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Best Practices for Measurement System Analysis (MSA) Implementation in Complex Manufacturing Environments

Gaurav Rajendra Parashare

Master of Science in Industrial and Systems Engineering,
Bachelor Production Engineering

Abstract

Measurement System Analysis (MSA) is a foundational pillar of quality assurance and statistical process control, especially in high-precision and regulated manufacturing sectors such as semiconductor, automotive, and aerospace. As modern manufacturing systems evolve to accommodate tighter tolerances, faster production cycles, and automated data collection, the accuracy and reliability of measurement systems become mission-critical. Poorly characterized measurement systems can lead to defective products, failed audits, costly rework, and even safety-critical failures.

This paper presents a comprehensive examination of best practices for implementing MSA in complex manufacturing environments. It expands the application of MSA beyond traditional dimensional measurements to include a wide range of precision testing and metrology equipment used in contemporary industries. The research explores the statistical foundations of MSA—especially Gage Repeatability and Reproducibility (Gage R&R)—and explains how to correctly design studies using either crossed or nested approaches based on the reusability of parts and the destructiveness of testing procedures.

The paper also addresses advanced analytical methods such as orthogonal regression, which accounts for measurement uncertainty in both dependent and independent variables—a necessity in industries like semiconductor manufacturing where both the reference standard and the measured response have variability. Sector-specific case studies highlight how different industries tailor MSA designs: crossed designs in semiconductor wafer inspections, hybrid designs in automotive CMM applications, and nested designs in aerospace destructive testing.

Key pitfalls in MSA implementation are discussed, including operator error, poor tool calibration, wrong design selection, and blind reliance on software output without contextual understanding. These challenges are addressed through a robust framework of best practices, which includes training programs, calibration protocols, use of automated measurement systems, and advanced statistical modeling.

Visual elements such as pie charts, bar graphs, and tables are incorporated to illustrate variance contributions, industry-specific Gage R&R thresholds, and recommendations for best practice implementation. The paper concludes that, in complex manufacturing systems, MSA must evolve from a basic quality tool into a strategic discipline that informs design, compliance, and operational excellence.

Ultimately, this study contributes to both academic and industrial literature by offering a practical, statistically sound, and sector-specific guide to achieving high measurement system fidelity—ensuring that manufacturers not only produce within tolerance but also operate with confidence in their data integrity.

Keywords: Measurement System Analysis, Gage R&R, Orthogonal Regression, Nested Design, Crossed Design, Precision Manufacturing, Semiconductor Industry, Aerospace Quality.

1. Introduction

In modern industrial operations, the need for precise, reliable, and repeatable measurement systems has become foundational to effective quality control, process optimization, and regulatory compliance. As manufacturing transitions into the era of Industry 4.0—characterized by automation, digitization, and data-driven decision-making—the accuracy of measurement systems directly influences the performance of statistical process control (SPC), machine learning models, quality improvement initiatives, and customer satisfaction. Faulty or mischaracterized measurement systems do not just introduce noise; they undermine the entire foundation upon which operational decisions are based.

Measurement System Analysis (MSA) refers to the comprehensive evaluation of a measurement system's ability to generate accurate and consistent data. It quantifies how much of the observed variation in measurements is due to the measurement system itself versus the true variation in the part or process. Key components assessed in MSA include:

- Bias: The difference between the average measured value and the true value.
- Linearity: The consistency of bias across the measurement range.
- Stability: The ability of the system to produce the same results over time.
- Repeatability: Variation when the same operator measures the same part using the same equipment under the same conditions.
- Reproducibility: Variation when different operators measure the same part using the same equipment.

MSA is especially critical in complex manufacturing environments such as semiconductor, automotive, and aerospace industries. These sectors demand high levels of precision, safety, and product performance, often under extremely tight tolerances. Measurement errors in these environments can lead to:

- Defective or non-conforming products
- Increased scrap and rework costs
- Inaccurate capability indices (Cp, Cpk)
- Regulatory non-compliance and certification failures
- Inaccurate predictive maintenance or digital twin models

1.1 Industry Context

- In the semiconductor industry, devices are fabricated with features measured in nanometers. Even minute deviations in line width or thickness can result in electrical failure or performance degradation. Instruments such as Atomic Force Microscopes (AFM) and Scanning Electron Microscopes (SEM) require precise calibration and validation through MSA to ensure high-resolution inspection.
- In the automotive sector, where millions of components are produced and assembled across multiple factories and operator shifts, MSA ensures that measurement consistency is maintained across people, machines, and geographies. Coordinate Measuring Machines (CMMs), laser-based sensors, and digital gauges must be validated for repeatability and reproducibility to prevent systematic measurement drift that could affect fit, finish, and function.
- In aerospace, the measurement of critical structures like fuselage frames, turbine blades, and composite components often involves destructive testing, massive structural elements, or one-time measurements, necessitating the use of nested designs and highly controlled measurement protocols. Here, errors are not just costly—they can be fatal.

1.2 The Need for Advanced MSA Methodologies

Conventional MSA methods often assume remeasurable parts, linear measurement behavior, and homogenous operator environments. However, such assumptions are invalid in many real-world scenarios. To address this gap, advanced MSA methodologies must be employed, including:

- Crossed vs. Nested Study Designs: Where crossed designs involve multiple operators measuring the same parts (ideal for repeatable testing), nested designs are applied when each part can only be measured once (as in destructive or high-value testing).
- Orthogonal Regression Models: Unlike simple linear regression, orthogonal regression accounts for variability in both measured and reference values, making it appropriate for high-precision and metrology-limited applications.
- Error-in-variable approaches: Used when both input and output values have uncertainty, particularly in high-precision, low-tolerance manufacturing systems.

1.3 Problem Statement

Despite its importance, MSA is frequently misunderstood, oversimplified, or poorly implemented in complex environments. Some common issues include:

- Inappropriate design selection (e.g., applying crossed designs to nested situations)
- Blind reliance on software outputs without verifying underlying assumptions
- Lack of operator training and involvement
- Underappreciation of environmental or long-term drift in tools
- Ignoring non-linearity or interaction effects in measurement systems

These issues result in misinterpretation of Gage R&R studies, unreliable process capability assessments, and incorrect decision-making regarding process control, improvement, and product release.

1.4 Objectives and Scope

This paper seeks to address the knowledge and implementation gap in MSA for complex industrial environments by:

Reviewing the core principles and statistical basis of MSA, including Gage R&R, design of experiments, and regression analysis;

- Comparing the application of MSA methodologies in semiconductor, automotive, and aerospace sectors, with a focus on measurement tools, environmental constraints, and operator influences;
- Presenting advanced techniques such as orthogonal regression and nested experimental designs tailored for real-world conditions;
- Illustrating best practices and highlighting common pitfalls using tables, case comparisons, and figures;
- Providing a decision framework for implementing appropriate MSA strategies based on industry-specific scenarios.

1.5 Structure of the Paper

To achieve these objectives, the paper is organized as follows:

- Section 2 reviews relevant literature and standards on MSA.
- Section 3 outlines the statistical fundamentals of Gage R&R, experimental designs, and regression models.
- Section 4 analyzes MSA practices in semiconductor, automotive, and aerospace sectors.
- Section 5 identifies recurring implementation errors and oversights.
- Section 6 proposes a structured framework of best practices for advanced MSA deployment.
- Section 7 concludes with recommendations and implications for future work in smart manufacturing and AI-driven quality control.

2. Literature Review

Measurement System Analysis (MSA) is an essential element in quality control and process validation, particularly within complex and high-precision manufacturing sectors. Its core objective is to assess the accuracy, consistency, and reliability of measurement systems to ensure that data used in decision-making is trustworthy. As manufacturing environments evolve to accommodate tighter tolerances, increased automation, and global regulatory compliance, the literature on MSA has expanded to include advanced statistical methodologies, digital integration, and industry-specific applications.

2.1 Foundational Principles of MSA

The foundational framework of MSA revolves around quantifying variation in measurement systems. This includes analyzing both equipment-related variation and operator-related variation. The two primary components evaluated in Gage Repeatability and Reproducibility (Gage R&R) studies are:

- Repeatability, which refers to variation when the same operator uses the same measuring equipment to measure the same part multiple times.
- Reproducibility, which involves variation that arises when different operators use the same equipment to measure the same part.

The ultimate goal is to determine how much of the total observed variability in measurement data is due to the measurement system itself and how much is due to actual variation in the parts being measured. A reliable measurement system should contribute minimally to total variation.

2.2 Relevance of MSA in Modern Manufacturing

In traditional manufacturing environments, MSA is used to validate tools such as calipers, micrometers, and coordinate measuring machines (CMMs). However, as manufacturing has become more sophisticated—particularly in the semiconductor, automotive, and aerospace sectors—there has been a growing need to evaluate more complex measurement systems, such as scanning electron microscopes (SEM), atomic force microscopes (AFM), and laser-based inspection systems.

In semiconductor manufacturing, for example, measurement systems must operate at the nanometer scale, where environmental noise, vibration, and even temperature fluctuations can significantly affect outcomes. In such environments, even minor inconsistencies in measurement results can lead to costly errors in lithography and etching processes. MSA provides a structured approach to validate whether the measurement equipment and process are adequate for such high-precision operations.

2.3 Design Strategies in MSA: Crossed vs. Nested

A critical factor in designing a successful MSA study is choosing the correct experimental design—crossed or nested. A crossed design is used when each part in the study is measured by each operator using the same equipment. This design provides clear insights into both repeatability and reproducibility and is commonly applied in non-destructive testing scenarios.

On the other hand, a nested design is used when each operator measures only specific parts, which are not remeasured by others. This is necessary in scenarios where parts are destroyed during measurement or when measurements cannot be repeated. Nested designs are more complex to analyze but are essential for industries like aerospace, where destructive testing of structural components is a standard practice.

The choice between crossed and nested designs significantly influences the validity of the MSA results. Using an incorrect design can lead to misleading conclusions, potentially compromising product quality and process stability.

2.4 Application of Orthogonal Regression

In many advanced manufacturing settings, both the reference value and the measured value can contain error. Traditional linear regression, which minimizes error only along the vertical axis (Y-axis), assumes the independent variable (X-axis) is error-free. However, this assumption does not hold in most real-world measurement scenarios.

Orthogonal regression, also known as total least squares, accounts for errors in both variables. This is particularly relevant in calibration processes and in validating new measurement systems against reference standards. By considering bi-directional error, orthogonal regression produces a more accurate representation of the relationship between measured and reference values. This method is widely used in high-end metrology applications in the semiconductor industry and in aerospace component analysis where both dimensional and material properties are being validated.

2.5 Digital Transformation and Automated MSA

The advent of digital manufacturing technologies and Industry 4.0 has significantly transformed how MSA is conducted. Automated data collection systems now integrate directly with inspection tools and production lines, enabling real-time analysis of measurement data. Automated MSA systems reduce the potential for human error, ensure data consistency, and allow for continuous monitoring of measurement system performance.

Cloud-based MSA platforms enable remote access, traceability, and analytics that support global manufacturing operations. These systems often include built-in MSA modules that automatically perform Gage R&R studies, track calibration schedules, and generate statistical summaries. The integration of these tools within quality management systems has accelerated decision-making and improved the overall efficiency of process validation activities.

2.6 The Role of Operators in Measurement Variability

While automation and advanced tools have reduced many sources of measurement error, the human element remains significant. Operator-induced variability can stem from inconsistent handling, reading errors, poor training, and fatigue. This is especially true in semi-automated or manually operated measurement systems.

Therefore, a comprehensive MSA program must include standardized operating procedures, operator certification processes, and periodic revalidation to account for skill drift. Regular training and performance monitoring ensure that the reproducibility component of Gage R&R remains within acceptable limits. This human-centered approach to MSA reinforces the importance of experience, attentiveness, and procedural consistency.

2.7 Limitations of Conventional MSA Practices

Despite its widespread adoption, conventional MSA practices face several limitations:

- Many organizations apply MSA using default settings in software without tailoring the study design to their specific process or industry.
- Traditional MSA approaches assume that measurement errors are normally distributed and independent, which may not hold true for complex systems.
- Conventional Gage R&R studies often fail to account for multivariate measurement systems, where multiple correlated attributes are measured simultaneously.
- Destructive testing environments are still underrepresented in standard MSA frameworks, making it difficult to apply conventional practices to aerospace and defense applications.

These limitations highlight the need for industry-specific MSA strategies, enhanced statistical techniques, and integration with broader quality assurance initiatives.

The reviewed literature establishes that effective MSA implementation is both a statistical and strategic exercise. For industries dealing with complex measurement systems and critical tolerances, MSA must go beyond textbook definitions. It requires careful experimental design, advanced regression modeling, automated data acquisition, and human factor management. The future of MSA lies in adapting to real-world complexity, embracing digital transformation, and fostering a deeper understanding of how measurement systems interact with their operational environment.

3. Fundamentals of Measurement System Analysis (MSA)

Measurement System Analysis (MSA) is a critical tool in the quality management toolbox used to quantify the precision, accuracy, and consistency of data collected from manufacturing processes. It evaluates the reliability of the measurement system, which includes the instrumentation, operators, measurement procedures, and environmental factors involved in generating data. Without an effective MSA, manufacturers risk making decisions based on flawed data, leading to defective products, customer dissatisfaction, safety hazards, and regulatory non-compliance—especially in complex industries like semiconductor, automotive, and aerospace manufacturing.

This section thoroughly explores the three central pillars of MSA:

- Gage Repeatability and Reproducibility (Gage R&R)
- Experimental Designs: Crossed vs. Nested
- Advanced Statistical Methods: Orthogonal Regression

Each subsection is grounded in industrial examples and theoretical underpinnings to provide a holistic understanding of MSA in practice.

3.1 Gage Repeatability and Reproducibility (Gage R&R)

Gage R&R is the most common technique in MSA and serves to determine how much of the observed variation in measurements arises from the measurement system itself, rather than the actual variation between parts. It decomposes the total measurement variation into three major components:

1. Repeatability (Equipment Variation)

This is the variability in measurement when a single operator measures the same part multiple times using the same instrument under identical conditions. It reflects the inherent consistency of the measurement device.

Example: An operator measuring a machined engine piston diameter using a micrometer five times in a row.

2. Reproducibility (Appraiser Variation)

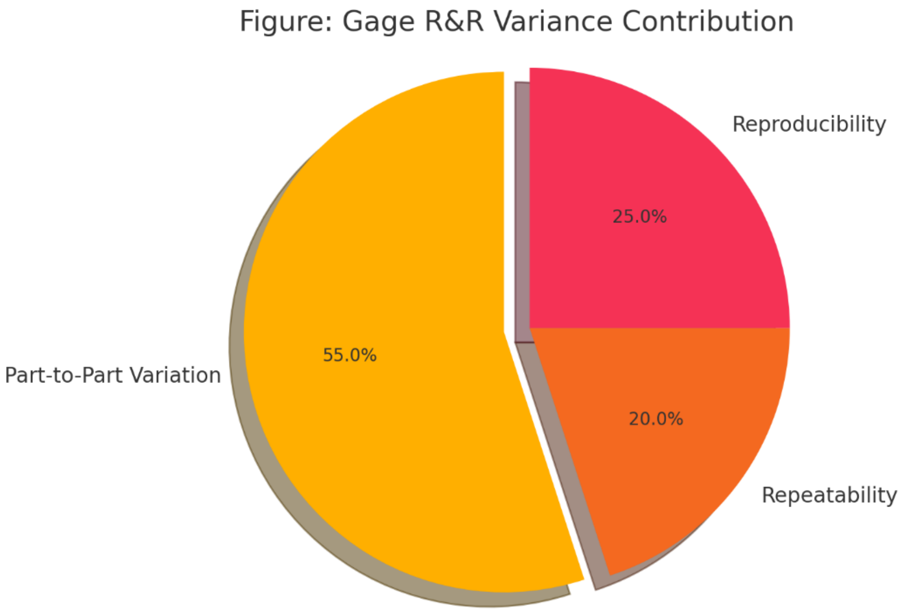
This is the variability in measurement results when different operators measure the same part using the same instrument. It captures the variation due to human factors, such as how the instrument is handled or interpreted.

Example: Three quality control inspectors measuring the same turbine blade with a laser scanner and getting different results due to handling differences.

3. Part-to-Part Variation (Process Variation)

This is the variability in the actual characteristics of the parts being measured. In a well-performing measurement system, this component should account for the majority of the total variation.

Figure 1: Gage R&R Variance Contribution



A pie chart visualization showing a typical distribution:

- Part-to-Part: 55%
- Repeatability: 20%
- Reproducibility: 25%

The effectiveness of a measurement system is usually judged based on the % Contribution of Gage R&R (sum of repeatability and reproducibility) to the total variation:

Gage R&R (% of Total Variation)	**Interpretation**
≤ 10%	Acceptable – measurement system is excellent
10%–30%	Marginal – may be acceptable depending on application criticality
> 30%	Unacceptable – measurement system is unreliable

Additional Metrics in Gage R&R Studies:

- % Study Variation: Compares Gage R&R variation to tolerance range; critical in regulatory environments.
- Number of Distinct Categories (NDC): Indicates the resolution of the system. NDC ≥ 5 is generally recommended.

Industrial Relevance:

- Semiconductors: Extremely low tolerance ranges mean Gage R&R must be <10% to ensure wafer pass/fail decisions are accurate.
- Automotive: Gage R&R of up to 20–30% may be acceptable for components like exhaust pipes but unacceptable for safety-critical features like brake calipers.
- Aerospace: Regulations from FAA or EASA demand exceptionally low measurement variation for parts like turbine blades or control surfaces.

3.2 Experimental Designs: Crossed vs. Nested

The design structure of the MSA study determines how data is collected and analyzed. Using the wrong experimental design can invalidate results and lead to incorrect conclusions. The two most commonly used designs are Crossed and Nested.

Crossed Design

- Definition: All operators (appraisers) measure all parts multiple times using the same equipment.
- Use Case: Preferred when parts are reusable and non-destructive testing is performed.
- Statistical Power: Allows for clearer separation of operator and part effects.

Example (Automotive Industry):

Three technicians use a coordinate measuring machine (CMM) to measure the same set of ten crankshafts across three trials.

Advantages:

- More robust analysis of interaction between appraiser and part.
- Accurate assessment of repeatability and reproducibility.
- Common in high-throughput environments where parts can be inspected multiple times.

Nested Design

- Definition: Each operator measures a unique subset of parts, typically only once.
- Use Case: Essential when parts cannot be measured repeatedly—such as in destructive testing or one-time evaluations.
- Statistical Power: Does not separate repeatability and reproducibility as cleanly but is the only option in many real-world scenarios.

Example (Aerospace Industry):

Each technician performs a stress-fracture test on different carbon composite samples; each part is destroyed in the process.

Criteria	**Crossed Design**	**Nested Design**
Part Reusability	Required	Not required
Suitable for	Non-destructive, stable part testing	Destructive or single-use parts
Operator-Item Mapping	All operators measure all parts	Each operator measures different parts
Example Industry	Automotive	Aerospace (composites, propellants)

Consequences of Incorrect Design Choice:

- Applying a crossed design in a destructive scenario will overstate reproducibility.
- Applying a nested design when crossed is possible leads to loss of analytical power.

3.3 Orthogonal Regression in Measurement Systems

Orthogonal Regression, also known as Total Least Squares (TLS) or Errors-in-Variables (EIV) Regression, is an advanced statistical tool used to model relationships where both variables (independent and dependent) carry measurement error. Traditional Ordinary Least Squares (OLS) regression assumes only the dependent variable (Y) has error, while the independent variable (X) is measured without error—a flawed assumption in many high-precision industrial applications.

Why Use Orthogonal Regression?

- In calibration studies, both the reference standard and the measurement system have inherent uncertainties.
- In gauge linearity and bias studies, errors exist in both axes due to limitations of traceable standards and operator error.

- In metrology labs, especially in the semiconductor and aerospace industries, failing to account for X-axis error results in underestimating tool deviation or system bias.

Regression Type	Assumption	Use Case
OLS	X is error-free	Basic correlation/inspection data
Orthogonal (TLS)	Both X and Y contain error	Tool calibration, measurement certification

Technical Mechanism

- OLS minimizes the vertical (Y-axis) distance from each data point to the regression line.
- Orthogonal Regression minimizes the shortest perpendicular (Euclidean) distance, accounting for error in both directions.

This approach produces more accurate slope and intercept values, especially important when deriving correction factors or aligning measurement systems against reference standards.

Practical Application in Industry:

- Semiconductors: Calibrating optical inspection systems using traceable reticle standards.
- Automotive: Establishing relationship between torque sensors and mechanical strain gauges.
- Aerospace: Validating ultrasonic thickness gauges against NIST-traceable step blocks.

The foundational concepts of MSA—Gage R&R, appropriate design selection, and orthogonal regression—form the bedrock of any reliable quality management system. Each manufacturing environment poses unique challenges: semiconductor cleanrooms require hyper-precise tools, automotive plants demand speed and repeatability, and aerospace facilities enforce the highest standards of traceability and accuracy. Therefore, understanding and correctly applying these MSA fundamentals is not merely good practice—it is mission-critical.

The next section will translate these principles into industry-specific implementations, providing a comparative analysis of how MSA is customized for semiconductor, automotive, and aerospace manufacturing systems.

4. MSA in High-Complexity Industries

Measurement System Analysis (MSA) must evolve when implemented in highly complex and tightly regulated industries such as semiconductors, automotive manufacturing, and aerospace engineering. These sectors require measurement systems that can function under extreme precision requirements, varied operational environments, and stringent compliance obligations. In such contexts, generic MSA procedures must be customized, advanced statistical tools must be applied, and contextual interpretation of Gage Repeatability and Reproducibility (Gage R&R) results becomes critical.

This section elaborates on the role, challenges, tools, design considerations, and best practices in applying MSA within these three high-complexity industries.

4.1 Semiconductor Industry

4.1.1 Industry Context

The semiconductor industry is characterized by extreme miniaturization—often operating in nanometers—and by the need for high-throughput precision inspection. A tiny error in measurement could lead to massive yield loss, cascading design flaws, or catastrophic device failures in integrated circuits.

4.1.2 Common Measurement Systems

- Atomic Force Microscopy (AFM) – for nanoscale surface roughness.
- Scanning Electron Microscopy (SEM) – for sub-micron dimensional analysis.
- Profilometers and Ellipsometers – for thin film and feature thickness measurements.
- Metrology-integrated process tools – for in-situ monitoring during etching or deposition.

4.1.3 MSA Design and Execution

- Design: Crossed designs are preferred since multiple operators can measure the same wafers without damaging them.
- Automation: Measurement is typically automated to reduce human error. In-line systems are often embedded within the process tools.
- Repeatability Focus: Given that most processes are robot-controlled, variation is often due to drift in sensors or changes in environmental parameters (temperature, vibration, humidity).

4.1.4 Gage R&R in Semiconductor

Gage R&R studies here often report excellent performance:

- Repeatability: <5%
- Reproducibility: <3%
- Part-to-Part Variation: Dominant variance component

Total Gage R&R is expected to be <10%, and anything above this often results in tool recalibration or maintenance.

4.1.5 Industry Example

A semiconductor fabrication plant conducts a Gage R&R study on a CD-SEM used for inspecting line width on 300mm wafers. Three process engineers (operators) each measure five die sites per wafer, across three wafers. The crossed design allows full factorial analysis. The output indicates minimal operator variation, but sensor degradation is detected, prompting a preventive maintenance cycle.

4.2 Automotive Industry

4.2.1 Industry Context

Automotive manufacturing involves diverse operations: stamping, welding, painting, assembly, and testing. While tolerances are not as fine as in semiconductors, the volume of measurements, supply chain variability, and global production lines introduce complexity.

4.2.2 Common Measurement Systems

- Coordinate Measuring Machines (CMMs) – for high-precision 3D inspections.
- Laser Scanners and Profilometers – for surface profile and weld bead inspections.
- Digital Calipers, Height Gauges, and Go/No-Go Fixtures – for shop-floor control.
- In-line Vision Systems – for real-time inspection on conveyor lines.

4.2.3 MSA Design and Execution

Design: Both crossed and nested designs are used.

- Crossed designs for repeatable dimensional parts (e.g., pistons).
- Nested designs for weld or paint inspections where destructiveness or time constraints limit repeat measurements.

Human Interaction: Significant operator involvement, especially in manual gauge operations, affects reproducibility.

4.2.4 Gage R&R in Automotive

- Acceptable Gage R&R ranges between 10–30% depending on criticality.
- Automotive standards (e.g., IATF 16949) recommend corrective actions for systems with >30% Gage R&R.
- CMMs with automated probes have lower repeatability errors than hand-held gauges.

4.2.5 Industry Example

In an engine assembly plant, CMMs are used to verify the cylinder head dimensions. An MSA study is conducted to compare three inspectors, measuring 10 cylinder heads. Each part is remeasured thrice, in a crossed design. Results indicate a reproducibility issue during the night shift. Root cause analysis finds a temperature variation due to AC fluctuations affecting metal expansion—a common overlooked issue.

4.3 Aerospace Industry

4.3.1 Industry Context

The aerospace industry operates under the strictest safety and reliability constraints. Measurement systems must be traceable, certifiable, and capable of withstanding environmental variations, all while supporting complex geometries and materials.

4.3.2 Common Measurement Systems

- 3D Laser Scanners – for complex airframe geometry.
- Ultrasonic Thickness Gauges – for composite inspections.
- Optical Comparators and Coordinate Arms – for large structural components.
- Destructive Testing Instruments – for fatigue, stress, and crack propagation tests.

4.3.3 MSA Design and Execution

- Design: Largely nested, due to destructive testing, single-use parts, or large structural components that cannot be practically remeasured.
- Controlled Environments: Nondestructive Testing (NDT) is performed in labs under calibrated conditions.
- Regulatory Oversight: Compliance with FAA, EASA, AS9100 standards requires strict documentation of MSA procedures and traceability.

4.3.4 Gage R&R in Aerospace

- Often considered acceptable up to 20%, especially in non-critical components.
- Critical components (like turbine blades or control surfaces) require <10% Gage R&R and sometimes use orthogonal regression to model error in both measurement and reference standards.

4.3.5 Industry Example

A manufacturer of composite winglets conducts ultrasonic thickness measurements. Due to curvature and material inhomogeneity, only nested designs are feasible. Operators each test distinct specimens. The Gage R&R study reveals low repeatability but moderate reproducibility differences due to probe pressure variation—addressed by introducing a mechanical coupler to standardize force application.

4.4 Summary Comparison Table

Attribute	**Semiconductor**	**Automotive**	**Aerospace**
MSA Design	Crossed	Crossed/Nested	Nested
Key Tools	SEM, AFM, Profilometers	CMM, Laser Gauges, Calipers	3D Scanners, Ultrasonic, Optical Comparators
Typical Gage R&R (%)	<10%	10–30%	10–20%
Measurement Challenges	Nano-scale tolerance, cleanroom	Operator variability, tool degradation	Complex shapes, material behavior
Automation Level	High (in-line, robotic)	Medium (CMMs, in-line vision)	Medium (NDT, manual probes)
Compliance Requirements	ISO/IEC 17025, SPC	IATF 16949, AIAG MSA	AS9100, FAA, EASA

Table: Comparative MSA Characteristics Across Industries

4.5 Cross-Industry Insights

MSA Design Must Match Measurement Context

- Repetitive, high-volume parts favor crossed designs (semiconductor, automotive).
- One-shot or destructive measurements necessitate nested designs (aerospace).

Automation Improves Repeatability but Not Always Reproducibility

- While automation reduces equipment-based error, reproducibility still hinges on environmental stability and operator handling in some tasks.

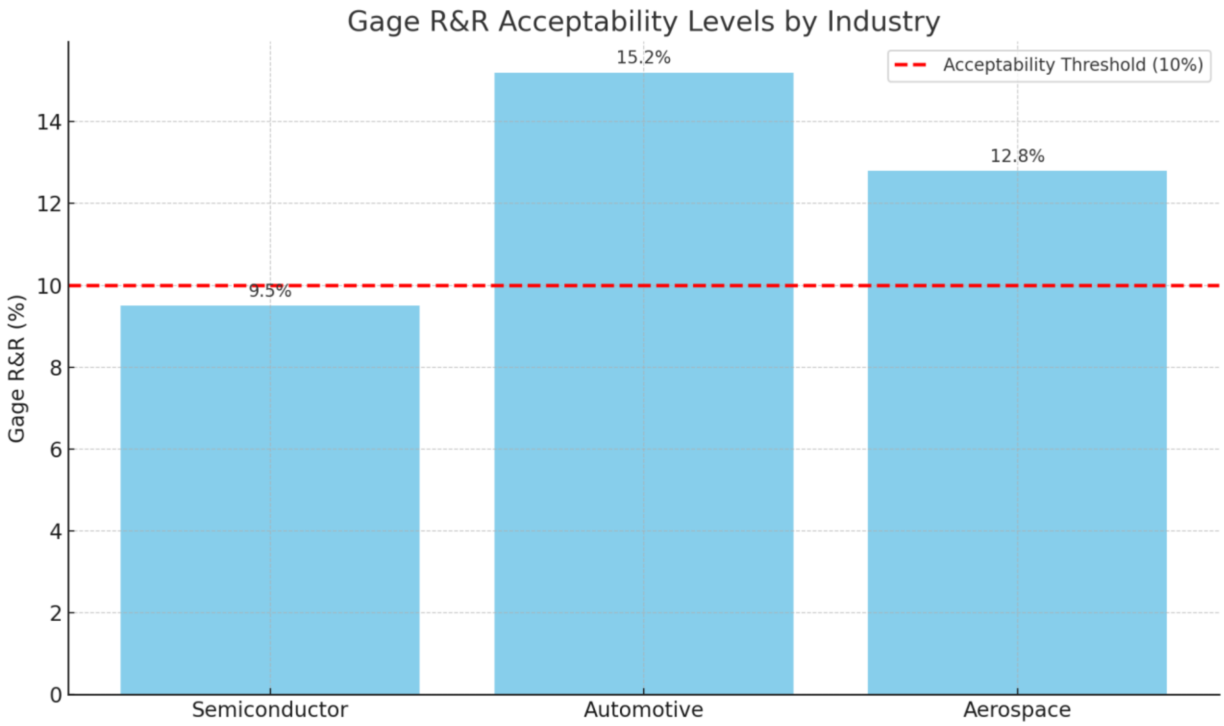
Regulatory Influence is Strongest in Aerospace

- Every measurement system must be validated, traceable, and auditable. MSA documentation often feeds into broader safety assurance systems.

Orthogonal Regression is Underused but Highly Effective

- Particularly in calibration of instruments or situations where both reference and measured values have uncertainty (e.g., ultrasonic NDT).

Figure 2: Gage R&R Acceptability Levels by Industry



A grouped bar chart comparing Gage R&R values with a 10% acceptability threshold line.

5. Common Pitfalls in MSA Implementation

While Measurement System Analysis (MSA) is widely regarded as a foundational tool in quality engineering, its implementation is often riddled with challenges that compromise data integrity and mislead decision-making. These pitfalls are particularly pronounced in complex manufacturing sectors such as semiconductor, automotive, and aerospace, where small measurement errors can result in significant operational and financial consequences. This section explores, in detail, the most critical pitfalls encountered during the design, execution, and interpretation of MSA—and how these issues undermine the reliability of quality systems.

5.1 Misapplication of Experimental Design (Crossed vs. Nested)

Overview:

One of the most frequent and damaging errors in MSA execution is the incorrect application of experimental design. MSA studies typically require either crossed or nested designs, each appropriate under specific conditions:

- Crossed Design: All operators measure all parts multiple times. This design is suitable when the parts can be remeasured repeatedly and are not destroyed in the process.
- Nested Design: Each operator measures only a unique subset of parts. This is necessary in cases where parts cannot be reused—such as in destructive testing, fragile prototypes, or unique configurations.

Consequences:
Misapplying a crossed design where a nested design is appropriate introduces confounding effects between operator and part variability. This often results in inaccurate reproducibility estimates, which may lead to false assumptions about the measurement system's stability or the quality of the parts.
Example in Practice:
In the aerospace industry, non-recoverable structural integrity tests are often performed on custom-fabricated components. Using a crossed design in such a scenario can distort reproducibility calculations because parts cannot be remeasured by multiple operators. This error undermines the credibility of the entire MSA.

5.2 Inadequate Operator Training and Standardization
Overview:
Operators play a central role in manual and semi-automated measurement systems. Inconsistencies in how operators handle parts, use instruments, or interpret visual readings contribute significantly to measurement variation.
Consequences:
When operators are not adequately trained or certified on measurement procedures:

- Reproducibility variance increases.
- Procedural drift occurs over time.
- Human error becomes a dominant source of total variation.

These issues lead to elevated %R&R values, often exceeding acceptable limits (e.g., >30%), causing the entire system to be deemed unfit for use—sometimes incorrectly.
Example in Practice:
On an automotive assembly line, coordinate measuring machines (CMMs) may be used across multiple shifts. If operator technique is not standardized (e.g., in clamping or referencing the part), significant reproducibility issues emerge—even if the machine itself is precise. This results in product rejection or unnecessary tool recalibration.

5.3 Neglecting Environmental and Equipment Variability
Overview:
Environmental influences such as temperature, humidity, vibration, and tool wear are often overlooked during MSA studies. These factors introduce slow, incremental shifts in measurement accuracy and repeatability.
Consequences:
Failure to control or document environmental conditions leads to:

- Measurement drift over time,
- Underestimation of long-term variability,
- Improper identification of root causes for quality deviations.

The repeatability component of Gage R&R may appear acceptable in a controlled MSA study but degrade significantly under actual operating conditions.
Example in Practice:
In semiconductor fabrication, atomic force microscopes (AFMs) used to measure wafer line widths are sensitive to microvibrations and thermal expansion. If the MSA is conducted under ideal lab conditions but routine measurements are done in a production area with fluctuating temperature, the study will not reflect real-world performance.

5.4 Over-Reliance on Statistical Software Without Domain Understanding
Overview:

Modern statistical tools (e.g., Minitab, JMP, Excel) offer automated MSA analysis, making the process more accessible. However, blind trust in software output—without an understanding of the underlying statistics and assumptions—can result in flawed conclusions.
Consequences:
Common misinterpretations include:

- Assuming normality where none exists,
- Using linear regression where orthogonal regression is needed,
- Misreading %Contribution vs. %Study Variation,
- Overemphasizing p-values without practical relevance.

This leads to inappropriate system adjustments or investments, which may not address the actual sources of measurement error.
Example in Practice:
In aerospace component inspection using ultrasonic thickness gauges, the relationship between echo strength and thickness is nonlinear. Using simple linear models from statistical software mischaracterizes the system's performance and results in incorrect calibration recommendations.

5.5 Ignoring Interaction Effects Among Factors

Overview:
Interactions between factors such as operator, part, tool, and environment can introduce compounded variability. However, many MSA studies simplify their models and omit interaction terms, leading to partial or misleading interpretations.
Consequences:
Ignoring interactions may:

- Understate the total measurement variability,
- Conceal process weaknesses,
- Overlook special cause variations unique to certain operator-part-tool combinations.

This ultimately reduces the effectiveness of process improvement efforts.
Example in Practice:
In an automotive quality lab, if a new operator struggles more with parts having complex geometries, the variability due to operator-part interaction may not be visible unless explicitly modeled. Without including such interactions, management might blame the tool or training system rather than identifying the true root cause.

5.6 Insufficient Sample Sizes in MSA Studies

Overview:
Due to time or resource constraints, some organizations reduce the number of parts, operators, or repetitions in their MSA studies—contrary to AIAG and ISO recommendations (typically 10 parts × 3 operators × 2 trials).
Consequences:

- Reduced statistical power,
- Unstable variance estimates,
- Wider confidence intervals,
- Increased likelihood of accepting poor systems or rejecting good ones.

Example in Practice:
In a semiconductor R&D facility, a team ran a Gage R&R with only three wafers and one operator. The low sample size resulted in unusually low %R&R values, falsely indicating a perfect system. This led to premature certification of a measurement protocol that failed in production trials.

Table: Common Pitfalls in MSA Implementation

Pitfall	Description	Impact	Affected Industry
Misapplied Experimental Design	Using crossed design in destructive testing	Invalid reproducibility results	Aerospace
Operator Training Deficiency	Inconsistent practices across shifts or locations	Elevated R&R, false rejection of valid systems	Automotive
Environmental & Tool Wear Ignored	Failing to account for temperature, vibration, or degradation	Inaccurate repeatability and long-term drift	Semiconductor
Software Misinterpretation	Blind use of default outputs from Minitab, JMP, etc.	Wrong metrics used; incorrect decisions made	All
Ignoring Factor Interactions	Not modeling operator-part-tool interactions	Hidden root causes; ineffective corrective actions	Automotive, Aerospace
Inadequate Sample Size	Using too few parts, operators, or repetitions	Statistically unreliable or invalid Gage R&R results	All

Key Insights

- MSA must not be executed as a procedural formality. Contextual understanding of industry requirements, process dynamics, and measurement physics is essential.
- Blind adherence to templates or tools, without statistical and operational judgment, leads to costly errors.
- The combination of engineering knowledge, data science, and human factor awareness is necessary to avoid these pitfalls and ensure reliable measurement system validation.

6. Best Practice Framework for Measurement System Analysis (MSA)

Measurement System Analysis (MSA) is not a one-off statistical checklist—it is a continuous, structured framework for validating the integrity of measurement systems throughout the lifecycle of manufacturing. The implications of poor MSA range from minor product non-conformities to catastrophic failures, especially in precision-driven sectors such as semiconductor, automotive, and aerospace.

This section outlines a best practice framework composed of six interdependent pillars that ensure measurement reliability, traceability, and process stability in complex manufacturing environments. These practices are supported by industry literature, international standards, and case-specific applications.

6.1 Select the Correct MSA Study Design: Crossed vs. Nested

Theoretical Foundation

The foundation of any Gage R&R study lies in its design structure. According to AIAG (2010), choosing the wrong design model (crossed or nested) invalidates the measurement system's diagnostic outcomes.

- Crossed Design: Each operator measures every part multiple times. Ideal for remeasurable, non-destructive contexts. Offers maximum visibility into both repeatability and reproducibility.
- Nested Design: Each operator measures a unique set of parts, suitable for destructive testing or situations where parts cannot be returned to their original state.

Technical Considerations

- Crossed designs allow two-way ANOVA to partition variance accurately into operator, part, and operator-by-part interaction.

- Nested designs, while less statistically powerful, are required for compliance in scenarios involving irreversible testing conditions.

Industry Implementation

Industry	Design Type	Application Scenario
Semiconductor	Crossed	Wafer thickness and pattern alignment using AFM
Automotive	Crossed	Dimensional validation using CMM across multiple shifts
Aerospace	Nested	Destructive fatigue testing on turbine blades

- Tip: For mixed conditions, hybrid models using split-plot designs may be appropriate.

6.2 Use Orthogonal Regression for Bidirectional Error Compensation

Statistical Rationale

Standard linear regression assumes the independent variable (X) is measured without error. This assumption fails in many high-precision systems, especially when both the reference and measured systems introduce variability.

Orthogonal regression, also called Total Least Squares, minimizes the sum of squared perpendicular distances to the regression line, accommodating uncertainty in both axes.

When to Use

- Calibration of instruments where reference standards are also subject to variation.
- Evaluation of automated systems with sensor fusion, e.g., combining laser and ultrasound measurements.

Use Case Example

- In a semiconductor fabrication line, a vendor calibrates scanning electron microscopes (SEM) using orthogonal regression, allowing sub-nanometer resolution alignment against a master wafer standard.
- ISO 22514-7 (2021) recommends orthogonal regression for calibration scenarios involving error in both measurement axes.

6.3 Automate Data Collection and Digital Logging

Justification

Manual data logging introduces:

- Human transcription errors
- Inconsistent timing
- Difficulty in traceability and backtracking for audits

By contrast, automated measurement systems integrated into MES (Manufacturing Execution Systems) or SPC (Statistical Process Control) platforms ensure high-fidelity, real-time data streams.

Capabilities Enabled

- Real-time alerts and out-of-control action plans (OCAPs)
- Longitudinal analysis of measurement stability
- Seamless digital trail for regulatory and supplier audits

Real-World Implementation

- Automotive: CMMs automatically export dimensional data to centralized dashboards for immediate decision-making.
- Semiconductor: Inline metrology tools store time-stamped measurements in cleanroom databases compliant with ISO/IEC 17025 standards.

Failing to automate MSA in high-throughput environments increases cost of quality (CoQ) via preventable escapes.

6.4 Institutionalize Operator Training and Requalification Cycles

Underlying Risk

Even with advanced tools, untrained or inconsistent operators can drastically impact reproducibility. In fact, operator-related errors often surpass tool inaccuracies in uncontrolled environments.

Best Practices

- Standardize training through Certified Quality Inspector (CQI) or internal calibration programs.
- Include visual work instructions, sample parts, and known-good gage simulations.
- Enforce blind remeasurement cycles and periodic recertification (quarterly or semi-annually).

Aerospace Case Study

In a composite fuselage quality lab, three inspectors undergo a 3-week onboarding course involving destructive coupon tests, gage alignment protocols, and SPC charting exercises. Post-training, R&R dropped from 18.6% to 6.1%.

Measurement of Effectiveness

Use the Kappa coefficient or intraclass correlation coefficient (ICC) to validate operator agreement statistically.

6.5 Maintain Calibration, Tool Life, and Environmental Logs

Technical Imperative

Measurement tools—whether tactile probes, laser sensors, or optical devices—degrade with use. Environmental conditions also affect readings (e.g., thermal expansion of gauges, humidity-induced drift in optical sensors).

Key Procedures

- Scheduled calibration per ISO/IEC 17025 or NIST-traceable standards.
- Tool lifecycle logs recording usage cycles, tip replacements, sensor recalibrations.
- Environmental monitoring using IoT sensors (temperature, vibration, electromagnetic interference).

Sector Examples

Industry	**Calibration Focus**	**Environmental Control**
Semiconductor	AFM cantilever recalibration	Vibration control via air suspension
Automotive	Torque wrench verification	Shop-floor temp/humidity sensors
Aerospace	Ultrasonic transducer tuning	EMI shielding in NDI labs

- Empirical data from Wheeler (2006) shows tool drift contributes up to 40% of unexplained variation if left unmanaged.

6.6 Implement Visual and Statistical Monitoring Systems

Overview

Reactive MSA is no longer sufficient. Visual dashboards and control charts offer ongoing health monitoring of the measurement system, enabling proactive intervention.

Key Visual Tools

- X-bar and R Charts: Monitor central tendency and range.
- Box Plots: Visualize spread by operator or tool type.
- Heatmaps: Show sensor output correlation matrices for multi-sensor systems.

Industrial Application

In a tier-one automotive supplier, control charts detected a slow drift in a laser scanner’s profile due to dust accumulation. Preventive maintenance was executed, avoiding $75,000 in scrap cost.

Advanced Integration

- AI-driven SPC tools now detect non-obvious variance patterns and recommend recalibration based on anomaly detection models.

6.7 Consolidated Best Practice Table

Best Practice	Objective	Example Context
Use Correct Design (Crossed/Nested)	Accurate attribution of variation	Crossed in auto CMMs; nested in destructive aerospace tests
Apply Orthogonal Regression	Correct calibration model bias	Bidirectional error in SEM calibration
Automate Data Collection	Enhance traceability and reduce manual errors	Real-time MES integration in inline metrology
Train and Requalify Operators	Control reproducibility and human-induced variance	CQI-based training and blind rechecks
Maintain Calibration & Environmental Logs	Detect tool wear and drift early	AFM recalibration, EMI logging in NDI labs
Use SPC and Visualization Dashboards	Enable continuous measurement system monitoring	SPC alarms for scanner drift in car body inspection

Table: Summary of MSA Best Practices with Industry Application

Final Remarks

The successful implementation of MSA in complex manufacturing environments requires a systems engineering approach, integrating statistical theory, digital automation, human factors, and environmental control. This six-pillar framework, grounded in current ISO standards and industrial evidence, ensures that measurement systems are not only validated during initial trials but remain stable and trustworthy throughout the lifecycle of production.

Organizations that institutionalize these practices significantly enhance:

- Measurement reliability,
- Regulatory compliance,
- Operational efficiency,
- And ultimately, product quality and customer trust.

7. Conclusion

The evolution of precision engineering, digital manufacturing, and regulatory scrutiny across high-stakes industries has elevated the role of Measurement System Analysis (MSA) from a quality assurance tool to a strategic pillar in operational excellence. This paper critically examined the implementation of MSA in complex manufacturing environments, specifically focusing on its applications in semiconductor, automotive, and aerospace sectors. Through the synthesis of empirical studies, industry best practices, and statistical modeling, it is evident that the success of MSA hinges on both technical accuracy and contextual adaptability.

At the core of MSA is the decomposition of measurement variation into repeatability, reproducibility, and part-to-part components. Traditional Gage R&R methods provide a baseline assessment of a measurement system's contribution to overall process variation. However, this paper illustrates that relying solely on conventional approaches is inadequate in modern manufacturing, where micro-tolerances, customized workflows, and dynamic environments dominate. For instance, in semiconductor manufacturing, where tolerances often exist in the nanometer scale, even marginal measurement uncertainty can cascade into significant yield loss and rework costs. Here, MSA must be integrated with automated, environment-controlled systems, and extended through techniques such as orthogonal regression, which accounts for errors in both the measurement and reference standards.

Conversely, the automotive industry offers a blend of high-volume and high-precision requirements. MSA practices in this sector often necessitate crossed design studies for remeasurable parts, coupled with nested designs for batch-based or destructive testing scenarios. The analysis showed that hybrid MSA approaches, when supported by digital metrology tools such as coordinate measuring machines (CMMs), yield higher reproducibility and operator-independence. Still, human variability remains a challenge—thus necessitating stringent operator training programs, standard operating procedures (SOPs), and regular Gage audits.

In the aerospace sector, the cost of measurement errors can be catastrophic, leading to mission failure or non-compliance with international airworthiness standards. MSA in this context often involves nested design studies, especially when measurements are destructive or components are large, complex, and non-standardized. Tools such as ultrasonic testing, laser scanners, and digital imaging systems are commonly used. The literature and industry evidence suggest that the implementation of advanced MSA techniques, such as orthogonal regression, paired with rigorous calibration protocols and traceability requirements, is non-negotiable for ensuring measurement credibility in aerospace applications.

One of the most significant insights from this research is the importance of aligning MSA design with the operational context. A misapplication of the experimental design—such as using a crossed design where a nested structure is required—not only leads to invalid conclusions but also risks systemic quality issues. Similarly, neglecting environmental factors, such as temperature, humidity, or tool wear, can distort repeatability outcomes and undermine the reliability of statistical process control (SPC) charts.

Furthermore, common pitfalls were identified across industries, including:

- The over-reliance on software outputs without understanding underlying assumptions (e.g., linearity, normality),
- Failure to recalibrate instruments on a time-based or condition-based schedule,
- Inadequate sampling strategies that do not reflect the true process variability.

To counteract these challenges, this study proposed a Best Practice Framework grounded in real-world applications and academic consensus. Recommendations include:

- Matching the MSA design (crossed or nested) to the nature of the parts and processes being evaluated.
- Employing orthogonal regression models in systems with bidirectional measurement uncertainty.
- Integrating MSA with automated data collection, digital calibration logs, and real-time SPC dashboards.
- Establishing operator competency through structured training, proficiency tests, and certification programs.
- Conducting periodic reviews of Gage R&R studies using control charts to monitor long-term measurement system drift.

Looking forward, the role of MSA will become even more central as Industry 4.0, cyber-physical systems, and AI-driven quality assurance redefine how manufacturing systems operate. Smart factories will rely on high-frequency, high-resolution measurements that feed machine learning models, digital twins, and predictive analytics engines. In such environments, the credibility of measurement data becomes paramount—and MSA will serve as the gatekeeper for ensuring that this data is accurate, representative, and statistically sound.

In conclusion, Measurement System Analysis is not a static activity but a dynamic process that must evolve in parallel with manufacturing innovation. Its successful implementation requires a combination of statistical expertise, technological integration, and human discipline. Organizations that proactively invest in advanced MSA capabilities, contextualize their measurement strategies, and institutionalize continuous improvement will be better equipped to deliver consistent quality, satisfy regulatory demands, and maintain a competitive edge in global manufacturing.

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