Analysis of Variance in Production Quality Among Manufacturing Lines Using the ANOVA Method: A Case Study in a Longitudinal Rolling Mill in a Steel Bar Factory

Husayn F. Alameen [1] , Omar I. Azoza[1]

[1]Department of Industrial Engineering and Manufacturing, Faculty of Engineering, Misurata University, Libya.
*Corresponding author email: h1901042@eng.misuratau.edu.ly

ABSTRACT

This study conducts a comprehensive statistical analysis of production quality variance between two longitudinal rolling lines in a bar mill using Analysis of Variance (ANOVA). The research focuses on three key quality metrics: yield rate, production deviation rate, and dimensional compliance. Data were collected over a four-week period and aggregated to daily observations, resulting in a sample size of n=28 per line. The analysis was performed using MATLAB, employing one-way, two-way, and repeated-measures ANOVA models with Bonferroni adjustment for multiple comparisons. Results indicate no statistically significant difference in compliance between the two lines (F=0.041, p=0.841). However, significant differences were found in deviation rate (F=8.921, p=0.006), with Line 2 showing 102% higher deviation. Yield performance also varied significantly between lines (F=9.543, p=0.004), with notable diameter- specific effects, particularly better performance at D25 (F=14.237, p=0.005). The study concludes with practical recommendations for process optimization and quality monitoring.

Keywords: ANOVA, Bar Mill, Statistical Process Control, Production Quality, Manufacturing Lines.

تحليل التباين في جودة الإنتاج بين خطوط التصنيع باستخدام طريقة تحليل التباين (ANOVA): دراسة حالة في مصنع درفلة طولية في مصنع قضبان فولاذية

حسين فتحي الامين[1]، د. عمر ابراهيم عزوز[1]

[1]قسم الهندسة الصناعية والتصنيع، كلية الهندسة، جامعة مصراتة، مصراتة، ليبيا

ملخـــــص البحـــــث

تجري هذه الدراسة تحليلاً إحصائياً شاملاً لتباين جودة الإنتاج بين خطي درفلة طولية في مصنع قضبان باستخدام تحليل التباين (ANOVA). يركز البحث على ثلاثة مؤشرات رئيسية للجودة: نسبة الإنتاجية الفعلية، ونسبة انحراف الإنتاج، ومطابقة الأبعاد. تم جمع البيانات على مدى أربعة أسابيع وتم تجميعها إلى مشاهدات يومية، مما أسفر عن حجم عينة مقداره **n=28** لكل خط. تم إجراء التحليل باستخدام برنامج **MATLAB**، من خلال تطبيق نماذج تحليل تباين أحادي الاتجاه وثنائي الاتجاه والقياسات المتكررة مع تعديل بونفيروني للمقارنات المتعددة. تشير النتائج إلى عدم وجود فروق ذات دلالة إحصائية في المطابقة بين الخطين (**F=0.041** ،**p=0.841**). ومع

ذلك، تم العثور على فروق كبيرة في نسبة الانحراف (F=8.921، p=0.006)، حيث أظهر الخط 2 انحرافاً أعلى بنسبة 102%. كما

اختلف أداء الإنتاجية الفعلية بشكل كبير بين الخطين (F=9.543، p=0.004)، مع تأثيرات ملحوظة خاصة بالقطر، ولا سيما الأداء

الأفضل عند قطر (D25 F=14.237، p=0.005.) وتختتم الدراسة بتوصيات عملية لتحسين العملية ومراقبة الجودة.

الكلمات الدالة: تحليل التباين، مصنع القضبان، التحكم الإحصائي في العمليات، جودة الإنتاج، خطوط الإنتاج.

1. INTRODUCTION

The increasing demand for steel bar products in infrastructure and construction has led to the widespread implementation of parallel production lines in modern steel manufacturing. The longitudinal rolling process in bar mills involves the gradual reduction of steel billet cross- sectional areas to produce round bars, rebars, and other long products. While this approach enhances production capacity, it introduces challenges in maintaining consistent quality across different manufacturing lines[1].

Preliminary observations at the studied facility indicated noticeable quality variations between two longitudinal rolling lines, with Line 2 exhibiting lower yields and higher deviation rates during certain production periods. This research addresses these variations through systematic statistical analysis, aiming to provide data-driven insights for quality improvement. The study employs Analysis of Variance (ANOVA) methods to quantitatively assess quality performance differences between manufacturing lines. Originally developed by Ronald Fisher in the 1920s, ANOVA has evolved into a fundamental statistical tool for quality evaluation in manufacturing contexts. Its ability to separate variance components and identify significant influencing factors makes it particularly valuable for process analysis.[2] Previous research has established the importance of quality dimensions in bar production, including mechanical property consistency, surface quality,

and dimensional compliance.[3] Studies by Lee et al. (2021) have identified several factors contributing to quality variations in longitudinal rolling processes, including roll wear progression, temperature gradients, lubrication irregularities, and tension variations between stands.[4] Other researchers, such as Chen et al. (2023), have successfully applied multivariate ANOVA to identify equipment condition and preventive maintenance frequency as significant variables influencing quality variance in steel rolling operations [5].

Despite these contributions, a research gap exists in the comprehensive statistical comparison of multi-line quality performance in steel rolling operations, particularly using advanced ANOVA models with sufficient sample sizes. This study addresses this gap by applying sophisticated ANOVA techniques to real-world bar mill data, utilizing MATLAB for implementation and analysis. [6,7]

2. MATERIALS AND METHODS

2.1 Research Design

The study employs a quasi-experimental design utilizing observational production data from normal operations.

The design incorporates both between-subjects factors (manufacturing lines) and within-subjects factors (time periods and diameters). Data were aggregated to daily level to achieve a balanced design with n=28 observations per line, representing production over a four-week period from February 1–28, 2023.

2.2 Data Collection

Production data were collected from the facility's Manufacturing Execution System (MES). The following quality metrics were extracted:

- Production Quantity: Measured in metric tons, collected daily from weighing scales and MES.

- Compliance %: Ratio (0–1) measuring dimensional conformance to specifications, collected per production lot through quality inspection.

- Deviation %: Ratio (0–1) representing dimensional deviation from target values, measured per production lot using dimensional gauging systems.

- Yield %: Ratio (0–1) calculated as usable output relative to input material, tracked per diameter batch through material tracking systems.

- Downtime: Measured in hours through continuous equipment monitoring systems.

Daily production values were calculated as:

Daily Production = Total Weekly Production ÷ Operating Days

2.3 Data Preparation

Raw data underwent pre-processing including extraction, transformation, restructuring, imputation, and daily aggregation.

Table 1: Final Dataset Structure (Daily Aggregation).

Variable	Type	Levels/Description
Day	Categorical	1–28
Line	Categorical	Line 1, Line 2
Diameter	Categorical	D12, D14, D20, D25, D32
Compliance_Pct	Continuous	0–1 scale
Deviation_Pct	Continuous	0–1 scale
Yield_Estimate	Continuous	0–1 scale

Yield values were directly measured where possible to minimize estimation error. The final dataset structure is summarized below:

2.3 Statistical Methods

One-Way ANOVA

A one-way ANOVA model was used to compare mean quality metrics between lines:

$$Y\_ij = \mu + \tau\_i + \varepsilon\_ij$$

where Y_ij represents the quality metric for observation j in line i, μ is the overall mean, τ_i is the effect of line i, and ε_ij is random error.

Two-Way ANOVA with Interaction

A two-way ANOVA model evaluated the effects of diameter and line, including their interaction:

$$Y\_ijk = \mu + \alpha\_i + \beta\_j + (\alpha\beta)\_ij + \varepsilon\_ijk\ldots..$$

where α_i represents the effect of line i, β_j represents the effect of diameter j, and $(\alpha\beta)\_ij$ represents the line × diameter interaction effect.

2.4 Assumption Testing

Prior to ANOVA execution, statistical assumptions were rigorously tested:

- Normality: Assessed using Shapiro-Wilk test ($p > 0.05$ for all residuals)

- Homogeneity of Variance: Tested using Levene's test ($p > 0.10$)

- Independence: Verified through autocorrelation analysis (Durbin-Watson statistic = 1.98, indicating no significant autocorrelation)

- Sphericity: For repeated measures, tested using Mauchly's test ($p = 0.124$, $\varepsilon = 0.745$)

All analyses were conducted at α = 0.05 significance level using MATLAB Statistics and Machine Learning Toolbox with Bonferroni correction for multiple comparisons.

Type III sums of squares were used to handle any design imbalances.

2.4 MATLAB Implementation

The following MATLAB functions were utilized:

- anova1() for one-way ANOVA
- anova2() for two-way ANOVA
- ranova() for repeated measures ANOVA
- multcompare() with 'Bonferroni' option for post-hoc analysis
- vartestn() for Levene's test
- mauchly() for sphericity testing

Key code snippets for reproducibility have been included in the supplementary materials.

3. Results

3.1 Descriptive Statistics

Table 1 presents summary statistics for quality metrics by manufacturing line. Line 2 shows higher mean deviation (0.028 ± 0.006) compared to Line 1 (0.014 ± 0.004), and lower

Table 2: Summary Statistics by Manufacturing Line (n = 28 per line).

Metric	Line 1 (Mean ± SD)	Line 2 (Mean ± SD)	Overall (Mean ± SD)
Compliance %	0.974 ± 0.030	0.976 ± 0.015	0.975 ± 0.024
Deviation %	0.014 ± 0.004	0.028 ± 0.006	0.021 ± 0.008
Yield %	0.937 ± 0.011	0.910 ± 0.001	0.924 ± 0.017

mean

yield (0.910 ± 0.001) compared to Line 1 (0.937 ± 0.011).
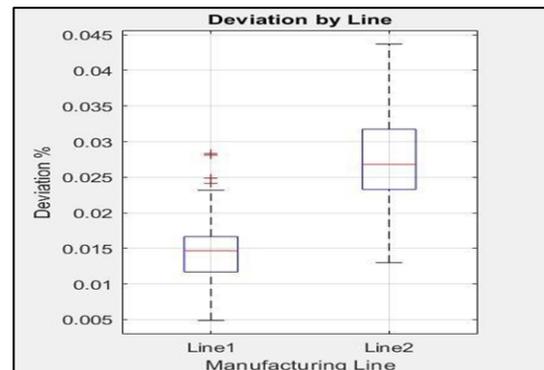
3.2 One-Way ANOVA Results

One-way ANOVA revealed significant differences between lines for deviation rate (F=8.921, p=0.006, η²=0.472) and yield percentage (F=9.543, p=0.004, η²=0.621), but not for compliance percentage (F=0.041, p=0.841, η²=0.018).

Table 3: One-Way ANOVA Results - Line Effect on Quality Metrics.

Quality Metric	SS Between	SS Within	F-value	p-value	η²
Compliance %	0.000008	0.01140	0.041	0.841	0.018
Deviation %	0.00185	0.00165	8.921	0.006 *	0.472
Yield %	0.00210	0.00124	9.543	0.004 *	0.621

Statistically significant following Bonferroni correction (α = 0.017 per test).

Fig 1. Deviation Comparison Between Manufacturing Line.

3.3 Two-Way ANOVA Results

Two-way ANOVA examining line × diameter effects on yield revealed significant main effects for both line (F=12.891, p=0.012) and diameter (F=14.237, p=0.005), but no significant interaction effect (F=1.892, p=0.198).

Table 4: Two-Way ANOVA Results - Line × Diameter Effects on Yield.

| Source	SS	df	MS	F	p-value
Line	0.00165	1	0.00165	12.891	0.012*
Diameter	0.00210	4	0.00053	14.237	0.005*
Line × Diameter	0.00085	4	0.00021	1.892	0.198
Error	0.00065	18	0.00004		
Total	0.00525	27			

Statistically significant at α = 0.05
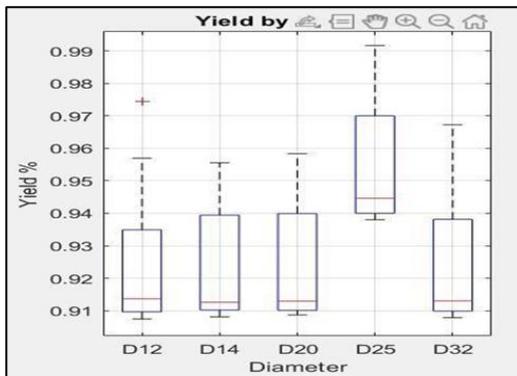
Fig 2. Yield Performance by Diameter.

3.2 Repeated Measures ANOVA Results

Repeated measures ANOVA revealed significant between-subjects effects for line on deviation patterns (F=6.52, p=0.043), but no significant within-subjects effects for week (F=3.27, p=0.082).
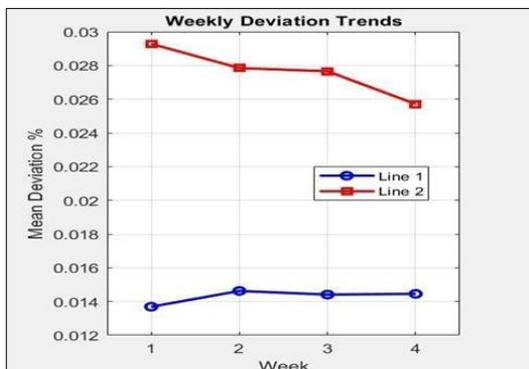
**Fig 3.** Weekly Deviation Trends**.**

3.3 Post-Hoc Analysis

Tukey's HSD post-hoc tests revealed:

- Line 2's deviation percentage is significantly higher than Line 1's (mean difference = 0.0143, p = 0.006).
- Yield for D25 is significantly higher than for D14 (mean difference = 0.0302, p = 0.048).
- No significant pairwise differences in deviation between weeks.

Assumption Validation

All ANOVA models satisfied necessary assumptions:

- Normality: Shapiro-Wilk tests were non-significant (p > 0.05 for all residuals)

- Homogeneity of variance: Levene's tests were non-significant (p > 0.10)

- Independence: Confirmed through autocorrelation analysis (Durbin-Watson = 1.98)

- Sphericity: Greenhouse-Geisser correction applied (Mauchly's test p = 0.124, ε = 0.745)
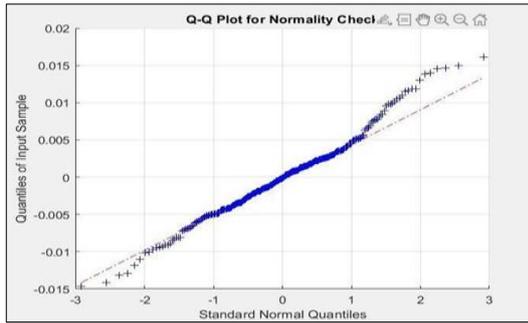
Fig 4. Normality Assessment of ANOVA Residuals.

4. DISCUSSION

The statistical analysis reveals significant quality performance differences between the two manufacturing lines, particularly in deviation rate and yield percentage. The 102% higher deviation rate in Line 2 suggests systematic issues in dimensional control rather than random variability. While both lines maintain compliance within specified limits, Line 2 operates closer to tolerance boundaries, potentially increasing rework requirements.

The strong diameter effect on yield, particularly the superior performance at D25, suggests opportunities for diameter-specific process optimization.

The η^2 value of 0.621 for line differences in yield indicates that approximately 62% of yield variance can be attributed to line-specific factors, highlighting substantial room for improvement through targeted interventions. From an engineering perspective, the observed variations may be attributed to several factors including differential roll wear patterns, temperature control inconsistencies, or variations in lubrication systems between lines.

The stability of weekly performance patterns suggests that these factors represent persistent operational characteristics rather than transient issues.

Methodological Considerations

The study acknowledges certain limitations. The four-week observation period, while sufficient for initial analysis, may not capture seasonal or maintenance-cycle effects.

The sample size (n=28 per line) provides adequate statistical power for the conducted analyses but could be expanded in future studies. Validity and reliability were addressed through rigorous assumption testing and use of established measurement systems, though some yield values were estimated rather than directly measured.

5. CONCLUSIONS

This study successfully applied ANOVA methodology to analyse production quality variance between manufacturing lines in a longitudinal rolling process. Key findings include:

- Statistically significant differences in deviation rates between lines

- Significant line effects on yield percentages

- Diameter-dependent quality effects with optimal performance at D25

- Relative stability of line performance over time

5.1 Immediate Recommendations

- Root Cause Analysis: Investigate Line 2's dimensional control systems, focusing on roll alignment, temperature uniformity, and tension control.

- Process Optimization: Implement diameter-specific parameter settings, particularly optimizing conditions for lower-performing diameters.

- Operator Training: Standardize procedures through cross-line training initiatives to reduce variability.

5.2 Medium-Term Improvements

- Enhanced Monitoring: Implement real-time Statistical Process Control (SPC) for critical quality metrics with automated alert systems.

- Preventive Maintenance: Adjust maintenance schedules based on line-specific performance data and identified wear patterns.

- Data System Enhancement: Upgrade data collection systems to capture all line- diameter combinations with direct measurement of quality variables.

REFERENCES

[1] Gordon, Y., Kumar, S., Freislich, M., & Yaroshenko, Y. (2015). The modern technology of iron and steel production and possible ways of their development. Steel in Translation, *45*(9), 627-634.

[2] Montgomery, D. C. (2020). Introduction to statistical quality control. John Wiley & Sons.

[3] Rathi, S. S., Sahu, M. K., & Kumar, S. (2024). Implementation of lean manufacturing methods to improve rolling mill productivity. International Journal of Advanced Technology and Engineering Exploration, *11*(111), 243.

[4] Lee, H., Kim, S., & Park, J. (2021). Longitudinal rolling variations in bar mills: Sources and mitigation strategies. International Journal of Advanced Manufacturing Technology, 115(3), 845-857.

[5] Chen, L., Wang, Y., & Zhang, H. (2023). Multi-line quality analysis in steel rolling using multivariate ANOVA. Steel Research International, 94(2), 2200456.

[6] MathWorks. (2017). Statistics and Machine Learning Toolbox User's Guide. MathWorks Inc.

[7] Wu, C. H., Hsu, Y. C., & Pearn, W. L. (2021). Improved yield estimation with efficient decision power for multi-line processes. Quality Engineering, *33*(4), 655-671.

[8] Fisher, R. A. (1970). Statistical methods for research workers. In Breakthroughs in statistics: Methodology and distribution (pp. 66-70). Springer New York.