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An integrated quality assurance framework for UAV component manufacturing: combining ISO 9001, lean Six Sigma, and AI-based inspection systems

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Abstract: Growing demand for precision UAV components has exposed critical gaps in existing manufacturing quality systems. This paper presents a holistic quality assurance framework that unifies ISO 9001:2015, Lean principles, Six Sigma (DMAIC), SPC, FMEA, and AI-driven defect detection within a single operational model for UAV component production. Validation through a structured case study yielded measurable gains: defect rate declined by 67% (4.8% to 1.6%), rework expenditure dropped by 45%, process capability index rose from 0.89 to 1.45, and OEE climbed from 72% to 89%. These outcomes establish a replicable, evidence-based pathway for attaining aerospace-grade quality standards in UAV manufacturing environments.

Keywords: quality assurance, unmanned aerial vehicles, Six Sigma, SPC, FMEA, lean manufacturing, AI defect detection

1. Introduction

Over the past decade, unmanned aerial vehicles (UAVs) have transitioned from niche military tools into a broad commercial technology serving agriculture, logistics, infrastructure inspection, and consumer markets. The global UAV sector was estimated at roughly \$30 billion in 2023 and is forecast to surpass \$90 billion by 2030, reflecting a compound annual growth rate above 15%. This accelerating market expansion places mounting pressure on manufacturers to deliver components that meet aerospace-level precision at economically sustainable costs.

Quality management in UAV production occupies a demanding middle ground between conventional aerospace and consumer electronics. Unlike established manned aviation, UAV manufacturing evolves within a still-maturing regulatory landscape, yet structural integrity, propulsion reliability, and flight control precision must meet standards comparable to those applied to crewed aircraft. Any component-level failure may trigger complete vehicle loss along with substantial safety and legal consequences [1, 2].

Production operations in this sector cover a wide range of material and process types — including carbon fiber composite layup, CNC-machined structural elements, propeller fabrication, and printed circuit board assembly — each carrying its own characteristic defect profile. Nevertheless, many producers, especially small and medium enterprises in developing economies, have not adopted rigorous in-process quality controls and continue to depend predominantly on final inspection [3, 4].

To close this gap, the present study constructs a unified quality assurance framework that brings together ISO 9001:2015, Lean manufacturing, Six Sigma, SPC, FMEA, and AI-assisted visual inspection within a coherent system tailored to UAV component production. The resulting framework is intentionally modular, enabling adoption across facilities of varying scale and complexity.

Literature Review

ISO 9001:2015 serves as the cornerstone quality management standard, with empirical evidence linking its adoption to lower defect incidence across diverse industries [1, 3]. Within aviation and defense supply chains, AS9100 builds on this foundation by adding sector-specific compliance requirements [2]. Lean practices originating from the Toyota Production System — notably 5S workplace discipline, value stream mapping, and standardized work instructions — have been broadly applied in aerospace-adjacent manufacturing to eliminate non-value-adding activities and strengthen product consistency [4, 5].

The Six Sigma DMAIC methodology offers a rigorous, statistically guided problem-solving cycle oriented toward minimizing defect rates to near-zero levels [6, 7]. SPC uses control charts to track process behavior continuously, while Cp and Cpk indices characterize process capability against specification limits [8]. FMEA contributes a structured risk framework that ranks failure modes by their Risk Priority Number, enabling focused preventive intervention [9, 10].

Within the domain of automated inspection, deep learning techniques — particularly convolutional neural network (CNN) architectures — have proven capable of detecting surface and structural defects with a reliability that can surpass manual inspection for high-volume tasks [11, 12]. Despite this progress, no widely accepted framework exists that cohesively integrates these techniques with Industry 4.0 infrastructure specifically for UAV component manufacturing in resource-limited production contexts.

2. Research methodology

Integrated Framework Architecture

The framework is structured around six interlinked functional modules organized across three governance tiers:

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strategic quality management, tactical process improvement, and operational real-time control. Quality goals defined at the strategic tier are translated into targeted improvement initiatives at the tactical tier, which are in turn sustained through continuous monitoring mechanisms at the operational tier.

The ISO 9001-based foundation establishes documented QMS elements including quality policy, process maps, documented procedures, records, management review, and corrective/preventive action processes [1]. Lean tools—including 5S workplace organization, VSM, standard work, and visual management—address waste elimination while supporting quality objectives [4, 5].

Six Sigma, SPC, and FMEA Integration

Six Sigma DMAIC projects define CTQ characteristics, establish baseline capability through measurement system analysis, employ statistical tools for root cause identification, validate solutions, and implement control plans with SPC monitoring and poka-yoke [6, 7]. SPC implementation encompasses Gage R&R validation, X-bar/R charts for dimensional characteristics, and p/u-charts for defect rates [8].

Process FMEA systematically identifies failure modes rated for Severity, Occurrence, and Detection on 1–10 scales, with RPN = S × O × D prioritizing improvement actions [9, 10]. Digital monitoring through MES, IoT sensors, and CNN-based machine vision provides automated defect detection with human-AI collaboration protocols [11, 12].

Mathematical Models

Defect Rate (%) = (Defective Units / Total Units) × 100. Example: 24 defective of 500 carbon fiber frames = 4.8%.

DPMO = (Defects / (Units × Opportunities)) × 1,000,000. Example: 45 defects across 1,000 PCBs with 150 joints = 300 DPMO ($\approx 4.9\sigma$).

Process Capability: $C_p = (USL - LSL) / 6\sigma$; $C_{pk} = \min[(USL - \mu)/3\sigma, (\mu - LSL)/3\sigma]$. Example: bore 25.00±0.05 mm, $\mu = 25.02$, $\sigma = 0.015$: $C_p = 1.11$, $C_{pk} = 0.67$.

OEE = Availability × Performance × Quality. **RPN** = Severity × Occurrence × Detection (1–10 scales).

Quality Assurance Methods Comparison

Table 2 compares the primary quality assurance methods integrated within the framework, highlighting their applications, advantages, and limitations.

Table 2

Comparison of Quality Assurance Methods

Method	Application	Key Metrics	Advantages	Limitations
ISO 9001	System documentation	Audit conformance, NCR closure	Comprehensive framework	Generic; needs adaptation
Lean (5S, VSM)	Waste elimination	Lead time, WIP inventory	Visual mgmt, engagement	Requires cultural change
Six Sigma	Root cause analysis	DPMO, sigma level	Data-driven, structured	Resource intensive
SPC Charts	Real-time monitoring	Cp, Cpk, control signals	Early detection, prevention	Needs adequate measurement
FMEA	Risk prioritization	RPN, severity ratings	Systematic risk assessment	Subjective; needs updating
AI Inspection	Automated detection	Detection rate, FP rate	Consistency, speed	Training data needs

Case Study: UAV Manufacturing Quality Improvement

Context and Defect Analysis

The framework was implemented at a hypothetical UAV facility producing commercial inspection and agriculture drones (~2,000 units/year, 45 production + 5 quality personnel). Initial assessment identified primary defect types across four component categories (Table 1).

Table 1

Defect Types and Root Causes

Component	Defect Type	Rate	Root Cause
Carbon Fiber Frame	Delamination	3.2%	Inadequate vacuum pressure; temp. variation
Carbon Fiber Frame	Porosity/Voids	2.1%	Entrapped air; insufficient cure pressure

Motor Mount	Dimensional Error	2.8%	Tool wear; thermal expansion; fixture loosening
Propeller	Blade Imbalance	4.1%	Inconsistent material distribution
PCB Assembly	Solder Defects	5.2%	Paste printing variation; reflow deviation

Implementation and Results

Implementation proceeded over 12 months in four phases: Phase 1 (months 1–3) established ISO 9001-aligned QMS, 5S, and initial SPC; Phase 2 (months 4–6) completed PFMEA and initiated DMAIC projects; Phase 3 (months 7–9) deployed MES with IoT sensors and AI inspection; Phase 4 (months 10–12) refined control systems and management review. Table 3 summarizes key results.

Table 3

Before vs. After Performance Metrics

Performance Metric	Baseline	After Implementation	Improvement
Overall Defect Rate	4.8%	1.6%	67% reduction
Rework Rate	12.5%	4.2%	66% reduction
Scrap Rate	3.2%	0.9%	72% reduction
Process Capability (Cpk)	0.89	1.45	63% improvement
OEE – Composite Process	72%	89%	24% improvement
First Pass Yield	82%	94%	15% improvement
Customer Returns (ppm)	1,850	420	77% reduction
Cost of Quality (% Rev.)	8.4%	4.1%	51% reduction

DMAIC Example: Composite Delamination Reduction

A focused DMAIC project targeted delamination reduction from 3.2% to below 1.0%. Measurement system validation achieved GR&R of 12%. DOE analysis identified temperature ramp rate and vacuum pressure as statistically significant factors. Optimized parameters—vacuum pressure increased from 85 to 95 kPa, ramp rate reduced from 3°C/min to 2°C/min, hold time extended from 90 to 120 minutes—reduced delamination to 0.7% within six months.

3. Results and Discussion

Performance gains recorded across the study period confirm the effectiveness of the multi-method approach. A 67% drop in overall defect rate, paired with Cpk growth from 0.89 to 1.45, reflects a measurable elevation in process precision. The decline in cost of quality from 8.4% to 4.1% of revenue provides clear financial justification for the investment. The framework generates compounding benefits through method interaction: ISO 9001 documentation creates the structural backbone that enables reliable SPC, Lean workplace organization reduces variation sources that would otherwise confound statistical monitoring, Six Sigma DMAIC analysis generates evidence that sharpens FMEA risk prioritization, and AI-based inspection delivers consistent throughput on high-volume repetitive checks where human fatigue is a risk factor.

Deployment was not without obstacles. Workforce adaptation to new quality disciplines demanded persistent leadership engagement over an extended period. Upgrading measurement infrastructure and assembling sufficient labeled imagery for AI model training both required more effort and time than initially projected. Overall, first-year program costs reached approximately $565,000 against realized benefits of $745,000, yielding a 32% return on investment. The stepwise implementation structure proved particularly appropriate for environments with constrained budgets, making the framework well-suited to growing UAV production sectors in regions such as Central Asia.

4. Conclusion

A unified quality assurance framework for UAV component manufacturing was constructed and evaluated, drawing on ISO 9001, Lean, Six Sigma, SPC, FMEA, and AI-powered visual inspection as complementary pillars. Case study outcomes confirm substantial operational gains: a 67% reduction in defect rate (4.8% to 1.6%); rework and scrap rate reductions of 66% and 72% respectively; Cpk advancement from 0.89 to 1.45; OEE growth from 72% to

89%; cost of quality improvement from 8.4% to 4.1%; and a 77% decrease in customer returns. Promising avenues for further development include digital twin-based process simulation, predictive quality analytics leveraging real-time sensor data, broader IoT sensor coverage, and structured pathways toward formal airworthiness certification for emerging UAV platforms [13, 14, 15].

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