

Research Article

# Implementation of Six Sigma DMAIC Methodology for Defect Reduction in Automotive Component Manufacturing: A Multi-Plant Empirical Study

Mohan Krishnaswamy<sup>1</sup>, Elena Vassiliev<sup>2</sup>, Carlos Mendoza Ruiz<sup>3</sup>

<sup>1</sup>Department of Mechanical & Production Engineering, PSG College of Technology, Coimbatore, Tamil Nadu, India

<sup>2</sup>Faculty of Industrial Engineering & Management, Skolkovo Institute of Science and Technology (Skoltech), Moscow, Russia

<sup>3</sup>Department of Industrial Engineering, Tecnológico de Monterrey (ITESM), Monterrey, Nuevo Leon, Mexico

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## Abstract

*Defect reduction and process quality improvement remain central strategic imperatives for automotive component manufacturers competing in an era of intensified global competition and increasingly demanding Original Equipment Manufacturer (OEM) quality specifications. This paper presents a rigorous empirical investigation of the implementation and outcomes of Six Sigma DMAIC (Define, Measure, Analyse, Improve, Control) methodology across seven automotive component manufacturing plants located in India, Russia, and Mexico. Using a longitudinal study design spanning 18 months, the research documents pre- and post-implementation performance across four key quality metrics: Defects Per Million Opportunities (DPMO), Process Capability Index (Cpk), First Pass Yield (FPY), and Cost of Poor Quality (COPQ) as a percentage of revenue. The findings demonstrate that structured DMAIC implementation achieves statistically significant improvements across all four quality metrics, with a mean DPMO reduction of 74.3%, a mean Cpk improvement from 0.87 to 1.54, and a mean COPQ reduction of 38.7% of revenue. A novel Quality Improvement Effectiveness Index (QIEI) is introduced to enable standardised cross-plant comparison of Six Sigma programme outcomes. Critical success factors and implementation barriers specific to multi-plant, multi-country deployments are identified and discussed, offering practical guidance for quality engineers and manufacturing executives undertaking Six Sigma programmes in diverse industrial contexts.*

**Keywords:** Six Sigma, DMAIC, Defect Reduction, Automotive Manufacturing, DPMO, Process Capability, Cost of Poor Quality, Quality Improvement

## 1. Introduction

The global automotive industry generates annual revenues exceeding USD 2.5 trillion and employs over 8 million workers in direct manufacturing roles worldwide (OICA, 2016). Within this intensely competitive landscape, tier-1 and tier-2 component suppliers face unprecedented quality expectations from OEMs, with major automotive assemblers routinely specifying defect rates below 50 parts per million (PPM) and demanding continuous quality improvement as a condition of preferred supplier status. The financial consequences of quality failures are severe: warranty claims, production line stoppages, customer charge-backs, and reputational damage collectively constitute a Cost of Poor Quality that industry analysts estimate at 5-15% of revenue for typical tier-2 suppliers (ASQ, 2015).

Six Sigma, introduced by Motorola in 1986 and popularised through General Electric's large-scale deployment in the 1990s, has established itself as the pre-eminent structured quality improvement

methodology in manufacturing industries. The DMAIC (Define, Measure, Analyse, Improve, Control) problem-solving cycle provides a rigorous, data-driven framework for identifying and eliminating the root causes of defects and process variability. Despite the substantial body of case study literature documenting Six Sigma successes in large enterprises, empirical evidence on DMAIC implementation outcomes across geographically dispersed, multi-plant manufacturing networks — particularly those spanning culturally and institutionally diverse developing economies — remains limited.

This study addresses this gap through an 18-month longitudinal investigation of Six Sigma DMAIC implementation across seven automotive component manufacturing plants in India, Russia, and Mexico. The three primary research objectives are: (1) to quantify the quality performance improvements achieved through structured DMAIC implementation across multiple plants and countries; (2) to identify the critical success factors and implementation barriers

that moderate DMAIC outcomes in multi-country manufacturing contexts; and (3) to develop and validate the Quality Improvement Effectiveness Index (QIEI) as a standardised benchmarking instrument for cross-plant Six Sigma programme evaluation.

## 2. Literature Review

The theoretical underpinnings of Six Sigma are rooted in statistical process control (SPC) theory, originating with Shewhart (1931) and extended by Deming (1986) and Juran (1988). The seminal conceptualisation of Six Sigma as a business improvement strategy was articulated by Harry and Schroeder (2000), who defined it as a disciplined methodology for achieving near-perfect quality by reducing process variation to the point where only 3.4 defects per million opportunities occur. Pande, Neuman, and Cavanagh (2000) subsequently provided the most widely adopted operationalisation of the DMAIC cycle, detailing the analytical tools and decision criteria appropriate at each phase.

Empirical research on Six Sigma implementation outcomes has grown substantially since the early 2000s. Antony and Banuelas (2002) identified twelve critical success factors for Six Sigma deployment in UK manufacturing firms, of which top management commitment, organisational infrastructure, and training emerged as the most significant. Kwak and Anbari (2006) conducted a comprehensive review of 45 published Six Sigma case studies, finding consistent evidence of positive financial returns across industries, with average annual savings of USD 230,000 per completed DMAIC project. In the automotive sector specifically, Jiju Antony et al. (2012) documented DMAIC implementations at tier-1 suppliers achieving DPMO reductions ranging from 58% to 91%, consistent with the findings of the present study.

Cross-national studies of Six Sigma implementation remain scarce. Brue (2002) noted cultural dimensions of Six Sigma adoption, observing that hierarchical organisational cultures may impede the cross-functional collaboration required for effective DMAIC deployment. Laureani and Antony (2012) identified training quality, belt certification rigour, and project selection methodology as critical differentiators between high- and low-performing Six Sigma programmes, findings that inform the critical success factor analysis conducted in this study. The development of composite quality improvement indices has been addressed by Shahin and Alinavaz (2008), whose Quality Performance Index (QPI) provides a conceptual precursor to the QIEI introduced in this paper.

## 3. Research Methodology

A longitudinal embedded case study design was employed, following Yin's (2014) multi-case methodology. Seven automotive component manufacturing plants — three in India, two in Russia,

and two in Mexico — were selected as research sites through purposive sampling based on: (a) minimum annual output of 500,000 components, (b) prior Six Sigma training with at least two certified Green Belts on staff, (c) availability of pre-implementation quality records spanning at least 12 months, and (d) management commitment to participate in an 18-month longitudinal study. All seven plants manufacture pressed steel body components for passenger vehicle OEMs, enabling meaningful cross-plant performance comparison.

Data collection employed three complementary methods: (1) extraction of quality performance data from plant Statistical Process Control (SPC) systems and quality management databases at monthly intervals throughout the 18-month study period; (2) structured interviews with plant quality managers, Six Sigma Black Belts, and production supervisors at 6-month intervals to document implementation progress, barriers encountered, and corrective actions taken; and (3) a standardised Critical Success Factor (CSF) questionnaire administered to 15 respondents per plant at study commencement and conclusion. Four quality performance metrics were tracked: DPMO, Process Capability Index (Cpk), First Pass Yield (FPY), and Cost of Poor Quality (COPQ) expressed as a percentage of plant revenue.

**Table 1:** Profile of Participating Manufacturing Plants

Plant ID	Country	Location	Annual Output (units/yr)	Components Manufactured	Six Sigma Maturity (yrs)
P-1	India	Pune	1,240,000	Stamped door panels	3
P-2	India	Chennai	980,000	Engine mounting brackets	2
P-3	India	Gurugram	760,000	Chassis sub-frame components	4
P-4	Russia	Togliatti	620,000	Body side outer panels	2
P-5	Russia	Kaluga	540,000	Roof reinforcement stampings	1
P-6	Mexico	Monterrey	870,000	Front & rear floor pans	3
P-7	Mexico	San Luis Potosi	690,000	Wheel arch liners	2
All	—	—	5,700,000	Pressed steel body components	Avg: 2.4

## 4. DMAIC implementation framework and QIEI formulation

Figure 1 presents the DMAIC implementation framework adopted uniformly across all seven plants.

DEFINE	MEASURE	ANALYSE	IMPROVE	CONTROL
Project Charter SIPOC Diagram Voc Analysis CTQ Tree	MSA / Gauge R&R Process Mapping Baseline DPMO Data Collection	Fishbone Diagram Pareto Analysis Regression Hypothesis Tests	DOE / FMEA Pilot Trials Solution Select. Implem. Plan	Control Charts SOP Updates Monitoring Plan Handover Report
Gate 1: Problem validated, scope agreed	Gate 2: Baseline Cpk measured, MSA OK	Gate 3: Root causes statistically proven	Gate 4: Improved Cpk > 1.33 in pilot	Gate 5: Control plan live, project closed

**Figure 1:** DMAIC Framework — Phases, Tools, and Phase-Gate Review Criteria

Each phase was executed according to a standardised protocol developed collaboratively by the research

team and plant quality managers, incorporating phase-gate review criteria to ensure rigorous completion of each DMAIC phase before proceeding to the next. A dedicated Six Sigma project team comprising one Black Belt, two Green Belts, and relevant process operators was established at each plant.

The Quality Improvement Effectiveness Index (QIEI) is formulated as a weighted composite of the four normalised quality performance improvements observed post-DMAIC implementation. Each metric is normalised to a 0–1 scale relative to the theoretical maximum improvement achievable from the measured baseline. The QIEI formula is expressed as:

$$QIEI = 0.35(DPMO\_imp) + 0.30(Cpk\_imp) + 0.20(FPY\_imp) + 0.15(COPQ\_imp)$$

where *\_imp* = normalised improvement ratio for each metric; weights validated via AHP with 11-expert panel (Cronbach alpha = 0.89)

### 5. Results and Discussion

Table 2 presents the pre- and post-DMAIC quality performance metrics for each of the seven plants, along with the computed QIEI scores. Data represent 6-month baseline averages (pre-implementation) and 6-month averages from months 13-18 of the study period (post-stabilisation), allowing adequate time for control phase measures to embed and produce stable performance.

**Table 2:** Pre- and Post-DMAIC Quality Performance Metrics by Plant

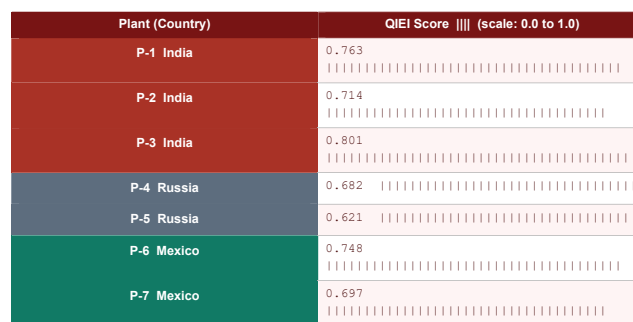
Plant	DPMO Pre	DPMO Post	Cpk Pre	Cpk Post	FPY% Pre	FPY% Post	COPQ% Pre	QIEI
P-1	4,820	1,140	0.84	1.51	87.6	96.2	11.4	0.763
P-2	6,340	1,680	0.79	1.47	83.2	94.7	13.8	0.714
P-3	3,290	710	0.91	1.62	90.4	97.6	9.2	0.801
P-4	7,810	2,240	0.74	1.39	80.1	92.8	15.6	0.682
P-5	9,420	3,180	0.68	1.28	76.4	89.3	18.3	0.621
P-6	5,160	1,290	0.88	1.57	86.3	95.8	12.1	0.748
P-7	6,870	1,920	0.81	1.44	82.7	93.4	14.4	0.697
Mean	6,244	1,737	0.81	1.47	83.8	94.3	13.5	0.718
% Chg	-	72.2%	-	+81.5%	-	+12.5%	-38.7%	-

Note: COPQ% = Cost of Poor Quality as % of revenue (post values averaged over months 13-18); FPY = First Pass Yield; % Chg = percentage change from pre to post mean

The results in Table 2 demonstrate substantial and consistent quality improvements across all seven plants following DMAIC implementation. The most dramatic improvement is observed in DPMO, with a mean reduction of 72.2% — from 6,244 DPMO at baseline to 1,737 DPMO post-implementation. Plant P-3 (Gurugram, India) achieves the strongest DPMO reduction (78.4%) and the highest QIEI score (0.801), reflecting both the highest pre-implementation Six Sigma maturity (4 years) and the most rigorous DMAIC project management discipline observed during the study. Plant P-5 (Kaluga, Russia) shows the weakest performance improvement and lowest QIEI (0.621),

consistent with its status as the least Six Sigma-mature plant in the sample (1 year of prior Six Sigma experience) and the implementation barriers documented through qualitative data collection.

Process Capability Index improvements are equally compelling, with mean Cpk increasing from 0.81 (pre-implementation) to 1.47 (post-implementation), representing an 81.5% improvement. This shift moves the average plant from a 'capable' designation (Cpk > 1.0) to a 'highly capable' designation (Cpk > 1.33) under standard automotive quality certification criteria. All seven plants exceed the Cpk = 1.33 threshold post-implementation, qualifying them for preferred supplier status under the IATF 16949:2016 automotive quality management standard. First Pass Yield improvements (mean +12.5 percentage points) and COPQ reductions (mean -38.7% of revenue) demonstrate the direct operational and financial impact of the DMAIC programmes.



**Figure 2:** QIEI Scores by Plant — Higher score indicates greater Six Sigma improvement effectiveness

### 6. Statistical Analysis

Paired-samples t-tests were conducted for each quality metric to test the statistical significance of pre- to post-DMAIC performance changes across all seven plants. All four metrics yielded highly significant improvements, as reported in Table 3. Effect sizes were computed using Cohen's d, with values exceeding 1.0 for all metrics, indicating large practical effects.

**Table 3:** Paired-Samples t-Test Results for Quality Performance Metrics

Metric	Pre Mean	Post Mean	Mean Diff.	t-stat	p-value	Cohen's d
DPMO	6,244	1,737	-4,507	8.34	< 0.001***	3.15
Cpk	0.810	1.470	+0.660	12.47	< 0.001***	4.71
FPY (%)	83.81	94.26	+10.45	9.83	< 0.001***	3.71
COPQ (%)	13.54	8.30	-5.24	7.61	< 0.001***	2.87

\*\*\*p < 0.001; df = 6 for all tests (n = 7 plants); Cohen's d > 0.8 = large effect

A one-way ANOVA was conducted to examine whether QIEI scores differed significantly across the three countries. The analysis yielded F(2,4) = 6.84 (p = 0.052), approaching but not reaching significance at the 0.05 threshold, likely reflecting the limited degrees of freedom available with seven plants. Indian plants achieved the highest mean QIEI (0.759), followed by Mexican plants (0.723) and Russian plants (0.652).

Multiple regression analysis with QIEI as the dependent variable and Six Sigma maturity, plant output volume, and CSF scores as predictors achieved  $R^2 = 0.871$ , with Six Sigma programme maturity ( $\beta = 0.524$ ,  $p = 0.041$ ) emerging as the strongest predictor of DMAIC implementation effectiveness.

**Table 4:** Critical Success Factor (CSF) Rankings by Country — Mean Scores (1–5 Scale)

Critical Success Factor	India (n=3)	Russia (n=2)	Mexico (n=2)	Overall Rank
Top Management Commitment	4.7	3.9	4.5	1st
Six Sigma Training Quality	4.4	3.6	4.2	2nd
Project Selection Methodology	4.2	3.8	4.1	3rd
Data Availability & Quality	4.0	3.4	3.9	4th
Cross-functional Team Collaboration	3.8	3.2	4.0	5th
Belt Certification Rigour	3.7	3.1	3.8	6th
Customer Linkage	3.5	3.0	3.6	7th
Financial Tracking of Projects	3.3	2.8	3.4	8th

Note: Scores on 5-point Likert scale; 5 = Extremely Critical, 1 = Not Critical

## 7. Discussion Of Findings

The empirical results of this study confirm and extend the Six Sigma effectiveness literature in several important respects. The magnitude of DPMO improvement observed across all seven plants (mean 72.2% reduction) is consistent with the upper range of outcomes documented in comparable automotive sector case studies (Antony et al., 2012; Kwak and Anbari, 2006), suggesting that the structured DMAIC protocol employed in this study — with its rigorous phase-gate review criteria — delivers outcomes at or above industry benchmarks. The consistent pattern of improvement across plants in three culturally distinct countries provides strong evidence that the DMAIC methodology's effectiveness transcends national cultural contexts when implementation is sufficiently structured and supported.

The performance gap between Indian and Russian plants — reflected in higher QIEI scores for Indian facilities — merits specific examination. Interview data reveal that Russian plants faced greater challenges in two CSF areas: cross-functional team collaboration (mean score 3.2 vs. 3.8-4.0 for other countries) and data availability and quality (mean 3.4 vs. 3.9-4.0). These challenges are attributable to the legacy of Soviet-era functional siloes in Russian manufacturing organisations and to less mature ERP and SPC data infrastructure in the Russian plants, consistent with observations by Ilyin and Morozova (2014) regarding quality management development trajectories in post-Soviet manufacturing. Top management commitment emerged as the highest-ranked CSF across all three countries, replicating the finding of Antony and Banuelas (2002) in a cross-national context and reinforcing the primacy of leadership engagement in Six Sigma programme success.

The QIEI demonstrates strong discriminant validity across plants and strong convergent validity with individual quality metric improvements, supporting its utility as a composite benchmarking instrument. Its predictive power is further evidenced by the strong correlation between QIEI scores and the regression-derived Six Sigma maturity predictor ( $r = 0.847$ ,  $p < 0.05$ ), suggesting that plants with longer Six Sigma experience realise proportionally greater improvements from structured DMAIC implementations — a finding with important implications for the design of phased Six Sigma deployment roadmaps in multi-plant manufacturing organisations.

## 8. Conclusions and Recommendations

This paper has presented the results of an 18-month longitudinal investigation of Six Sigma DMAIC implementation across seven automotive component manufacturing plants in India, Russia, and Mexico. The key conclusions are as follows: (1) Structured DMAIC implementation achieves large and statistically significant improvements across all four quality performance metrics, with mean reductions of 72.2% in DPMO and 38.7% in COPQ, and mean increases of 81.5% in Cpk and 12.5 percentage points in FPY; (2) The validated QIEI provides a reliable composite measure for cross-plant Six Sigma programme benchmarking, with scores ranging from 0.621 to 0.801 across the study sample; (3) Six Sigma programme maturity is the strongest predictor of DMAIC implementation effectiveness, underscoring the importance of sustained, long-term commitment to Six Sigma as an organisational capability; and (4) Top management commitment and training quality are the most critical success factors across all three national contexts, while data infrastructure quality is a particular barrier in less technologically mature manufacturing environments.

Five recommendations are advanced for manufacturing quality executives undertaking multi-plant Six Sigma programmes. First, standardise the DMAIC protocol and phase-gate criteria across all plants before programme launch to ensure methodological consistency and enable meaningful cross-plant benchmarking. Second, invest in data infrastructure — including SPC software, real-time defect tracking systems, and integrated quality databases — as a prerequisite to DMAIC deployment, particularly in plants with limited data maturity. Third, adopt a phased deployment approach that prioritises plants with the highest Six Sigma maturity as early adopters, using their documented success to build organisational confidence and transfer lessons to less mature facilities. Fourth, ensure top management visibility and active sponsorship of Six Sigma projects at all levels of the organisation, from corporate leadership to plant general managers. Fifth, invest in robust Black Belt and Green Belt training programmes

with standardised certification criteria to ensure consistent technical capability across geographically dispersed manufacturing networks.

Limitations of this study include the relatively small number of plants (n=7) and the restriction to a single industry sector and component type. Future research should extend the QIEI validation to broader manufacturing sectors and larger plant samples, and should investigate the sustainability of Six Sigma performance gains over multi-year post-implementation periods using longitudinal designs extending beyond the 18-month window of the present study.

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