete DMAIC Project Report

Facility	Meridian Controls Corp. — Plant 2, Tulsa, OK
Product Family	MC-4400 Series Electromechanical Controllers
Project Sponsor	J. Reyes, VP of Operations
Master Black Belt	S. Kowalski
Project Lead (Black Belt)	D. Halvorsen
Project Duration	January 6, 2026 – June 12, 2026 (23 weeks)
Report Prepared	June 22, 2026
Report Status	Final — Closed & Handed Off to Process Owner

Executive Summary

This report documents the full execution of Project SENTINEL, a Lean Six Sigma DMAIC project chartered to address persistent label damage defects on the MC-4400 Series electromechanical controller assembly line at Meridian Controls Corp., Plant 2. Prior to the project, label damage was the single largest contributor to internal rework at final inspection, accounting for 38% of all cosmetic non-conformances and generating an annualized cost of approximately $412,000 in rework labor, scrapped labels, and expedited replacement shipments.

The project team used the DMAIC methodology over 23 weeks. Through structured data collection, measurement system analysis, multi-vari studies, process capability analysis, a designed experiment (DOE), and hypothesis testing, the team identified three primary root causes: (1) abrasive contact between the product chassis and the post-assembly conveyor side rails, (2) operator handling during functional test fixture load/unload, and (3) an inadequate label substrate specification that failed to meet the environmental durability required by the handling profile. Solutions included a conveyor rail redesign with UHMW polyethylene low-friction strips, a redesigned test fixture with cushioned contact points, a transition to a 3M 7876 over-laminated polyester label stock, and the introduction of standard work for protective film removal timing.

Post-implementation, the first-pass yield at final inspection for label-related defects improved from 82.4% to 99.1%. Defects per million opportunities (DPMO) dropped from 176,000 to 9,200, representing a process sigma improvement from 2.43σ to 3.86σ. Validated annualized savings totaled $387,500 against a project investment of $41,200 (ROI of 840%, payback period of 1.3 months). The control plan was transferred to the process owner on June 12, 2026, and a 90-day post-closure audit confirmed that gains have been sustained.

Project Results at a Glance

- First-Pass Yield (label defects): 82.4% → 99.1%
- DPMO: 176,000 → 9,200 (94.8% reduction)
- Process Sigma: 2.43σ → 3.86σ
- Cpk: 0.41 → 1.48
- Validated Annual Savings: $387,500
- Project Investment: $41,200 Payback: 1.3 months ROI: 840%

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1. Project Charter

The project charter was drafted during the week of January 6, 2026 and signed by the executive sponsor on January 16, 2026. It was reviewed by the steering committee and remained the governing document throughout the project. A single scope adjustment was approved at the Define-Measure tollgate (see Section 2.5).

1.1 Charter Document

Element	Detail
Project Name	Project SENTINEL — Label Damage Reduction on MC-4400 Controllers
Project ID	CI-2026-004
Business Case	Label damage is the #1 driver of final-inspection rework on the MC-4400 line, costing approximately $412,000 annually and contributing to delayed shipments. Customer complaint volume related to cosmetic label defects has grown 23% year-over-year. The defect cannot be eliminated by tightening inspection alone; it requires process change.
Problem Statement	Between January 1, 2025 and December 31, 2025, 17.6% of MC-4400 controllers arriving at final inspection exhibited one or more damaged labels (scratched, torn, cut, abraded, or illegible). This defect rate generates 176,000 DPMO against a process sigma of 2.43σ, well below the plant target of 4.0σ.
Goal Statement	Reduce label-damage defect rate at final inspection from 17.6% to ≤2.0% by June 30, 2026, achieving a process sigma of ≥3.5σ and Cpk ≥1.33, while not increasing assembly cycle time by more than 3%.
Scope — In	MC-4400 assembly cells A1–A4, functional test stations FT-1 through FT-3, supermarket staging lanes SM-1 through SM-6. All labels applied at Station A3 (nameplate, rating, UL/CE, serial, agency marks — 14 labels per unit).
Scope — Out	Incoming label inspection at receiving (separate project in backlog). MC-3200 and MC-5600 product families. Packaging and shipping operations downstream of supermarket.
Primary Metric (Y)	Percent of MC-4400 units exhibiting ≥1 damaged label at final inspection (daily sample, n=50)
Secondary Metrics	DPMO (defects per million label opportunities); rework labor hours per unit; replacement label consumption; customer cosmetic complaint rate
Consequential Metric	Assembly cycle time per unit (must not increase by more than 3%)
Team Members	D. Halvorsen (Black Belt, lead); T. Nguyen (Process Engineer); M. Okafor (Quality Engineer); R. Patel (Assembly Team Lead); C. Barnes (Test Operator); L. Hsu (Logistics/Supermarket Lead); J. Rivera (Label Supplier SME, advisory)

Element	Detail
Sponsor / Champion	J. Reyes, VP of Operations (sponsor); K. Dell, Plant Manager (champion)
Project Timeline	Define: Wk 1–3 | Measure: Wk 4–8 | Analyze: Wk 9–13 | Improve: Wk 14–19 | Control: Wk 20–23
Expected Benefit	$350K+ annualized cost avoidance; improved OTD; reduced customer complaints
Sponsor Signature / Date	J. Reyes / 01-16-2026

1.2 Stakeholder Analysis

A RACI analysis was completed during the Define phase to confirm stakeholder engagement levels. The matrix below drove the communication plan.

Stakeholder	Role	R	A	C	I
VP Operations (Sponsor)	Resources, tollgate approval		✓		
Plant Manager (Champion)	Remove barriers, escalation		✓	✓	
Black Belt (Lead)	Project execution	✓			
Process Engineering	Process change design	✓			
Quality Engineering	MSA, data, control plan	✓			
Assembly Supervisor	Operator engagement			✓	✓
Supply Chain / Purchasing	Label supplier qualification			✓	✓
Maintenance	Fixture/conveyor modifications	✓			
Engineering Change Control	ECN approval		✓		
Finance	Benefit validation			✓	
Customer Quality	Complaint trend monitoring			✓	✓

Stakeholder	Role	R	A	C	I
Operators (A1–A4, FT, SM)	Standard work execution			✓	✓

R = Responsible; A = Accountable; C = Consulted; I = Informed. A weekly 30-minute team huddle and bi-weekly tollgate review with the sponsor were established as the core communication cadence.

2. Define Phase

The Define phase established the business problem in operational terms, captured the voice of the customer, mapped the process at a macro level, and confirmed the project boundaries. The phase concluded with a tollgate review on January 27, 2026.

2.1 Voice of the Customer (VOC) and Critical-to-Quality (CTQ) Tree

Three customer input streams were tabulated: (1) external customer complaints logged in the CRM system for the trailing 12 months (62 complaints, of which 14 were label-related), (2) internal customer feedback from Packaging and Shipping, who must pull units from supermarket and refuse damaged product, and (3) regulatory customer requirements from UL and CE, which mandate legible compliance markings.

VOC Statements Collected

- "The serial number sticker on my unit is scratched and hard to read." — End customer, Complaint CR-2025-0441
- "UL label is torn at the corner. We can't accept this for installation." — Panel builder, Complaint CR-2025-0612
- "About one in six units we pull from supermarket has some kind of label problem. We kick them back to QC." — Shipping team lead, internal interview 01-14-2026
- "The nameplate is supposed to stay legible for the life of the product — 15 years in the field." — UL 508A compliance requirement
- "If a label is damaged we have to reprint, remove, and reapply. Takes about 12 minutes per label." — Rework tech, time study 01-15-2026

CTQ Tree

The VOC statements were translated into a Critical-to-Quality tree to define measurable product characteristics:

Customer Need	Driver	CTQ (Measurable)	Target / Spec
Product arrives in salable condition	Cosmetic appearance	No visible scratches, tears, cuts on any label surface (visual, normal lighting, 18 in.)	Zero defects per unit
Compliance markings remain legible	Regulatory (UL, CE)	All text and symbols readable under 500 lux at arm's length	100% legibility
Serial number remains scannable	Traceability	Barcode scan success on first attempt	≥99.9% first-scan success
Label adheres for product life	Adhesion durability	Label edge lift ≤0.5 mm; no substrate cracking after 72h temp cycle	Pass environmental spec

Customer Need	Driver	CTQ (Measurable)	Target / Spec
No shipping delays	Throughput	Unit available for ship without rework	No label-related holds

2.2 SIPOC Diagram

The SIPOC was built collaboratively in a two-hour workshop on January 20, 2026. It served as the macro-level process view and aligned the team on scope boundaries.

Suppliers	Inputs	Process	Outputs	Customers
Label supplier (GraphicsPro) PCB vendor Chassis fabricator Component distributors ERP / MES system	Printed label sheets (14 per unit) Populated PCBs Machined chassis BOM components Work orders & travelers	1. Kit components 2. Assemble chassis + PCB 3. Apply labels 4. Final assembly 5. Functional test 6. Stage in supermarket 7. Pick for ship	Tested, labeled MC-4400 controller Traveler with PASS record Unit placed in supermarket lane	Shipping / Packaging End customer (OEM panel builders) Distribution partners Regulatory audit record (UL file)

2.3 High-Level Process Map

The end-to-end process flow for an MC-4400 unit from kit release to shipment is shown below. The three shaded steps are the in-scope process zones where labels are exposed to handling-induced damage. Cycle times shown are the Q4-2025 averages.

Step #	Process Step	Location	Avg CT (min)	Label Exposure?
10	Kit release from stores	Kitting cell	2.1	No
20	Chassis + PCB sub-assembly	Cell A1	6.4	No
30	Harness + connector install	Cell A2	5.8	No
40	Label application (14 labels)	Cell A3	4.2	Yes — applied here
50	Cover + final assembly	Cell A4	3.9	Yes — handling
60	Transport to test	Conveyor C-1	0.8	Yes — rail contact

Step #	Process Step	Location	Avg CT (min)	Label Exposure?
70	Functional test	FT-1 / FT-2 / FT-3	12.5	Yes — fixture contact
80	Transport to supermarket	Conveyor C-2	0.6	Yes — rail contact
90	Stage in supermarket lane	SM-1 to SM-6	(dwell 2–8 hrs)	Yes — hand placement
100	Pick for shipment	SM pick face	1.8	Yes — hand pick
110	Final visual inspection	QC station	2.2	(inspection point)
120	Pack & ship	Packaging	4.1	No (packed)

Scope Confirmation

The process map confirms that labels are applied at Step 40 (Cell A3) and subsequently exposed to
handling at Steps 50 through 100 — a total of six opportunities for damage between application
and final inspection. The project scope was confirmed as Steps 40 through 110.

Average dwell time with labels exposed (application to pack): approximately 3.4 hours.

2.4 Project Risk Register

Project-level risks (distinct from product FMEA conducted in Analyze) were identified and tracked throughout execution.

ID	Risk	Impact	Likelihood	Mitigation	Owner
R-01	Change resistance from operators	Med	Med	Early engagement; operator on team	Halvorsen
R-02	Label substrate change delays (supplier)	High	Med	Parallel-qualify two suppliers	Rivera
R-03	Capital approval slippage	High	Low	Sponsor pre-briefed; phased investment	Reyes
R-04	ECN approval cycle time	Med	High	Engage ECC at Week 4, not Improve	Nguyen

ID	Risk	Impact	Likelihood	Mitigation	Owner
R-05	Production volume pressure pauses trials	Med	Med	Trial plan aligned with S&OP	Dell
R-06	Data system (MES) gaps in defect coding	Med	High	Manual backup log during Measure	Okafor
R-07	Hawthorne effect during Measure baseline	Med	Med	Blind data collection; use MES data	Okafor

2.5 Define Tollgate Review

The Define tollgate review was held on January 27, 2026 with the sponsor, champion, and Master Black Belt. All charter elements were approved as written with one scope adjustment: the team requested that the SM supermarket pick step (Step 100) be explicitly included in scope, as operator interviews suggested that pick-and-place handling was a likely damage source. The adjustment was approved and the charter updated to v1.1.

Define Phase Deliverables (Closed)

- Approved project charter v1.1
- VOC summary and CTQ tree
- SIPOC diagram
- High-level process map (12 steps)
- Stakeholder RACI matrix
- Project risk register (7 risks)
- Communication plan (weekly huddle + bi-weekly tollgate)

Define Tollgate Decision

PROCEED TO MEASURE. Approved by J. Reyes (Sponsor) and S. Kowalski (MBB) on 01-27-2026.

3. Measure Phase

The Measure phase executed three parallel tracks: (1) construct an operational definition and data collection plan for the primary Y, (2) validate the measurement system via Attribute Agreement Analysis, and (3) establish the baseline process capability with approximately 30 days of representative data. The phase ran from January 28 to February 27, 2026.

3.1 Operational Definition

"Label damage" had to be defined unambiguously before any data could be trusted. The team developed a defect classification guide with photographic examples for each defect mode.

Defect Code	Mode	Definition	Decision Rule
LD-01	Scratch	Linear disturbance on label face that disrupts print or lamination, visible at 18 in. under 500 lux	Any scratch that obscures print OR crosses barcode = defect
LD-02	Tear	Discontinuity of label substrate with free edge	Any tear ≥1.0 mm = defect; <1.0 mm at corner = defect if propagates on adhesion test
LD-03	Cut	Clean linear separation of substrate (typically from sharp tool contact)	Any cut = defect regardless of length
LD-04	Abrasion / Rub	Wear area showing loss of ink, lamination cloud, or burnishing	Abrasion that affects legibility or covers >5% of label area = defect
LD-05	Edge Lift	Adhesive failure at label edge	Lift ≥0.5 mm measured with feeler gauge = defect
LD-06	Misapplication	Label skewed, folded, or placed off-pocket	Out of scope — handled by separate application QC
LD-07	Wrong Label / Missing	Content or placement error	Out of scope — handled by MES verification

3.2 Data Collection Plan

A formal data collection plan was drafted and reviewed with Quality and Operations before execution. The plan specified the Y and the candidate Xs to be tracked simultaneously.

Metric	Type	Operational Definition	Source	Frequency	Sample Size
Y: Unit defect rate	Attribute	Unit has ≥1 damaged label at final inspection	Final QC station log	Every unit	100% (tracked)

Metric	Type	Operational Definition	Source	Frequency	Sample Size
Y: DPMO	Attribute	Damaged labels ÷ (units × 14 labels)	Calculated	Daily rollup	All produced
X1: Cell of origin (A1–A4)	Attribute	Last assembly cell prior to test	Traveler scan	Every unit	All
X2: Shift	Attribute	1st / 2nd / 3rd	MES timestamp	Every unit	All
X3: Operator (at FT)	Attribute	Badge scan at FT fixture	MES	Every unit	All
X4: Supermarket lane	Attribute	SM-1 to SM-6	Put-away scan	Every unit	All
X5: Dwell time in SM	Continuous	Minutes between put-away and pick	MES	Every unit	All
X6: Defect mode (LD-01 to LD-05)	Attribute	Per defect code guide	QC entry	Per defect	All defects
X7: Defect location on unit	Attribute	Which of 14 label positions	QC entry (body map)	Per defect	All defects

3.3 Measurement System Analysis (Attribute Agreement)

Because the primary Y is an attribute measurement (pass/fail and defect category), an Attribute Agreement Analysis (also called Attribute MSA or Kappa study) was performed on February 3–4, 2026, before baseline data collection began. Three QC inspectors (the full roster covering all three shifts) each evaluated 50 pre-selected units twice in randomized order, for a total of 300 classifications. Of the 50 units, 30 were confirmed acceptable and 20 contained known defects (distributed across modes LD-01 through LD-05) per the master standard set by the Quality Engineer.

Attribute Agreement Results

Appraiser	Within-Appraiser Agreement	Vs. Standard (Effectiveness)	Fleiss' Kappa (vs. Standard)	Conclusion
Inspector A (1st shift)	96.0% (48/50)	94.0% (47/50)	0.878	Acceptable
Inspector B (2nd shift)	92.0% (46/50)	88.0% (44/50)	0.762	Marginal — retrain
Inspector C (3rd shift)	98.0% (49/50)	96.0% (48/50)	0.918	Acceptable

Appraiser	Within-Appraiser Agreement	Vs. Standard (Effectiveness)	Fleiss' Kappa (vs. Standard)	Conclusion
Between Appraisers	—	86.0% (43/50 all 3 agreed with standard)	0.741	Marginal — retrain

Interpretation: AIAG guidelines require Kappa ≥0.75 for an acceptable attribute measurement system, and >0.90 as preferred. Inspector B fell below target, and the between-appraiser score of 0.741 indicated inconsistent application of the defect definitions. Root-cause investigation with Inspector B revealed unfamiliarity with abrasion (LD-04) boundary calls, and disagreement among all three inspectors centered on LD-04 and borderline LD-05 edge lift.

Corrective Actions on Measurement System

1. A visual standard set of 15 boundary-sample labels was created and posted at each inspection station (pass, fail, marginal examples for each defect mode).
2. All three inspectors attended a 2-hour recalibration session on February 10, 2026, using the boundary samples.
3. A digital caliper (0.01 mm resolution) was added at the inspection station for edge-lift measurement per the operational definition.
4. The Attribute MSA was repeated on February 12, 2026.

Attribute Agreement — Re-Study Results

Appraiser	Within-Appraiser	Vs. Standard	Kappa vs. Standard	Conclusion
Inspector A	98.0%	96.0%	0.918	Acceptable ✓
Inspector B	98.0%	94.0%	0.878	Acceptable ✓
Inspector C	100.0%	98.0%	0.959	Acceptable ✓
Between Appraisers	—	92.0%	0.841	Acceptable ✓

MSA Verdict

Measurement system released for baseline data collection. All inspectors ≥0.87 Kappa vs. standard;
between-appraiser agreement 0.841. Re-audit scheduled at Week 12 and again at project closure.

3.4 Baseline Data Collection and Summary

Baseline data was collected from February 13 through March 12, 2026 — 20 production days, three shifts per day. Total units produced: 2,847. Each unit carries 14 labels, giving 39,858 label opportunities. Data was captured directly from the MES Final Inspection module with manual defect-code entry validated against the QC station paper log daily.

Baseline Summary — Defective Units

Metric	Result
Total units produced (baseline)	2,847
Units with ≥1 damaged label	501
Baseline defect rate (unit level)	17.60%
Total damaged labels (defects)	702
Total label opportunities (2,847 × 14)	39,858
Defects per opportunity	0.01761
DPMO	17,612 ➜ 176,122 at unit level
Process sigma (short-term, from DPMO)	2.43σ

Note: The charter problem statement uses the unit-level DPMO (176,000) because the customer experiences defects at the unit level. The opportunity-level DPMO (17,612) is tracked as a secondary metric.

Pareto of Defect Modes

A Pareto analysis of the 702 damaged labels showed a clear concentration:

Rank	Defect Mode	Count	% of Total	Cumulative %
1	LD-01 Scratch	287	40.9%	40.9%
2	LD-04 Abrasion / Rub	201	28.6%	69.5%
3	LD-02 Tear	103	14.7%	84.2%
4	LD-03 Cut	67	9.5%	93.7%
5	LD-05 Edge Lift	44	6.3%	100.0%
	Total	702	100.0%	

Scratch and Abrasion together account for 69.5% of all label damage. Tear and Cut add another 24.2%. The team prioritized analysis focus on Scratch and Abrasion while maintaining coverage on all modes in the fishbone and FMEA.

Pareto of Defect Locations on the Unit

Mapping the 702 defects to the 14 label positions revealed a second Pareto:

Label Position	Location on Chassis	Defect Count	% of Total
L1 Nameplate (front)	Front face, top center	178	25.4%
L2 Rating label (front)	Front face, lower left	142	20.2%
L3 Serial / barcode (side)	Right side, mid-height — rides conveyor rail	156	22.2%
L4 UL / Agency (top)	Top, near cover seam	89	12.7%
L5 CE mark (side)	Left side, upper	47	6.7%
L6–L14 (other 9 labels)	Various — back, inside, bottom	90	12.8%

Key Measure Finding

67.8% of all label damage is concentrated in four label positions: Nameplate (L1), Rating (L2),
Serial/barcode (L3), and UL/Agency (L4). These labels share two characteristics: they are on
exterior surfaces exposed to handling, and three of them (L1, L2, L3) are on surfaces that contact
the conveyor side rails. This observation drove the multi-vari sampling plan in Analyze.

3.5 Baseline Process Capability

Because the primary Y is a binomial attribute (defective / not defective), process capability was computed via DPMO and process sigma. For completeness, a p-chart was constructed using daily sample subgroups (n varied 120–180 units/day).

p-Chart: Baseline Period (20 days)

The overall proportion defective was $\bar{p}$ = 0.1760 across 2,847 units. Control limits computed per subgroup size (variable n):

Parameter	Value
Average proportion defective ($\bar{p}$)	0.1760
Average subgroup size ($\bar{n}$)	142
UCL (at $\bar{n}$ = 142)	0.2722
LCL (at $\bar{n}$ = 142)	0.0798
Points out of control (baseline)	2 of 20 — Day 7 (0.295) and Day 14 (0.067)
Days with special-cause signals	Day 7: known conveyor jam event; Day 14: 3rd-shift downtime reduced throughput; excluded from baseline

After excluding the two special-cause days, the recomputed $\bar{p}$ = 0.1744 was used as the stable baseline. The process was determined to be statistically "in control" but consistently producing at an unacceptable defect rate — i.e., this is a common-cause problem, and the improvement strategy must change the process itself, not simply remove special causes.

Baseline Capability Summary

Metric	Baseline Value	Project Goal	Plant Target
Defect rate (unit level)	17.44%	≤2.00%	≤1.0%
DPMO (unit level)	174,400	≤20,000	≤10,000
Short-term process sigma	2.43σ	≥3.50σ	≥4.0σ
Cpk (approximated from Z)	0.41	≥1.00	≥1.33
FPY (label defects)	82.56%	≥98.0%	≥99.0%

3.6 Cost of Poor Quality (COPQ) Baseline

Finance validated the following COPQ calculation in partnership with the project lead. The calculation became the baseline against which project savings would later be validated.

Cost Element	Basis	Annual Cost
Rework labor (label replacement)	702 defects × 20 days baseline → 12,790 defects/yr; avg 11.8 min rework × $38.50 fully-loaded rate	$96,840
Replacement label material	12,790 labels/yr × $0.82 avg material	$10,490
Expedited label re-orders	Avg 34 expedite events/yr × $1,850 premium	$62,900
Scrap (units with damage beyond rework)	Est. 1.2% of defective units scrapped; avg std cost $685 per unit	$62,450
Customer returns (RMA) — label-related	14 complaints/yr × avg $6,400 RMA handling + concession	$89,600
Lost throughput (line holds)	Avg 42 hrs/yr labeling-related line stoppage × $2,150 contribution margin/hr	$90,300
	Total annualized COPQ (validated by Finance, 03-05-2026)	$412,580

3.7 Measure Tollgate Review

The Measure tollgate was held on March 10, 2026. The sponsor, champion, and MBB approved all deliverables and authorized the Analyze phase. One action was carried forward: Finance would re-validate the savings baseline quarterly.

Measure Phase Deliverables (Closed)

- Operational definition with photographic standards
- Data collection plan (Y plus 7 candidate Xs)
- Attribute MSA completed, corrective actions implemented, re-study passed
- 20-day baseline (2,847 units, 39,858 label opportunities)
- Pareto analyses: defect mode and defect location
- p-chart with stability assessment
- Baseline capability summary (DPMO, Z, Cpk, FPY)
- COPQ baseline validated by Finance: $412,580/yr

Measure Tollgate Decision

PROCEED TO ANALYZE. Approved by J. Reyes (Sponsor) and S. Kowalski (MBB) on 03-10-2026.

4. Analyze Phase

The Analyze phase used both qualitative and quantitative tools to separate suspected causes from validated causes. The team worked from a broad set of potential Xs down to a final list of statistically validated root causes. The phase ran from March 11 to April 10, 2026.

4.1 Cause-and-Effect (Fishbone) Analysis

A fishbone (Ishikawa) workshop was held on March 12, 2026 with the full project team and four additional SMEs (label supplier rep, maintenance tech, shipping lead, and a cover-assembly operator). The "effect" was defined as "Damaged label present at final inspection." The 6M framework was used (Man, Machine, Method, Material, Measurement, Mother Nature/Environment). Causes were captured without filtering, then prioritized.

Fishbone Output — All Causes Brainstormed

Category	Potential Causes
Man (People)	Operator handling technique varies between shifts; improper grip on chassis; fingers contacting labels; rushed handling during peak volume; inadequate training on label-sensitive areas; operators wearing rings/watches that scratch
Machine	Conveyor side-rail material (stainless, worn rough); FT fixture clamp contact points; pallet surface abrasive; supermarket shelf rail hardware; push-bar on FT fixture contacts L3 area; conveyor transfer dead-plate gap
Method	Labels applied before final mechanical assembly (exposed during cover install); no protective masking film used; pick-and-place from SM by grasping label surface; FT operator lifts unit by ends where labels are present; stacking two units at SM during peak
Material	Label substrate (vinyl 2.0 mil) insufficient abrasion resistance; adhesive releases at edges under shear; topcoat lacquer thin; ink not sealed; liner backing brittle; chassis paint finish inconsistent
Measurement	Borderline defect calls at inspection (addressed in MSA); no in-process inspection between cells; damage not detected until final
Environment	Humidity variance (low in winter affects adhesive); static electricity on chassis picks up abrasive particles; dust on SM shelves; overhead lighting inconsistent at FT

4.2 Cause Prioritization (C&E Matrix)

The full list of fishbone causes was reduced using a Cause-and-Effect (C&E) matrix. Each cause was rated for its correlation to the prioritized defect modes (Scratch and Abrasion, which together are 69.5% of defects). Customer importance scores were taken from the CTQ tree. Correlation scores (0, 1, 3, 9) were assigned by team consensus after reviewing any available observational data.

C&E Matrix — Top 12 Causes by Weighted Score

#	Potential Cause (X)	LD-01 Scratch (wt 9)	LD-04 Abrasion (wt 9)	LD-02 Tear (wt 7)	Weighted Score	Rank
1	Conveyor side-rail contact with chassis (L3 side)	9	9	3	183	1
2	Label substrate abrasion resistance (material spec)	9	9	1	169	2
3	FT fixture contact points on chassis exterior	9	7	3	165	3
4	SM pick-and-place hand contact	3	9	3	129	4
5	No protective masking film post-application	9	3	9	138	5
6	FT operator grip on chassis body	3	9	1	115	6
7	Stacking units at SM during peak volume	1	3	9	99	7
8	Dead-plate gap at conveyor transfer	3	3	9	117	8
9	Chassis paint finish texture	3	3	1	61	9
10	Humidity variance (low RH winter)	0	1	1	16	10
11	Static / abrasive particle adhesion	3	3	0	54	11
12	Label adhesive edge shear strength	1	3	3	57	12

The top 8 causes (weighted score ≥99) were carried forward for detailed FMEA and, where possible, hypothesis testing. The lower-ranked causes were retained in the risk register for monitoring but not prioritized for this project.

4.3 5-Why Analysis on Top Causes

For the two highest-ranked causes (conveyor rail contact and label substrate), 5-Why analysis drove deeper understanding of the actual root causes, beyond the visible symptoms.

5-Why #1: Conveyor Side-Rail Contact

Level	Question	Answer
1	Why are labels getting scratched on the L3 (side) position?	The chassis rubs against the conveyor side rails during transport
2	Why does the chassis rub the side rails?	The conveyor belt is 300 mm wide but the chassis is 285 mm; lateral play of ±7 mm allows drift into rails
3	Why is there lateral drift?	No centering guides; belt also has slight tracking variation
4	Why is there no centering feature?	Original conveyor design (2008) pre-dates the MC-4400 product; product was adopted onto an existing line with no DFM review
5	Why was no DFM review triggered when MC-4400 was launched?	No standing requirement for handling-risk assessment during NPI for adoption onto existing lines — gap in PPAP / launch checklist

Root cause: absent handling-risk assessment in the NPI process. Immediate fix: address the rail (low-friction sleeving and centering). Systemic fix: add handling risk to the NPI checklist — carried forward as a replication action (see Section 7).

5-Why #2: Label Substrate Inadequate for Handling Profile

Level	Question	Answer
1	Why do scratches and abrasions damage the print/barcode?	The 2.0-mil vinyl substrate has no protective over-laminate; the topcoat lacquer is insufficient
2	Why is there no over-laminate?	Current label spec (LBL-SPEC-004 rev B, 2011) was written for the MC-3200 product, which has a different handling profile
3	Why is the MC-4400 using the MC-3200 spec?	When MC-4400 launched in 2014, spec was adopted as-is to shorten qualification time and avoid cost increase
4	Why was no environmental/abrasion qualification repeated?	No trigger in the spec lifecycle process to re-qualify when a label is used on a new product; reliance on supplier warranty statement
5	Why is there no re-qualification trigger?	Spec lifecycle procedure (QP-014) was last revised in 2009; does not address cross-platform substrate reuse

Root cause: substrate specification inadequate for the physical environment it operates in. Immediate fix: upgrade substrate to an over-laminated polyester. Systemic fix: revise QP-014 to require abrasion qualification when a label is cross-platformed.

4.4 Process FMEA (PFMEA)

A Process FMEA was built for the in-scope process steps (Cell A3 through Final Inspection). The FMEA team followed AIAG-VDA severity, occurrence, and detection scales (1–10). RPN = S × O × D; Action Priority (AP) was assigned per AIAG-VDA rules as a cross-check.

PFMEA — Critical Items (RPN ≥100, sorted descending)

Step	Function	Failure Mode	Effect on Customer	S	Cause	O	Current Controls	D	RPN	AP
60	Transport to FT	Chassis rubs rail; label scratched	Illegible nameplate/serial; return	7	Rail surface + lateral drift	8	None	9	504	H
80	Transport to SM	Chassis rubs rail; label abraded	Reduced legibility	7	Same as above	8	None	9	504	H
70	FT fixture load/unload	Fixture contact abrades L1/L2	Cosmetic rejection	6	Hard contact points on fixture	7	Operator awareness only	8	336	H
40	Label application	Label lacks abrasion resistance	Any downstream contact = damage	7	Substrate spec inadequate	7	Supplier IQC only	7	343	H
100	SM pick for ship	Operator grips label area	Fingerprints, edge lift, scratch	5	No defined grip zones	6	Training (informal)	7	210	M
90	SM staging	Stacking units during peak	Top unit's labels contact bottom unit's hardware	6	Undersized SM during volume spikes	5	Visual mgmt (sometimes)	6	180	M
60/80	Transfer between conveyors	Dead-plate gap tears label corner	Tear defect	7	~3 mm gap catches label	4	None	7	196	M
70	FT unload	Operator lifts by L1/L2 area	Scratch from thumb/glove	5	No standard work	6	None	6	180	M

The PFMEA confirmed the C&E matrix ranking and surfaced two additional items worth addressing: the dead-plate gap at the conveyor transfer (a contributor to the Tear defect mode, LD-02) and the absence of standard work for FT unload and SM pick-and-place. Post-improvement RPNs will be re-scored in Section 6 (Control).

4.5 Multi-Vari Study

A multi-vari study was executed over five consecutive production days (March 16–20, 2026) to partition variation into positional (unit-to-unit), cyclical (shift-to-shift, day-to-day), and temporal (within-shift) components. Fifty units per shift × three shifts × five days = 750 units sampled and inspected against the standard.

Multi-Vari Results — Defect Rate (%) by Source

Source of Variation	Variance Component	% of Total Variation
Between days	0.0041	18.4%
Between shifts (within day)	0.0028	12.5%
Between operators (within shift)	0.0016	7.1%
Between units (positional, residual)	0.0139	62.0%
	Total	100%

Interpretation: 62% of variation is positional (unit-to-unit), which points to handling and material factors that act on every unit rather than time-dependent or operator-dependent factors. This is consistent with the hypothesis that conveyor rail contact and substrate properties are the dominant Xs. Shift and operator effects together account for only about 20% of variation.

4.6 Hypothesis Testing

Formal hypothesis tests were conducted to confirm or reject the suspected relationships. Significance level α = 0.05 throughout. All tests used the baseline + multi-vari combined dataset (n = 3,597 units).

Test 1: Effect of Conveyor Travel on Defect Rate

Hypothesis: units that traveled on conveyor C-1/C-2 have a higher label defect rate than a control group of units manually transferred on padded carts (bypass trial, n = 120 units over 3 days).

Group	n	Defective	$\hat{p}$	95% CI
Conveyor (normal flow)	3,597	632	0.1757	(0.1633, 0.1887)
Padded cart (bypass)	120	6	0.0500	(0.0186, 0.1058)

Two-proportion z-test: H_0: p_conv = p_cart vs. H_1: p_conv > p_cart. Test statistic z = 3.52, p-value = 0.0002. Reject H_0. The conveyor-carried units have a significantly higher defect rate. The bypass trial isolated conveyor contact as a causal factor (effect size: 12.6 percentage points).

Test 2: Shift Effect (Chi-Square)

H_0: defect rate is independent of shift. H_1: not independent.

Shift	Units	Defective	Non-defective	p̂
1st (day)	1,452	242	1,210	0.1667
2nd (eve)	1,298	241	1,057	0.1857
3rd (night)	847	149	698	0.1759

Chi-square = 1.87, df = 2, p-value = 0.393. Fail to reject H_0. Shift is NOT a significant factor. Combined with the multi-vari variance component (12.5%), this confirms that while minor shift variation exists, it is not dominant. The team removed "shift" from the priority factor list.

Test 3: FT Fixture Effect (Chi-Square, 3 fixtures)

H_0: defect rate is independent of which FT fixture (FT-1, FT-2, FT-3) the unit was tested on.

Fixture	Units	Defective	p̂
FT-1 (oldest, 2008)	1,220	268	0.2197
FT-2 (2014)	1,198	195	0.1628
FT-3 (2020)	1,179	169	0.1434

Chi-square = 22.4, df = 2, p-value < 0.0001. Reject H_0. FT-1 has a significantly higher defect rate. Post-hoc comparison: FT-1 vs. FT-3 has a 7.6 percentage point absolute difference (z = 4.69, p<0.0001). Inspection of FT-1 revealed harder rubber clamp pads (worn/compressed) compared to FT-3's newer softer pads. Fixture age/design is a confirmed X.

Test 4: Dwell Time in Supermarket (Regression)

Hypothesis: longer dwell in SM increases the probability of defect (via handling events and potential stacking during volume spikes). Simple logistic regression, outcome = defective (0/1), predictor = dwell minutes.

Term	Coefficient	SE	z	p-value
Intercept	-1.732	0.052	-33.3	<0.0001
Dwell (min)	+0.00082	0.00029	2.83	0.0047

Coefficient on dwell time is positive and statistically significant (p = 0.0047), though the effect size is small: holding all else constant, each additional hour of dwell increases the log-odds of defect by 0.049, corresponding to an odds ratio of 1.050 per hour. Practically meaningful only for units dwelling >8 hours. Stacking events (which co-occur with long dwells) are the likely mechanism.

4.7 Validated Root Causes

Combining the C&E matrix, 5-Why analyses, PFMEA, multi-vari, and hypothesis tests, the team converged on four validated root causes. The distinction between "suspected" and "validated" is that each of the below is supported by at least one statistical test or a clear cause-effect chain confirmed by physical observation (e.g., the rail-contact bypass trial).

#	Validated Root Cause	Supporting Evidence	Target Defect Modes
RC-1	**Conveyor side rails abrade chassis side labels (L3, L5) during transport**	Bypass trial ($p<0.001$); multi-vari positional dominance; PFMEA RPN 504	Scratch, Abrasion
RC-2	**Label substrate (2.0 mil vinyl, no laminate) inadequate for handling profile**	5-Why root; abrasion bench test (see Improve); supplier confirmation	Scratch, Abrasion, Cut
RC-3	**FT fixture hard contact points abrade front-face labels (L1, L2); FT-1 fixture worst**	Chi-square across 3 fixtures ($p<0.0001$); PFMEA RPN 336	Abrasion, Scratch
RC-4	**SM pick handling and stacking during peak volume damage labels**	Logistic regression on dwell ($p=0.005$); operator interviews; PFMEA RPN 210	Tear, Edge Lift, Scratch

4.8 Analyze Tollgate Review

The Analyze tollgate was held on April 10, 2026. The sponsor questioned whether the project had sufficient evidence that the substrate change (a capital expense) was justified without direct DOE evidence. The team committed to running a DOE in the first two weeks of Improve to quantify the substrate contribution before authorizing the full supplier change. Tollgate approved conditionally on that commitment.

Analyze Phase Deliverables (Closed)

- Fishbone diagram (6M, ~45 causes)
- C&E matrix (top 12 causes)
- 5-Why analyses on top 2 causes
- PFMEA (22 total items, 8 RPN ≥100)
- Multi-vari study (750 units, variance decomposition)
- Hypothesis tests: 4 tests, 3 significant factors confirmed, 1 factor eliminated
- Final list of 4 validated root causes

Analyze Tollgate Decision

PROCEED TO IMPROVE (conditional on DOE confirming substrate effect before PO release).
Approved by J. Reyes and S. Kowalski on 04-10-2026.

5. Improve Phase

The Improve phase translated validated root causes into tested countermeasures. The phase was organized into four workstreams (one per root cause), plus a DOE to confirm the label substrate decision before capital commitment. Pilot runs validated each solution before full implementation. The phase ran from April 11 to May 22, 2026.

5.1 Solution Generation

A structured solution-generation session was held on April 14, 2026 using SCAMPER and brainstorm-sort methods. Each potential solution was evaluated against four criteria: effectiveness (1–5), cost (1–5, inverse — 1 = high cost, 5 = low cost), implementation time (1–5 inverse), and cross-platform applicability (1–5).

Solution Candidates (post-screening)

RC	Candidate Solution	Eff.	Cost	Time	Repl.	Total	Selected?
RC-1	UHMW-PE low-friction strips on conveyor side rails	5	4	4	5	18	✓ Primary
RC-1	Add urethane centering guides before rail zones	4	4	3	5	16	✓ Primary
RC-1	Replace conveyor belt with narrower belt + rails wider	4	1	1	3	9	Rejected — cost/time
RC-1	Suspend labels until after transport	5	3	2	2	12	Rejected — process impact
RC-2	Over-laminated 3M 7876 polyester label stock	5	3	4	5	17	✓ Primary
RC-2	Thicker vinyl (5 mil) with harder topcoat	3	4	4	4	15	Backup
RC-2	Recessed label pocket on chassis (redesign)	4	1	1	5	11	Long-term (next platform)
RC-3	Replace FT-1 hard clamp pads with closed-cell silicone	5	5	5	5	20	✓ Primary
RC-3	Redesign all FT fixtures with soft contact zones	5	2	2	4	13	Rejected — excess cost
RC-4	Standard work for SM pick (grip zones; no stacking)	4	5	5	5	19	✓ Primary
RC-4	Expand SM capacity to remove stacking need	4	2	2	4	12	Deferred — facilities planning
RC-4	Visual management: grip-zone graphics on chassis	4	5	5	5	19	✓ Primary

5.2 Design of Experiments — Label Substrate Qualification

The sponsor's conditional tollgate approval required DOE evidence on the substrate before supplier qualification. A full factorial 2^3 experiment was designed to quantify the effect of the three controllable substrate factors identified with the label supplier.

DOE Setup

Element	Detail
Design	Full factorial 2^3 with 3 center points = 11 runs, randomized order
Response (Y)	Cycles-to-failure on abrasion bench test (Taber Abraser, CS-10 wheel, 500 g load, readings every 25 cycles; failure = first visible substrate wear through topcoat)
Factor A: Substrate	− = 2.0 mil vinyl (baseline); + = 2.5 mil polyester
Factor B: Over-laminate	− = None; + = 1.0 mil polyester over-laminate
Factor C: Topcoat	− = Standard lacquer; + = UV-cured hardcoat
Replicates per corner	3 label samples per run; averaged
Blocking	None (single Taber machine, single operator, single day)
Randomization	Run order randomized using random.org seed 4482

DOE Results (Cycles-to-Failure)

Run	Std Order	A (Substrate)	B (Laminate)	C (Topcoat)	Avg Cycles to Failure	Std Dev
1	1	−	−	−	82	8
2	8	+	−	−	168	12
3	5	−	+	−	385	22
4	3	+	+	−	472	31
5	7	−	−	+	154	15
6	2	+	−	+	245	19
7	4	−	+	+	510	29

Run	Std Order	A (Substrate)	B (Laminate)	C (Topcoat)	Avg Cycles to Failure	Std Dev
8	6	+	+	+	712	38
9	9	0	0	0	318	25
10	10	0	0	0	331	28
11	11	0	0	0	305	23

DOE Analysis — Main Effects and Interactions

Term	Effect	Coefficient	Std Error	t-value	p-value	Significant (α=0.05)?
Intercept	—	341	18.2	18.7	<0.0001	—
A (Substrate)	+122	61.0	20.3	3.00	0.040	✓
B (Laminate)	+265	132.5	20.3	6.53	0.003	✓ (largest)
C (Topcoat)	+76	38.0	20.3	1.87	0.135	Not significant
A×B	+45	22.5	20.3	1.11	0.329	Not significant
A×C	+34	17.0	20.3	0.84	0.449	Not significant
B×C	+88	44.0	20.3	2.17	0.096	Marginal
A×B×C	+29	14.5	20.3	0.71	0.516	Not significant
Curvature test (from center pts)	—	—	—	1.02	0.365	No significant curvature

Model: $R^2 = 0.967$, $R^2\text{-adj} = 0.886$, lack-of-fit $p = 0.41$ (acceptable). The over-laminate (Factor B) is the dominant effect — alone it delivers an average increase of 265 cycles-to-failure. Substrate upgrade (A) is also significant but with about half the effect size. The UV hardcoat (C) was not statistically significant at $\alpha = 0.05$. A B×C marginal interaction ($p = 0.096$) exists; the team retained the UV hardcoat only where the supplier provides it as a standard option, as it adds no cost and the marginal interaction suggests a modest benefit in combination.

DOE Conclusion

DOE Recommendation

Selected formulation: A+ B+ C+ (polyester substrate + over-laminate + UV hardcoat) = 712 cycles avg

vs. baseline A− B− C−: 82 cycles avg → 8.7× durability improvement

The 3M 7876 polyester over-laminated label stock from GraphicsPro matches this formulation at a
unit cost of $0.94 per label set (vs. $0.71 baseline; +$0.23/unit × 14 labels is not applicable —
the $0.94 is for the full 14-label set). Incremental material cost per unit: $0.23.

5.3 Selected Solutions — Detailed

Solution 1 (RC-1): Conveyor Rail Modifications

Install 12 mm × 1.5 mm UHMW-PE (ultra-high-molecular-weight polyethylene) strips on all contact surfaces of conveyor C-1 and C-2 side rails (total 48 linear feet). UHMW-PE has a coefficient of friction approximately 0.15 against steel versus 0.45 for uncoated stainless — a 67% friction reduction. The strips attach with 3M VHB adhesive (tested to 180°F for washdown compatibility). Supplementary: install two sets of urethane centering wheels at the inlet of each rail zone to reduce lateral drift from ±7 mm to approximately ±2 mm.

- Parts: UHMW strip (48 ft), urethane wheels (4 sets), 3M VHB adhesive, mounting hardware
- Cost: $6,800 material, $2,200 maintenance labor (16 hrs) = $9,000
- Installation window: Saturday 04-25-2026 (scheduled shutdown)
- Engineering Change Notice: ECN-2026-087 (approved 04-22-2026)

Solution 2 (RC-2): Label Substrate Upgrade

Transition all 14 MC-4400 labels from 2.0 mil vinyl (GraphicsPro PN LBL-4400-001) to 3M 7876 over-laminated polyester (new PN LBL-4400-001-R2). Full qualification plan followed QP-014 including adhesion test, environmental chamber (−20°C to +70°C, 85% RH for 72 hr), and abrasion (Taber). Supplier provided first-article samples, and incoming inspection protocol was updated. A 6,000-unit bridge stock of legacy labels was consumed before cutover to avoid scrap.

- Incremental material cost: +$0.23 per unit × 14,400 units/yr = $3,310/yr
- One-time qualification cost: $4,200 (engineering time + samples + chamber)
- Part number changeover in MES and ERP: completed 05-06-2026
- Engineering Change Notice: ECN-2026-091 (approved 05-01-2026)

Solution 3 (RC-3): FT Fixture Clamp Pad Replacement

Replace hard rubber clamp pads on FT-1 with closed-cell silicone foam pads (Shore A 20 durometer, 40 mil thickness) matching the FT-3 specification. Same replacement performed preventively on FT-2. Additionally, a soft-touch overlay was added to fixture load rest points (three contact pads per fixture). A 500-cycle wear test was performed in-house before release.

- Parts: silicone foam pads (12 ea, 3 fixtures), adhesive, PTFE overlay strips
- Cost: $1,400 parts, $900 labor = $2,300
- Preventive maintenance trigger added: replace every 12 months or 100k cycles
- Engineering Change Notice: ECN-2026-094 (approved 05-08-2026)

Solution 4 (RC-4): Standard Work for Handling

A combined solution: (a) standard work instructions with photos for the three operator-handling steps (FT load/unload, SM put-away, SM pick); (b) grip-zone graphics silkscreened on the chassis top and bottom showing "green" handling zones and "red" no-touch zones around labels; (c) revised supermarket rack with individual slots per unit (no stacking) for the high-volume L1/L2 label surfaces facing up. Training on the new SOPs was conducted for all 14 in-scope operators during the week of 05-11-2026.

- Standard work documents: SW-MC4400-07 (FT handling), SW-MC4400-08 (SM handling)
- Grip-zone silkscreen: chassis drawing revision MC4400-100 rev D; added to supplier print

- SM rack modification: divider inserts (no new rack purchase)
- Cost: $2,100 silkscreen tooling, $900 rack dividers, $1,800 training = $4,800

5.4 Investment Summary

Item	One-Time Cost	Recurring Annual
Conveyor rail modifications (UHMW + guides)	$9,000	—
Label substrate qualification	$4,200	—
Label substrate unit-cost premium	—	$3,310
FT fixture clamp pads + overlay	$2,300	$400 (PM replacement)
Standard work + grip-zone silkscreen + rack dividers + training	$4,800	—
Bench testing / Taber consumables	$1,100	—
Project overhead (black belt time, meetings)	$19,800	—
	Total one-time: $41,200	Total recurring: $3,710/yr

5.5 Pilot Run and Validation

All four solutions were implemented between April 25 and May 11, 2026. A formal pilot / validation period ran from May 12 to May 22, 2026 — 8 production days, 1,142 units produced.

Pilot Results

Day	Units	Defective	p̂	95% CI (upper)
May 12	148	2	0.0135	0.035
May 13	151	1	0.0066	0.024
May 14	142	3	0.0211	0.044
May 15	139	1	0.0072	0.026
May 18	145	0	0.0000	0.020
May 19	143	2	0.0140	0.036

Day	Units	Defective	p̂	95% CI (upper)
May 20	138	1	0.0072	0.026
May 21	136	1	0.0074	0.027
	8-day total: 1,142	11	0.0096	(0.005, 0.017)

Before / After Hypothesis Test (Two-Proportion)

H_0: p_before = p_after vs. H_1: p_before > p_after

Period	n	Defective	p̂
Baseline (pre-implementation)	2,847	501	0.1760
Pilot (post-implementation)	1,142	11	0.0096

Two-proportion z-test: z = 14.12, p-value < 0.00001. Reject H_0 with overwhelming significance. The pilot defect rate is statistically and practically lower than baseline. Effect size: 16.64 percentage point absolute reduction (94.5% relative reduction in defect rate).

Capability After Pilot

Metric	Baseline	Pilot	Target	Pilot vs. Target
Unit-level defect rate	17.60%	0.96%	≤2.0%	✓ Met
DPMO (unit level)	176,000	9,632	≤20,000	✓ Met
Process sigma (short-term)	2.43σ	3.84σ	≥3.5σ	✓ Met
Cpk	0.41	1.45	≥1.00	✓ Met
First-pass yield (label defects)	82.4%	99.04%	≥98.0%	✓ Met
Assembly cycle time per unit (Cell A3)	4.2 min	4.3 min	≤4.33 min (+3%)	✓ Met

5.6 Improve Tollgate Review

The Improve tollgate was held on May 26, 2026. All targets were met or exceeded in the pilot period. The sponsor authorized transition to Control with no reservations.

Improve Phase Deliverables (Closed)

- Solution prioritization matrix (12 candidates, 4 selected)
- DOE (2^3 full factorial) on label substrate — B (laminate) confirmed dominant
- Four solutions implemented, each with ECN and cost approval
- 8-day pilot, 1,142 units, defect rate = 0.96% (baseline 17.60%)
- Before/after hypothesis test: $p < 0.00001$
- All capability targets met; cycle time impact within consequential metric limit

Improve Tollgate Decision

PROCEED TO CONTROL. All targets met. Authorize full production cutover and begin control plan
handoff to process owner. Approved by J. Reyes and S. Kowalski on 05-26-2026.

6. Control Phase

The Control phase institutionalized the gains and handed the process to the owner. The phase ran from May 26 to June 12, 2026, with a 90-day post-closure audit period extending through September 10, 2026.

6.1 Control Plan

The control plan below is the governing document for sustaining the improvements. It integrates with the existing Plant 2 control plan library under document control (QMS reference CP-MC4400-R4).

Process Step	Characteristic	Spec / Limit	Method	Sample / Freq.	Responsible	Reaction Plan
40 — Label application	Correct label PN (substrate)	LBL-4400-001-R2 only	MES PN scan at issue	Every unit	Assembly lead	Stop; verify kit; reissue correct PN
40 — Label application	Application quality (no bubbles, correct location)	Pocket registration ≤0.5 mm	Visual vs. aid	Every unit	A3 operator	Reapply or scrap per disposition
60/80 — Conveyor transport	UHMW rail condition	No gouges, wear ≤0.3 mm	Visual + caliper	Weekly	Maintenance	Replace segment; doc in CMMS
60/80 — Conveyor centering	Lateral drift	≤3 mm	Visual / witness marks	Monthly	Maintenance	Re-adjust guide wheels; PM
70 — FT fixture	Clamp pad condition (all 3 FTs)	No compression set >10%; no tearing	Visual + durometer	Monthly	Test tech	Replace pad kit; record
70 — FT handling	Standard work SW-MC4400-07 followed	Compliance audit score ≥95%	Gemba audit	2×/month per shift	Quality	Retrain individual; re-audit
90/100 — SM handling	Standard work SW-MC4400-08 followed	Compliance audit score ≥95%	Gemba audit	2×/month per shift	Quality	Retrain; re-audit
90 — SM staging	No stacking	Zero stacked units	Visual + layered daily check	Daily	SM operator	Unstack immediately; investigate cause
110 — Final inspection	Label defect rate (Y)	$\hat{p}$ ≤0.020 weekly; p-chart stable	p-chart (weekly n≥400)	Weekly	Quality	OCAP triggered if point > UCL
— Material IQC	Incoming label lot qualification	Taber ≥500 cycles (sample)	IQC abrasion test	First article every lot	IQC	Reject lot; escalate to supplier

6.2 Statistical Process Control

A p-chart with weekly subgroups (n ≥400) was established at the Final Inspection station. The chart is posted visually at the QC workstation and reviewed in the daily production huddle. Control limits were computed using the post-implementation data:

Parameter	Value
Center line ($\bar{p}$) — based on first 4 post-implementation weeks	0.0096
Average subgroup size ($\bar{n}$)	625 units/week
UCL (at $\bar{n}$ = 625)	0.0213
LCL (at $\bar{n}$ = 625)	0.0000 (floor)
Target (project goal)	≤0.0200
Plant aspirational target	≤0.0100

Out-of-Control Action Plan (OCAP)

The OCAP below was posted at the QC workstation and in the daily production huddle area. Any trigger initiates a formal investigation.

Trigger	Action	Owner	Escalation
Any single point > UCL (0.0213)	Stop, investigate (5-Why); check rails, fixtures, substrate lot	Quality Eng.	Within 4 hours to Prod. Supervisor
7 consecutive points above center line	Assignable cause investigation; audit standard work	Quality Eng.	Within 24 hours to Plant Manager
Trend of 6 increasing points	Early warning; check recent changes (lot, personnel, rails)	Quality Eng.	Monitor, notify
Any customer complaint (label-related)	Containment (sort current stock); investigate; CAPA	CQE + Quality Eng.	Within 24 hours to Plant Manager
IQC fail on Taber test	Hold lot; 3rd-party verification; supplier SCAR	IQC + SCM	48 hrs to supplier
Monthly audit compliance <95%	Retrain affected operators; reinforce with supervisor	Training + Super.	Monthly to Plant Manager

6.3 Standard Work Summary

Two standard work documents were created, controlled through QMS, and posted at the point of use with laminated copies. A summary of the critical content is below; full documents are referenced in Appendix B.

SW-MC4400-07: Functional Test Handling

5. Approach FT fixture with two hands; grip chassis only on the identified green grip zones (rear lower corners — confirmed away from all label positions).
6. Lower unit vertically into fixture; do NOT slide horizontally into cradle (prevents drag across front-face labels L1/L2).
7. After test, lift vertically; never pivot on front edge.
8. Transfer to outfeed conveyor using both hands, green grip zones only.
9. If unit shows any label damage at this step, place on red "Inspect/Rework" rack and notify lead — do not continue to SM.
10. Check fixture clamp pads at start of each shift; any visible wear → notify maintenance before next unit.

SW-MC4400-08: Supermarket Put-Away and Pick

11. Approach SM lane with unit held on green grip zones; orient front face (L1/L2) away from shelving hardware.
12. Place unit in designated slot — ONE unit per slot, no stacking, regardless of volume.
13. If slots are full, place overflow on padded staging table and notify supervisor (not on floor, not stacked).
14. For pick: approach slot, grasp green grip zones with both hands, lift vertically.
15. Do NOT grasp by front face, side labels, or top cover seam area.
16. If label damage is observed during pick, place unit on red "Inspect/Rework" rack and log defect code on QC app.

6.4 Updated PFMEA (Post-Improvement RPN)

The PFMEA was re-scored after implementation. Severity scores remained unchanged (defect effects are inherent). Occurrence and Detection were updated based on pilot evidence and new controls.

Failure Mode	S	O (Before)	O (After)	D (Before)	D (After)	RPN Before	RPN After	Δ
Chassis rubs rail (C-1)	7	8	2	9	6	504	84	−420
Chassis rubs rail (C-2)	7	8	2	9	6	504	84	−420
FT fixture contact abrasion	6	7	3	8	5	336	90	−246
Substrate inadequate for handling	7	7	3	7	4	343	84	−259
SM pick grip on label area	5	6	3	7	4	210	60	−150
SM stacking during peak	6	5	1	6	3	180	18	−162

Failure Mode	S	O (Before)	O (After)	D (Before)	D (After)	RPN Before	RPN After	Δ
Dead-plate gap at transfer	7	4	4	7	7	196	196	0 (not addressed)
FT unload by label area	5	6	3	6	4	180	60	−120

Total RPN reduction across the addressed modes: 2,453 → 676 (−72.4%). The dead-plate gap item (RPN 196) was not closed in this project; it is carried forward in the replication plan (Section 7.4) because addressing it would require a conveyor re-design out of scope for this project.

6.5 Financial Validation

Finance validated the post-implementation benefits using the same basis as the Measure baseline. Validation spanned the first 30 days of full production (May 26 – June 24, 2026).

Cost Element	Baseline (Annual)	Post (Annualized)	Savings
Rework labor (label replacement)	$96,840	$5,290	$91,550
Replacement label material	$10,490	$570	$9,920
Expedited label re-orders	$62,900	$6,200	$56,700
Scrap (beyond rework)	$62,450	$3,400	$59,050
Customer returns (label RMAs)	$89,600	$4,800 (proj.)	$84,800
Lost throughput (line holds)	$90,300	$4,200	$86,100
Sub-total gross savings	$412,580	$24,460	$388,120
Less: recurring material premium (+$0.23/unit × 14,400)	—	($3,310)	($3,310)
Less: annual PM replacement (FT pads)	—	($400)	($400)
		Net validated annual savings	$384,410
Finance adjustment (conservatism factor, −1%)			($3,890)
		Reported validated annual savings	$380,520

Project ROI

Metric	Value
Total one-time investment	$41,200
Net validated annual savings (Finance-reported)	$380,520
Simple payback period	1.30 months (~ 40 days)
Year-1 net benefit (savings − investment)	$339,320

Metric	Value
3-year cumulative benefit (undiscounted)	$1,100,360
3-year NPV (8% discount rate)	$944,100
ROI (Year-1)	823%

6.6 90-Day Post-Closure Audit

A 90-day sustainment audit was conducted on September 10, 2026 by an independent Quality auditor (not a project team member) to verify that gains had held.

Metric	Project Goal	Pilot Result	90-Day Audit Result	Status
Defect rate	≤2.0%	0.96%	0.91%	✓ Sustained
DPMO (unit level)	≤20,000	9,600	9,200	✓ Sustained
Process sigma	≥3.5σ	3.84σ	3.86σ	✓ Sustained
Cpk	≥1.00	1.45	1.48	✓ Sustained
Standard work compliance (audit)	≥95%	98%	96%	✓ Sustained
Customer complaints (label, rolling 90d)	(track)	0	0	✓ Sustained
p-chart control	In control	In control	In control, no OCAP triggers	✓ Sustained

Audit finding: one instance of a stacking event was observed on 08-14-2026 during a short volume surge (new customer order, unexpected). The SM operator took correct action (unstacked within 15 minutes, notified supervisor, logged event). No defects resulted from the event. Audit recommendation: carry forward the deferred SM capacity expansion item to the facilities planning backlog — noted in Section 7.4.

Project Closure

Project SENTINEL formally closed 06-12-2026. Process ownership transferred to T. Nguyen (Process Engineering). Sustainment audit 09-10-2026 confirmed gains held. Finance certified savings 09-22-2026. Project record archived in CI portfolio with full traceability.

7. Lessons Learned and Replication Plan

7.1 What Went Well

- Early and sustained sponsor engagement. The sponsor's conditional approval on the substrate DOE kept the team disciplined about evidence before spend.
- Measurement system analysis before baseline data collection. Catching the Kappa issue with Inspector B up front prevented weeks of bad data.
- The bypass trial (padded-cart transfer) isolated the conveyor-rail contribution with a simple experiment — no statistical heavy lift needed.
- Including a line operator on the core team from Day 1. The operator identified the FT-1 fixture difference before the data did.
- DOE before capital commitment. The 2^3 experiment took 4 days and $1,100 and de-risked a $3,310/yr recurring commitment.

7.2 What We'd Do Differently

- Engage the label supplier as an SME earlier — ideally at the C&E matrix stage rather than during Improve. GraphicsPro had abrasion data on competing substrates that would have accelerated material selection.
- Budget more time for ECN approval cycles. Two of our four ECNs took longer than expected; we absorbed the schedule risk, but it was close.
- Include the Training team formally as a stakeholder. Training scheduling conflicts delayed operator rollout by 3 days.
- The Measure baseline would have benefited from a defect location body-map captured as image data, not just category. The post-hoc mapping worked but cost time.

7.3 Systemic / Business Process Gaps Identified

Two systemic gaps surfaced during the 5-Why analyses were escalated to the Quality Management System team for consideration outside this project:

17. Gap in NPI process: no handling-risk assessment is required when an existing product is adopted onto an existing line. Recommended QMS action: add "Handling Risk Assessment" as a gated item in the NPI checklist. Owner: Director of NPI. Target: Q3 2026.
18. Gap in material spec lifecycle: QP-014 does not require re-qualification of a substrate when it is used on a new platform. Recommended QMS action: revise QP-014 to trigger abrasion/environmental re-qualification on cross-platform use. Owner: QA Director. Target: Q3 2026.

7.4 Replication Plan

The following items are candidates for extending the project's learnings across the plant and across the product portfolio. Each has been reviewed with the process owner and entered into the CI portfolio backlog.

#	Replication Opportunity	Target	Owner	Status
RP-1	Extend UHMW conveyor treatment to MC-3200 line (similar architecture)	Q3 2026	T. Nguyen	Chartered as CI-2026-018
RP-2	Upgrade MC-5600 labels to same 3M 7876 substrate (economies of scale)	Q4 2026	J. Rivera	Purchasing scoping
RP-3	Close dead-plate gap at conveyor transfer (carried-over PFMEA item)	Q4 2026	Maintenance	Engineering assessment
RP-4	SM capacity expansion (remove stacking need permanently)	2027 CapEx	Facilities	Facilities backlog
RP-5	Roll out grip-zone silkscreen standard to all Plant 2 products	Q1 2027	Manufacturing Eng.	Standard drafted
RP-6	NPI handling-risk assessment (systemic fix)	Q3 2026	Director of NPI	QMS change package drafted
RP-7	QP-014 revision (substrate cross-platform re-qualification)	Q3 2026	QA Director	QMS change package drafted

7.5 Team Recognition

The project team was formally recognized at the Plant 2 monthly all-hands on June 17, 2026. The line operator (C. Barnes) was specifically called out for bringing the FT-1 fixture condition to attention before the data analysis revealed it. Project artifacts were entered into the internal CI portfolio and submitted for consideration to the annual corporate CI award.

8. Appendices

Appendix A — Glossary

Term	Definition
Cpk	Process Capability Index (minimum-side); measures how well a process is centered within its specification limits. Cpk ≥1.33 is the common industrial target.
CTQ	Critical-to-Quality: a measurable product or process characteristic that directly affects customer perception of quality.
DMAIC	Define, Measure, Analyze, Improve, Control — the standard Six Sigma problem-solving framework.
DOE	Design of Experiments — a structured method for evaluating multiple factors simultaneously.
DPMO	Defects Per Million Opportunities.
ECN	Engineering Change Notice — controlled document authorizing a process or product change.
FMEA	Failure Mode and Effects Analysis — structured method for identifying and prioritizing risk.
FPY	First-Pass Yield — percentage of units passing inspection on the first attempt.
Gemba	Japanese for "the real place" — where work actually happens. A Gemba walk is direct on-site observation.
IQC	Incoming Quality Control — inspection of purchased materials upon receipt.
Kappa	Cohen's / Fleiss' Kappa statistic — measure of inter-rater agreement beyond chance.
MSA	Measurement System Analysis — evaluation of a measurement method's accuracy and repeatability.
OCAP	Out-of-Control Action Plan — documented reaction to SPC chart signals.
PFMEA	Process FMEA — FMEA focused on process failure modes (as opposed to Design FMEA).
PPAP	Production Part Approval Process — automotive-origin approval framework for new parts/processes.
RACI	Responsible, Accountable, Consulted, Informed — stakeholder role matrix.
RPN	Risk Priority Number — FMEA score = Severity × Occurrence × Detection.

Term	Definition
SCAR	Supplier Corrective Action Request — formal supplier quality escalation.
SIPOC	Suppliers, Inputs, Process, Outputs, Customers — macro-level process view.
SM (Supermarket)	Lean term for a small, controlled in-process inventory buffer.
SPC	Statistical Process Control — data-driven monitoring of process performance.
UHMW-PE	Ultra-High-Molecular-Weight Polyethylene — engineering plastic with very low coefficient of friction.
VOC	Voice of the Customer — qualitative and quantitative input capturing customer needs.

Appendix B — Document Index

The following controlled documents were created, revised, or referenced during Project SENTINEL. All documents are in the QMS and available to authorized personnel.

Document ID	Title	Rev	Status
CHARTER-CI-2026-004	Project SENTINEL Charter	1.1	Closed
CP-MC4400-R4	MC-4400 Control Plan	R4 (new)	Released
LBL-SPEC-004	Label Material Specification	C (revised)	Released 05-01-2026
ECN-2026-087	Conveyor rail UHMW + centering	—	Approved 04-22-2026
ECN-2026-091	Label substrate change	—	Approved 05-01-2026
ECN-2026-094	FT fixture clamp pad replacement	—	Approved 05-08-2026
ECN-2026-098	Chassis grip-zone silkscreen (drawing MC4400-100 Rev D)	—	Approved 05-05-2026
SW-MC4400-07	FT Handling Standard Work	A	Released
SW-MC4400-08	SM Put-Away and Pick Standard Work	A	Released
PFMEA-MC4400-R3	MC-4400 Process FMEA	R3	Updated post-improvement

Document ID	Title	Rev	Status
QP-014 (proposed)	Spec Lifecycle Procedure (pending revision)	(rev pending)	In QMS change queue

Appendix C — Key Calculations Reference

Defect Rate to Process Sigma

Process sigma (short-term) ≈ Z_bench + 1.5 shift for long-term:

For baseline $p = 0.1760$: Z_bench = NORM.INV(1 − 0.1760) = 0.930 → long-term sigma = 0.93 + 1.5 = 2.43σ

For post-improvement $p = 0.0091$: Z_bench = NORM.INV(1 − 0.0091) = 2.36 → long-term sigma = 3.86σ

p-Chart Control Limits (variable n)

$UCL = \bar{p} + 3 \times \sqrt{\bar{p}(1-\bar{p})/n}$; $LCL = \max(0, \bar{p} - 3 \times \sqrt{\bar{p}(1-\bar{p})/n})$

Two-Proportion z-Test

$z = (\hat{p}_1 - \hat{p}_2) / \sqrt{\hat{p}\_pooled(1-\hat{p}\_pooled)(1/n_1 + 1/n_2)}$ where $\hat{p}\_pooled = (x_1+x_2)/(n_1+n_2)$

DOE — Effect Estimate (2^3 full factorial)

Effect = (average response at + level) − (average response at − level). Coefficient = Effect / 2. Standard error = σ_pooled × √(1/N_plus + 1/N_minus).

Appendix D — Project Timeline (Gantt Summary)

Phase	Start	End	Duration	Key Milestones
Define	01-06-2026	01-27-2026	3 weeks	Charter signed 01-16; VOC/SIPOC/process map; Tollgate 01-27
Measure	01-28-2026	03-10-2026	6 weeks	MSA + re-study; 20-day baseline; COPQ validated; Tollgate 03-10
Analyze	03-11-2026	04-10-2026	4.5 weeks	Fishbone/C&E/5-Why/FMEA/multi-vari/hypothesis tests; Tollgate 04-10
Improve	04-11-2026	05-26-2026	6.5 weeks	DOE; 3 ECNs; 8-day pilot; Tollgate 05-26
Control	05-26-2026	06-12-2026	2.5 weeks	Control plan; SPC; standard work; handoff 06-12

Phase	Start	End	Duration	Key Milestones
Sustainment (post-closure)	06-13-2026	09-10-2026	13 weeks	90-day audit 09-10; Finance cert 09-22

Project Closure Sign-Off

By signature below, the listed stakeholders confirm that Project SENTINEL (CI-2026-004) has delivered against the chartered goals, that the control plan is in place, that the process owner has accepted handoff, and that the financial savings have been validated by Finance.

Role	Name	Signature / Date
Sponsor	J. Reyes, VP of Operations	____________________ / __________
Champion	K. Dell, Plant Manager	____________________ / __________
Master Black Belt	S. Kowalski	____________________ / __________
Project Lead (Black Belt)	D. Halvorsen	____________________ / __________
Process Owner	T. Nguyen, Process Engineering	____________________ / __________
Finance	(designate)	____________________ / __________

— End of Report —