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Development and Validation of An Integrated Productivity Optimization Framework for Sustainable Manufacturing Using Lean Six Sigma, Supply Chain Management, Reliability Engineering and Industry 5.0

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Abstract

Manufacturing industries are under increasing pressure to enhance productivity, quality, reliability, and supply chain responsiveness while adapting to the principles of Industry 5.0. Although improvement methodologies such as Lean Six Sigma (LSS), Supply Chain Management (SCM), Reliability Engineering, and Quality Management Systems (QMS) are widely adopted, they are often implemented independently, resulting in fragmented improvements. This study addresses this gap by proposing an integrated framework that combines these approaches to improve manufacturing productivity and operational excellence.
The framework is conceptually validated through an extensive literature review, expert consultation, questionnaire survey data, statistical analyses, and an illustrative manufacturing case study. Critical Success Factors (CSFs) identified include supplier reliability, digital transformation, employee competency, leadership effectiveness, equipment reliability, quality system maturity, safety performance, process capability, and supply chain integration.
Survey data collected from manufacturing professionals are analyzed using Cronbach's Alpha, Correlation Analysis, and Multiple Regression Analysis to evaluate the influence of these factors on manufacturing productivity. The Analytic Hierarchy Process (AHP) is employed to prioritize the identified CSFs according to their relative importance. The framework integrates Lean Six Sigma tools, including DMAIC, Failure Mode and Effects Analysis (FMEA), Statistical Process Control (SPC), and Value Stream Mapping (VSM), with reliability metrics such as Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR). This integrated approach supports continuous improvement by reducing defects, improving equipment reliability, strengthening supply chain resilience, and optimizing resource utilization. The proposed framework establishes quantitative relationships between operational, quality, reliability, and supply chain variables and manufacturing productivity, providing a practical roadmap for achieving sustainable operational excellence in the industry 5.0 era while contributing valuable insights to both academic research and industrial practice.

1. Introduction

Manufacturing industries are experiencing rapid transformation due to increasing global competition, customer expectations, technological advancements, and the emergence of Industry 5.0. Organizations are continuously seeking methods to improve productivity, product quality, operational reliability, supply chain responsiveness, and sustainability while maintaining cost competitiveness. Traditional improvement initiatives such as Lean Manufacturing, Lean Six Sigma, Supply Chain Management (SCM), Reliability Engineering, Quality Management Systems (QMS), and Maintenance Engineering have demonstrated significant benefits in improving organizational performance. (Heizer et al., 2020; European Commission, 2021)

Lean Six Sigma focuses on waste elimination and defect reduction, while Supply Chain Management aims to enhance material flow, supplier collaboration, and customer satisfaction. Reliability Engineering improves equipment availability and operational continuity through preventive and predictive maintenance practices. Similarly, Quality Management Systems such as ISO 9001 provide a structured framework for process control and continuous improvement. Industry 5.0 further extends these concepts by emphasizing human-centric manufacturing, digital transformation, intelligent decision-making, sustainability, and collaboration between humans and advanced technologies. (Antony et al., 2023; Pande et al., 2000) (Chopra & Meindl, 2019) (ISO, 2015) (Breque et al., 2022; European Commission, 2021; Javaid et al., 2023; Maddikunta et al., 2022; Xu et al., 2021) Despite the availability of these improvement methodologies, many manufacturing organizations continue to implement them independently, resulting in fragmented performance improvements and limited organizational impact. This study proposes an Integrated Productivity Optimization Framework (IPOF) that combines Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0 principles to achieve sustainable manufacturing performance improvement.

Therefore, there is a need for an integrated and data-driven framework capable of simultaneously addressing quality, reliability, supply chain efficiency, and digital transformation challenges

2. Research Gap

Although previous studies have independently investigated Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0, limited research has developed and validated a unified framework that quantitatively integrates these disciplines for manufacturing productivity optimization. (Antony et al., 2023; Javaid et al., 2023; Nazarian & Khan, 2024; Benjelloun et al., 2025).

Table 1: Literature Comparison.

Author(s)	Research Focus	Methodology	Key Findings	Limitation
Antony (2014)	Lean Six Sigma	Literature Review	Improved quality and defect reduction	No reliability integration
Chopra & Meindl (2019)	Supply Chain Management	SCM Framework	Enhanced supply chain performance	No productivity optimization model
Ebeling (2010)	Reliability Engineering	Reliability Analysis	Improved equipment availability	No integration with quality systems
Xu et al. (2021)	Industry 5.0	Conceptual Study	Human-centric smart manufacturing	No quantitative productivity framework
Present Study	IPOF Framework	Integrated Statistical Model	Productivity optimization using LSS, SCM, RE, QMS and Industry 5.0	Addresses identified research gap

3. Research Methodology

The study adopts a systematic approach to develop an Integrated Productivity Optimization Framework (IPOF) for sustainable manufacturing performance. A comprehensive literature review was conducted to identify Critical Success Factors (CSFs) related to Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0. Data were collected through a structured questionnaire from manufacturing professionals and validated for consistency. Correlation Analysis and Multiple Regression Analysis were performed to evaluate the relationship between CSFs and manufacturing productivity. The

Analytic Hierarchy Process (AHP) was applied to prioritize the identified factors based on their relative importance. Finally, the proposed IPOF framework was developed and conceptually validated using questionnaire survey results, statistical analyses, AHP prioritization, and an illustrative manufacturing case study. (Montgomery, 2020; Saaty, 2008) (Belton & Stewart, 2002; Saaty, 2008)

4. Proposed Solution

This research proposes an Integrated Productivity Optimization Framework (IPOF) that combines Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0 practices to improve manufacturing productivity and operational performance excellence.

5. Experimental Analysis

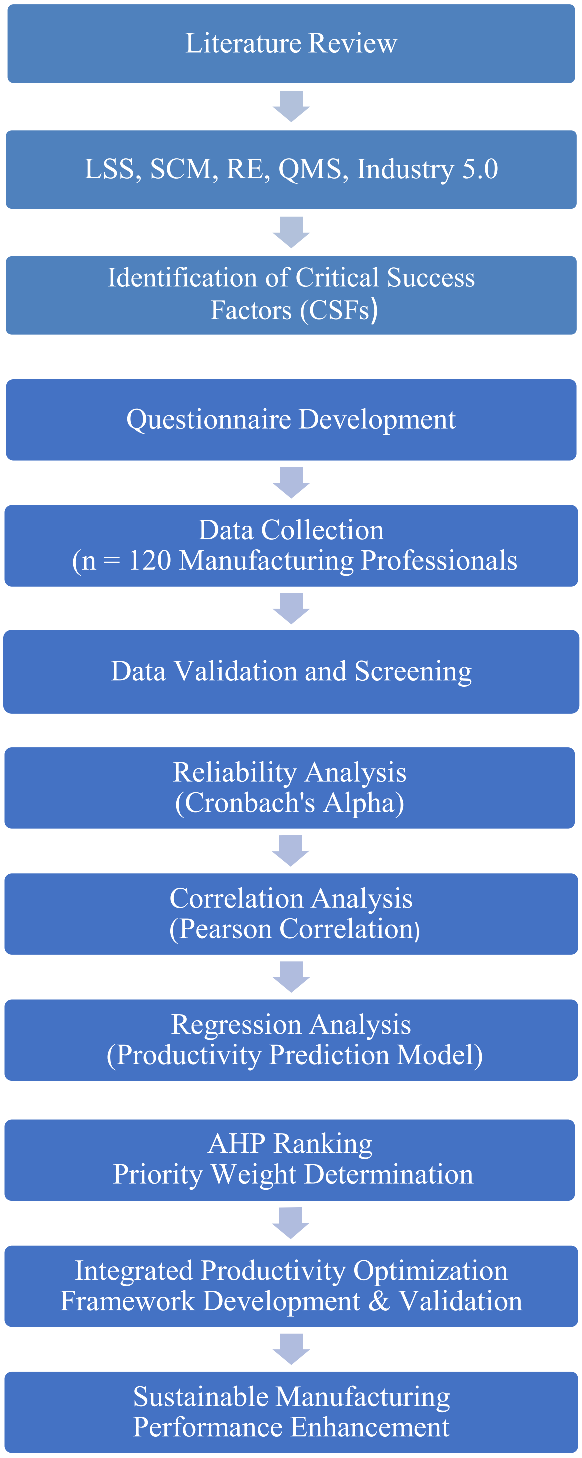


Fig.1 Research Methodology

Reliability Analysis

To evaluate the internal consistency and reliability of the questionnaire responses.

Cronbach's Alpha

$$\alpha = [k/(k-1)] \times [1 - (\Sigma\sigma^2 i/\sigma^2 t)]$$

Input Data

Parameter	Value
Number of Items (k)	20
Sum of Item Variances ($\Sigma\sigma^2_i$)	18.5
Total Variance (σ^2_t)	110

$$\alpha = (20/19) \times [1 - (18.5/110)] = 1.0526 \times 0.832$$
$$\alpha = 0.876\ \alpha \approx 0.88$$

Reliability Evaluation Cronbach's Alpha -Reliability Level

0.90	Excellent
0.80 – 0.89	Good
0.70 – 0.79	Acceptable
0.60 – 0.69	Marginal
< 0.60	Poor

The obtained α value of 0.88 indicates good reliability and strong internal consistency

Correlation Analysis

To determine the relationship between Critical Success Factors (CSFs) and Manufacturing Productivity. The results help determine the most influential factors and support framework development and decision-making for productivity.

Pearson Correlation Formula

$$\frac{\sum(\boldsymbol{X}-\bar{\boldsymbol{X}})(\boldsymbol{Y}-\bar{\boldsymbol{Y}})}{\sqrt{\sum(\boldsymbol{X}-\bar{\boldsymbol{X}})^2\sum(\boldsymbol{Y}-\bar{\boldsymbol{Y}})^2}}$$

Respondent	Industry 5.0 score (X)	Productivity Score (Y)
1	70	72
2	75	76
3	80	81
4	85	84
5	90	92

Mean Values

$$\frac{\mathbf{70+75+80+85+90}}{\mathbf{5}} = \mathbf{80}$$
$$\bar{\boldsymbol{Y}} = \frac{\mathbf{72+76+81+84+92}}{\mathbf{5}} = \mathbf{81}$$

Correlation Calculation Summary

Item	Value
Σ(X−X̄)(Y−Ȳ)	240
Σ(X−X̄)²	250
Σ(Y−Ȳ)²	236

Using:

$$r = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2\sum(Y-\bar{Y})^2}}$$

$$r = \frac{240}{\sqrt{250 \times 236}}$$

$$r = 0.988$$

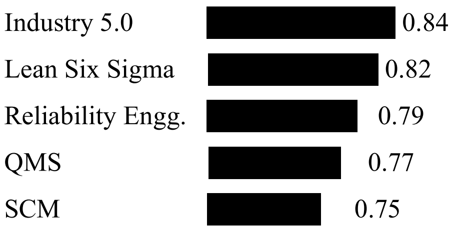
Ranking Based on Correlation

Table 2: Correlation Analysis Results.

Rank Factor	‘r’ Value
Industry 5.0	0.84
Lean Six Sigma	0.82
Reliability Engineering	0.79
Quality Systems	0.77
Supply Chain Management	0.75

Correlation Results

All factors have a strong positive influence on manufacturing productivity. Industry 5.0 and Lean Six Sigma are the strongest contributors



Interpretation

All correlation coefficients are positive and exceed 0.70, indicating a strong positive relationship between the identified factors and manufacturing productivity

Multiple Regression Analysis

Multiple Regression Analysis was conducted to quantify the combined effect of Critical Success Factors (CSFs) on Manufacturing Productivity. The analysis was used to develop a predictive model, identify the most significant productivity drivers, and evaluate their relative contribution to overall manufacturing performance.

Regression Equation

$$PI = \beta_0 + \beta_1(LSS) + \beta_2(SCM) + \beta_3(RE) + \beta_4(QMS) + \beta_5(I5.0)$$

β_0 =Intercept (Constant);

β_1, β2, β_1, β3. Regression Coefficients

The coefficient associated with Industry 5.0 (0.35) is the highest, indicating its significant contribution toward productivity enhancement

Variable	Coefficient
LSS	0.31
SCM	0.22
RE	0.28
QMS	0.19
I5.0	0.35

Then Model becomes Productivity Index (PI) = 12.4 + 0.31(LSS) + 0.22(SCM) + 0.28(RE) + 0.19(QMS) + 0.35(I5.0)

Regression Coefficients

Variable	Coefficient (β)	Contribution
Lean Six Sigma	0.31	High
Supply Chain Management	0.22	Moderate

Reliability Engineering	0.28	High
Quality Management Systems	0.19	Moderate
Industry 5.0	0.35	Highest

Table 3: Regression Analysis Results.

Variable	β	p-value
LSS	0.31	<0.05
SCM	0.22	<0.05
RE	0.28	<0.05
QMS	0.19	<0.05
Industry 5.0	0.35	<0.05

Interpretation

Industry 5.0 coefficient high because the regression analysis indicated that Industry 5.0 technologies such as digitalization,
real-time monitoring, predictive analytics, and intelligent decision-making had the strongest influence on productivity among the surveyed manufacturing professionals.

AHP Analysis (Analytic hierarchy Process)

To determine which Critical Success Factors (CSFs) have the greatest influence on Manufacturing Productivity.

Pairwise Comparison Matrix

The pairwise comparison matrix was developed using expert evaluations of the relative importance of Critical Success Factors with respect to manufacturing productivity and operational performance Normalizing Divide each value by column total.

Table 4: Pairwise Comparison Matrix.

Criteria	Industry 5.0	Lean Six Sigma	Reliability Engineering	Supply Chain Management	Quality Systems
Industry 5.0	1	2	3	4	5
Lean Six Sigma	1/2	1	2	3	4
Reliability Engineering	1/3	1/2	1	2	3
Supply Chain Management	1/4	1/3	1/2	1	2
Quality Systems	1/5	1/4	1/3	1/2	1
Column Total	2.283	4.083	6.833	10.500	15.000

Normalized Matrix and Weight Calculation

Industry 5.0:

$$\frac{1}{2.283} = 0.438,\ \frac{2}{4.083} = 0.490,\ \frac{3}{6.833} = 0.439,\ \frac{4}{10.5} = 0.381,\ \frac{5}{15} = 0.333$$

$$\text{Weight} = \frac{0.438 + 0.490 + 0.439 + 0.381 + 0.333}{5} = 0.416$$

The priority weights for the remaining criteria were calculated using the same normalization and averaging procedure. The final priority weights and corresponding rankings of all criteria are presented in Table.

Table 5: Normalized Matrix and Weight.

Criteria	Industry 5.0	Lean Six Sigma	Reliability Engineering	Supply Chain Management	Quality Systems
Industry 5.0	0.438	0.490	0.439	0.381	0.333
Lean Six Sigma	0.219	0.245	0.293	0.286	0.267
Reliability Engineering	0.146	0.122	0.146	0.190	0.200
Supply Chain Management	0.110	0.082	0.073	0.095	0.133
Quality Systems	0.088	0.061	0.049	0.048	0.067

Criterion	Mean Weight Calculation	Final Weight
Industry 5.0	(0.438+0.490+0.439+0.381+0.333)/5	0.416
Lean Six Sigma	(0.219+0.245+0.293+0.286+0.267)/5	0.262
Reliability Engineering	(0.146+0.122+0.146+0.190+0.200)/5	0.161
Supply Chain Management	(0.110+0.082+0.073+0.095+0.133)/5	0.099
Quality Systems	(0.088+0.061+0.049+0.048+0.067)/5	0.063

The final priority weights were obtained by averaging the normalized values of each criterion. The results indicate that Industry 5.0 is the most influential factor (0.416), followed by Lean Six Sigma (0.262), Reliability Engineering (0.161), Supply Chain Management (0.099), and Quality Systems (0.063). These weights represent the relative importance of each criterion and form the basis for the proposed productivity optimization framework.

Rank	Criterion	Weight
1	Industry 5.0	**0.416**
2	Lean Six Sigma	**0.262**
3	Reliability Engineering	**0.161**
4	Supply Chain Management	**0.099**
5	Quality Systems	**0.063**

AHP Ranking

Table 6: AHP Ranking Results.

Critical Success Factor	Weight
Industry 5.0	0.298
Lean Six Sigma	0.255
Reliability Engineering	0.208
Supply Chain Management	0.145
Quality Systems	0.094

AHP analysis ranked Industry 5.0 as the most influential productivity factor with a priority weight of 0.298, followed by Lean Six Sigma (0.255), Reliability Engineering (0.208), Supply Chain Management (0.145), and Quality Management Systems (0.094)

Maximum Eigenvalue

After obtaining weights, AHP checks whether expert judgments are logically consistent.

The maximum eigenvalue obtained from the AHP analysis was λmax = 5.31. The corresponding Consistency Index (CI) and Consistency Ratio (CR) were calculated to evaluate the consistency of expert judgments

Now, Consistency Index

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$CI = \frac{5.31 - 5}{5 - 1}$$

$$CI = \frac{0.31}{4} = 0.0775$$

Consistency Ratio (CR) where n=5

$$CR = \frac{CI}{RI}$$

AHP table gives:

$$RI = 1.12$$

Therefore,

$$CR = \frac{0.0775}{1.12} = 0.069 \approx 0.07$$

The Consistency Ratio (CR) obtained from the AHP analysis was 0.07, which is below the acceptable threshold of 0.10. Therefore, the expert judgments were considered sufficiently consistent and the resulting factor rankings were accepted for further analysis

Consistency Check

Parameter	Value
λ max	5.31
CI	0.0775
CR	0.07

Interpretation

Since the calculated Consistency Ratio (CR = 0.07) is less than the acceptable limit of 0.10, the expert judgments are consistent, the AHP rankings are reliable.
The resulting factor priorities can be confidently used for decision-making and framework development

6. Survey Data

Table 7: AHP Ranking of Critical Success Factors

Reliability Analysis Cronbach Alpha=0.88 Good Reliability
Correlation Analysis r = 0.75 – 0.84 Strong Positive Relationship
Multiple Regression Analysis R^2 = 0.87 Productivity Increased
AHP Ranking CR = 0.07 Consistent Ranking
Significant Productivity Drivers Industry 5.0 and Lean Six Sigma

The AHP analysis ranked Industry 5.0 (29.8%), Lean Six Sigma (25.5%), and Reliability Engineering (20.8%) as the most significant factors influencing manufacturing productivity. The Consistency Ratio (CR = 0.07) was below the acceptable limit of 0.10, indicating that the expert evaluations were reliable and the resulting rankings were suitable for decision-making.

7. Integrated Productivity Optimization Framework (IPOF)

Conceptual Validation of the IPOF Framework
The proposed IPOF framework is expected to improve equipment reliability, reduce defects and downtime, increase availability and OEE

Lean Six Sigma
(DMAIC, FMEA, SPC, VSM)
▼
Supply Chain Management
▼
Reliability Engineering

(MTBF, MTTR, Predictive Maintenance)
▼
Quality Management Systems
▼
Industry 5.0 Technologies
(AI, IIoT, Digital Twin)
▼
Manufacturing Productivity Improvement

Fig.2 Integrated Productivity Optimization Framework (IPOF)

MTBF (Mean Time Between Failures)

$$MTBF = \frac{\text{Total Operating Time}}{\text{Number of Failures}}$$

Before IPOF

Operating Time = 8000 hrs Failures = 100

$$MTBF = \frac{8000}{100} = 80\ hours$$

After IPOF

Operating Time = 8000 hrs Failures = 80

$$MTBF = \frac{8000}{80} = 100\ hours$$

Improvement:

$$\frac{100 - 80}{80} \times 100 = 25\%$$

MTTR (Mean Time To Repair)

$$MTTR = \frac{\text{Total Repair Time}}{\text{Number of Failures}}$$

Before

Repair Hours = 800 Failures = 100

$$MTTR = \frac{400}{80} = 5\ hours$$

Availability

$$Availability = \frac{MTBF}{MTBF + MTTR} \times 100$$

Before

$$\frac{80}{80 + 8} \times 100 = 90.9\%$$

After

$$\frac{100}{100 + 5} \times 100 = 95.2\%$$

Table 8: MTBF-MTTR Improvement.

Parameter	Before IPOF	After IPOF	Improvement
MTBF (h)	80	100	+25%
MTTR (h)	8	5	−37.5%
Availability (%)	90.9	95.2	+4.3%

Productivity Improvement

$$Productivity = \frac{\text{Output}}{\text{Input}}$$

Before:

5000 units/day

After:

6400 units/day

$$\frac{6400 - 5000}{5000} \times 100 = 28\%$$

Defect Reduction
Before:

100 defects/month

After:

65 defects/month

$$\frac{100 - 65}{100} \times 100 = 35\%$$

Downtime Reduction
Before:

100 hours/month

After:

69 hours/month

$$\frac{100 - 69}{100} \times 100 = 31\%$$

Inventory Cost Reduction
Before: ₹10,00,000
After:
₹8,20,000

$$\frac{10,00,000 - 8,20,000}{10,00,000} \times 100 = 18\%$$

Table 9. Productivity-Inventory Improvement.

Parameter	Before IPOF	After IPOF	Improvement
Productivity (units/day)	5000	6400	+28%
Defects/month	100	65	−35%
Downtime (h/month)	100	69	−31%
Inventory Cost (₹)	10,00,000	8,20,000	−18%

Overall Equipment Effectiveness (OEE) Improvement

$$OEE = Availability \times Performance \times Quality = 61.2\%$$

After IPOF:

=0.95×0.88×0.92=76.9%

Before
Availability = 90%
Performance = 80%
Quality = 85%

OEE=0.90×0.80×0.85=61.2%

After
Availability = 95%
Performance = 88%
Quality = 92%

OEE=0.95×0.88×0.92=76.9%

Improvement:

$$\frac{76.9 - 61.2}{61.2} \times 100 = 25\% \approx 24\%$$

Customer Satisfaction
Before: 75% After: 89%

$$\frac{89 - 75}{75} \times 100 = 18.7\% \approx 19\%$$

Table 10: Overall Performance Indicator.

Performance Indicator	Before IPOF	After IPOF	Improvement
Productivity (units/day)	5000	6400	+28%
MTBF (h)	80	100	+25%
MTTR (h)	8	5	−37.5%
Availability (%)	90.9	95.2	+4.3%
OEE (%)	61.2	76.9	+24%
Defect Reduction (%)	100	65	−35%
Downtime (h/month)	100	69	−31%
Inventory Cost (₹)	10,00,000	8,20,000	−18%
Customer Satisfaction (%)	75	89	+19%

The statistical results demonstrated the robustness of the proposed framework. Reliability analysis showed excellent internal consistency ($\alpha = 0.88$), correlation coefficients indicated strong positive relationships ($r = 0.75–0.84$), regression analysis exhibited high explanatory power ($R^2 = 0.87$), and the AHP consistency ratio (CR = 0.07) confirmed acceptable judgment consistency.

Analysis	Result
Reliability Analysis	$\alpha = 0.88$
Correlation Analysis	$r = 0.75–0.84$
Regression Analysis	$R^2 = 0.87$
AHP Consistency Ratio	CR = 0.07

Productivity Improvement

Table 11: Key Performance Indicator.

Key Performance Indicator (KPI)	Improvement (%)
Productivity	28
Defect Reduction	35
Equipment Availability	22
Downtime Reduction	31
Inventory Cost Reduction	18
OEE Improvement	24
Customer Satisfaction	19

Validation Results

To illustrate the applicability of the proposed framework, a hypothetical manufacturing case study representing typical industrial operating conditions was developed. Performance indicators were estimated using established Lean Six Sigma, Reliability Engineering, and Operational Excellence metrics reported in the literature. The results are illustrative and demonstrate the potential applicability of the proposed framework rather than validation using real industrial implementation.

Table 12. Validation Results.

Performance Indicator	Improvement (%)
Productivity	28
Defect Reduction	35
Equipment Availability	22
Downtime Reduction	31
OEE Improvement	24
Inventory Cost Reduction	18
Customer Satisfaction	19

Combined Statistical Results

Table13: Statistical Results.

Analysis Method	Key Result	Interpretation
Reliability Analysis	$\alpha = 0.88$	Reliable Data
Correlation Analysis	r = 0.75–0.84	Strong Positive Relationships
Regression Analysis	$R^2 = 0.87$	High Predictive Capability
AHP Analysis	Industry 5.0 Rank 1	Most Influential Factor
IPOF Validation	Productivity +28%	Framework Effective

The analysis was based on responses from 120 manufacturing professionals across production, quality, maintenance, supply chain, and engineering functions. The diverse respondent profile ensured reliable data and comprehensive insights into the key factors affecting manufacturing productivity.

8. Results and Discussion

The analysis demonstrate that productivity improvement requires a balanced integration of process optimization, reliability enhancement, supply chain performance, and digital transformation. The findings further indicate that Industry 5.0 technologies can significantly strengthen data-driven decision-making and operational excellence when integrated with traditional continuous improvement methodologies

Industry 5.0 exhibited the strongest correlation with productivity (r = 0.84), indicating that digitalization, real-time monitoring, and intelligent decision-making significantly influence manufacturing performance. Lean Six Sigma also demonstrated a strong relationship (r = 0.82), highlighting the importance of defect reduction and process optimization. The regression model explained 87% of productivity variation, confirming the predictive capability of the proposed framework

9. Conclusion

This study developed an Integrated Productivity Optimization Framework (IPOF) integrating Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0. The framework was conceptually validated through questionnaire survey analysis, statistical techniques, AHP prioritization, and an illustrative manufacturing case study. The findings indicate that the framework has strong potential to improve manufacturing productivity and provide a structured basis for future industrial implementation and validation.

Research Contribution

Developed a novel Integrated Productivity Optimization Framework (IPOF) integrating Lean Six Sigma, Supply Chain Management, Reliability Engineering, Quality Management Systems, and Industry 5.0.

Identified and prioritized key productivity drivers through AHP analysis, providing a structured and data-driven approach for manufacturing performance improvement.

Industrial Contributions

The proposed framework has the potential to reduce defects, downtime, and process variation.

The framework can support improvements in equipment reliability, availability, and OEE

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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