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Research Article

Application of the 4M Framework in Reducing Defect Rates: A Case Study from Thailand's Plastic Mats Manufacturing Sector

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ABSTRACT

This study examines the impact of four key production factors - Manpower, Machine, Material, and Method (4M) on defect rates in the plastic mat manufacturing process. Conducted at a plastic mat factory in Khon Kaen province, Northeastern Thailand, the research employed a quantitative approach with data collected from 100 operational staff through structured questionnaires. Descriptive statistics and multiple regression analysis were used to analyze the data at a 0.05 significance level.

The findings indicate that Manpower, Material, and Method significantly affect defect rates, while Machine does not show a statistically significant influence. Among the significant predictors, Material has the greatest impact, followed by Manpower and Method. The results underscore the critical role of skilled labor, consistent raw material quality, and clearly defined production procedures in minimizing defects and improving production efficiency. The study provides practical insights for manufacturers aiming to enhance product quality and operational performance through systematic quality management and workforce development.

Keywords: 4M, Defect, Waste, Lean, Manufacturing, Plastic Mat, Production.

INTRODUCTION

Thailand's plastics industry serves as a cornerstone of the national economy, supplying a wide spectrum of consumer and industrial products and generating substantial employment. Within this sector, plastic mat manufacturing occupies a strategically important niche. Plastic mats are omnipresent in Thai households, religious venues, educational facilities, and commercial establishments because they combine affordability, durability, and cultural familiarity. They also constitute a notable share of Thailand's export basket of household plastic goods. The Department of International Trade Promotion (2023) reports that plastic-product exports surpassed 113 billion baht in 2023, and sectoral forecasts anticipate continued growth as regional demand rises in tandem with urbanization and tourism. Despite its relatively simple technology base, the plastic-mat segment therefore warrants careful scholarly attention.

Although production technology in this industry is less complex than in high-tech manufacturing, quality-related losses remain acute. Evidence from XYZ Plastic Mat Factory in Khon Kaen Province, Northeastern Thailand illustrates the scale of the problem: recent operational data show 104,181 defective mats annually, equivalent to 8.33 % of total output, with direct losses exceeding 5 million baht per year. These figures do not capture hidden costs such as overtime, production rescheduling, warranty claims, or reputational damage. Typical non-conformities include irregular weaving patterns, inconsistent thickness, surface blemishes, inaccurate dimensions, and colour variation. Each defect triggers either scrap disposal or rework, eroding profit margins and weakening the factory's competitive position in both domestic and foreign markets.

Quality losses of this magnitude call for structured, data-driven improvement programmes that target root causes rather than symptoms. Industries worldwide have embraced frameworks such as Lean Manufacturing, Six Sigma, Total Productive Maintenance (TPM), the DMAIC cycle, and Failure Mode and Effects Analysis (FMEA) to reduce waste and variability (Delano, 2022; Hakeem et al., 2022; Psarommatis et al., 2021). These methods routinely deliver sizeable cost savings and lead-time reductions in automotive, aerospace, and electronics production, yet evidence of their systematic deployment in low- to medium-technology sectors, including plastic mats remains scarce in the scholarly record.

A central diagnostic lens in quality engineering is the 4M framework (Manpower, Machine, Material, and Method) popularised through Ishikawa's fishbone diagram and adopted in numerous continuous-improvement toolkits (Knop & Mielczarek, 2018; Lee et al., 2012). Although conceptually straightforward, the actual weight carried by each "M" differs across industries and processes. Existing studies tend to focus on high-capital or highly automated environments, wherein Machine and Method often dominate statistical models of defect incidence (Najmuddin et al., 2014; Psarommatis et al., 2021). Empirical investigations addressing the interplay of the four factors in semi-automated, labour-intensive industries such as plastic mat production are noticeably absent. Moreover, prior research seldom provides a comparative quantification of each factor's relative contribution to total defect rates, thereby limiting the practical usefulness of published findings for operational managers.

Thailand's plastic-mat industry features several characteristics that make it fertile ground for quality-management inquiry. First, labour intensity remains high, rendering human performance pivotal to process stability. Second, raw-material variability is common; polymer resins sourced from multiple suppliers can differ in melt flow index, colour dispersion, and moisture content, each of which affects mat aesthetics and structural integrity. Third, semi-automated equipment often requires frequent set-ups and operator intervention, heightening the probability of process drift. Finally, the market for plastic mats is price-sensitive, which constrains the margin that manufacturers can allocate to rework or scrap. Understanding how the 4M elements combine to influence defect occurrence in this precise context is therefore both academically meaningful and managerially urgent.

This study responds to the identified gap by empirically analysing the relative impact of the 4M factors on defect-related waste at a representative Thai plastic-mat factory. The research addresses three interrelated questions: Which of the 4M factors exert statistically significant effects on defect rates in plastic mat manufacturing? Answering these question will enrich the literature on quality management in labour-intensive, low-technology settings and provide managers with an evidence-based rationale for resource allocation.

The study is anchored in two complementary theoretical streams. Lean Manufacturing theory posits that waste defined as any activity that does not add value from the customer's perspective should be relentlessly eliminated. The 4M framework acts as an operational bridge between these high-level philosophies and plant-floor realities.

For practitioners, discerning whether workforce skills, machinery reliability, material consistency, or procedural rigour is the principal driver of non-conformities informs strategic choices about capital budgeting, training plans, supplier partnerships, and digital-monitoring investments. In SMEs, resource scarcity intensifies the need for precise prioritisation. Investments misaligned with true root causes risk yielding marginal returns while leaving the primary problem unaddressed. By statistically estimating the marginal effect of each 4M variable on defect incidence, the present study equips managers with a decision-support tool to optimise improvement roadmaps.

A notable methodological contribution lies in the study's integration of shop-floor data into a multivariate regression framework, thereby transforming qualitative observations into quantifiable evidence. Most case studies in the low-technology literature rely on descriptive or anecdotal analysis; far fewer employ inferential statistics to validate the intuitive beliefs of production supervisors. This research therefore demonstrates how routine manufacturing records, when systematically aggregated and analysed, can yield rigorous insights that transcend the anecdotal.

The remainder of the article is organised as follows. Section 2 reviews the extant literature on defect reduction in low- and medium-technology industries, with an emphasis on previous applications of the 4M model. Section 3 outlines the research design, detailing data collection procedures, variable operationalisation, and the statistical methods used to test each hypothesis. Section 4 presents and interprets the empirical results, while Section 5 discusses managerial implications, theoretical contributions, and avenues for future research. Section 6 concludes or summarising key findings.

Given the economic footprint of plastic mat manufacturing and the pronounced defect rates reported by Thai producers, a nuanced understanding of the underlying causative factors is indispensable. By situating the 4M framework within Lean and applying rigorous quantitative analysis to a real-world dataset, the present study aspires to close a salient gap in the literature and furnish actionable guidance for quality-driven competitiveness in the Thai plastics sector.

Expected Contributions of the Study

This study offers both theoretical and practical contributions. Theoretically, it expands the current body of knowledge by providing empirical evidence on how 4M production factors influence defect rates in the under-researched context of plastic mat manufacturing. This contributes to a broader understanding of Lean principles in niche manufacturing sectors.

Practically, the study provides valuable insights for manufacturing managers and practitioners. By identifying the most influential factors driving defect generation, the findings can inform the development of targeted quality improvement initiatives. These insights will support efforts to optimize resource utilization, minimize waste, and enhance operational efficiency, thereby improving the competitiveness and sustainability of plastic mat manufacturers in both domestic and global markets.

LITERATURE REVIEW

1. Waste from Defects in Manufacturing Process

Waste reduction is widely recognized as a fundamental objective within manufacturing systems. Ohno (1990), a pioneer of the Toyota Production System, defined Muda—activities that consume resources without adding value to the final product—as a primary target for elimination. The seven categories of waste identified by Ohno encompass overproduction, unnecessary processing, excessive inventory, unnecessary motion, waiting time, transportation, and defects. Among these, defects represent one of the most critical and detrimental forms of waste, exerting a direct negative impact on product quality, customer satisfaction, and overall production efficiency.

Waste arising from defects is characterized by errors or non-conformities occurring during production that result in products or services failing to meet established quality standards. Such waste contributes to increased costs across multiple dimensions, including financial expenditures, time, material usage, and equipment utilization. In many cases, defect-related waste necessitates rework or additional production cycles to replace non-conforming items, thereby compounding resource consumption and operational inefficiencies.

Jones (2018) underscores that defect waste constitutes a significant threat to business sustainability, given its adverse effects on production costs through wasted time, capital, and resources. The root causes of defect waste frequently include inadequate communication, insufficient quality control procedures, suboptimal employee training, and the absence of clear and comprehensive process documentation. Without the implementation of effective defect prevention strategies, organizations face the risk of escalating operational costs and declining competitiveness over time.

Moreover, defect waste not only impairs internal production efficiency but also undermines customer satisfaction and corporate reputation. Darsini (2022) illustrated this phenomenon within the copper craft industry, where defect waste was identified as a critical issue necessitating systematic process evaluation and continuous improvement. Such findings highlight the broader relevance of defect waste across diverse manufacturing sectors and emphasize the imperative for sustained quality enhancement efforts aimed at mitigating its detrimental effects.

Lean Manufacturing has evolved as a comprehensive approach to waste elimination, with Zero Defect Manufacturing (ZDM) emerging as a complementary philosophy designed to minimize defects and promote process stability (Psarommatis et al., 2021; Delano, 2022; Hakeem et al., 2022; Febianti et al., 2022). Both frameworks advocate for

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the systematic identification and elimination of root causes of defects, thereby supporting continuous improvement and operational excellence in manufacturing processes.

2. The 4M Framework in Manufacturing Quality Management

The 4M framework—comprising Manpower, Machine, Material, and Method factors—has been widely recognized as an effective diagnostic tool for identifying root causes of quality problems in manufacturing processes (Knop & Mielczarek, 2018; Lee et al., 2012). Originating from quality engineering practices such as Ishikawa (cause-and-effect) diagrams, the 4M framework provides a systematic structure for analyzing the various dimensions of production that contribute to defect generation and process variability. Numerous empirical studies have demonstrated the value of applying the 4M framework in diverse manufacturing contexts.

Manpower factors

Manpower factors, including employee skills, training, and adherence to standard operating procedures, have consistently been shown to influence defect rates, particularly in labor-intensive operations (Psarommatis et al., 2021). Deficiencies in workforce competency and engagement often result in process errors and inconsistent product quality.

Material factors

Material factors, such as variability in raw material quality, insufficient material inspection, and inadequate storage practices, have also been identified as significant contributors to defect generation (Febianti et al., 2022). Material-related issues can introduce variability that compromises product consistency and increases waste.

Machine factors

The role of machine factors - encompassing equipment condition, maintenance practices, and process stability has been widely acknowledged in the literature (Najmuddin et al., 2014). Well-maintained and calibrated equipment can enhance process capability and reduce defect rates, while neglected machinery can introduce undesirable variation.

Method factors

Method factors, including process design, standardization, and quality assurance procedures, are equally critical. Poorly defined work instructions and lack of process control can lead to process instability and defect occurrence (Hakeem et al., 2022). Lee et al. (2012) proposed the use of real-time 4M data collection systems to enhance production monitoring and improve process control.

Despite these valuable insights, most prior studies have focused on individual 4M factors or applied the framework in high-technology manufacturing sectors. There is a notable gap in the literature concerning systematic empirical analysis of the combined impact of all four 4M factors on defect rates, particularly in low- to medium-technology industries such as plastic mat manufacturing. Given the unique production characteristics of this sector - including significant human involvement, variable material inputs, and manual process elements - addressing this gap is essential for developing targeted and context-specific quality improvement strategies.

3. Prior Studies on Defect Reduction in Manufacturing Processes

Prior research has employed a range of methodologies to reduce defect-related waste across various manufacturing sectors. Delano (2022) demonstrated the effectiveness of DMAIC, Six Sigma, and FMEA in improving process quality. Similarly, Hakeem et al. (2022) applied Lean tools to reduce both waiting time and defect waste in press machine operations. Febianti et al. (2022) further showcased the potential of Lean Manufacturing principles to enhance production efficiency and mitigate defect waste in plastic injection molding processes.

While these studies collectively highlight the significant contributions of Lean and Six Sigma methodologies to defect reduction, they predominantly emphasize process optimization techniques without systematically examining the combined influence of Manpower, Machine, Material, and Method (4M) factors on defect generation. Moreover, much of the existing literature focuses on high-technology sectors, where advanced automation and process control mechanisms are prevalent. In contrast, there is limited understanding of how 4M factors interact to influence defect

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rates in low- to medium-technology industries, such as plastic mat manufacturing, where manual labor, material variability, and process complexity play a more pronounced role.

Addressing this knowledge gap is critical for developing targeted and context-specific quality improvement strategies. Accordingly, this study aims to advance the literature by empirically investigating the relative impact of Manpower, Machine, Material, and Method factors on defect-related waste within the plastic mat manufacturing sector.

Conceptual Framework

Building on the insights from prior research, this study adopts the 4M framework—comprising Manpower, Machine, Material, and Method—as the conceptual basis for examining factors influencing defect rates in plastic mat manufacturing. Each of these factors is hypothesized to exert a measurable influence on defect generation through distinct mechanisms: human factors (e.g., operator skills and adherence to procedures), equipment-related factors (e.g., machine condition and maintenance), material factors (e.g., raw material consistency), and process-related factors (e.g., process design and standardization).

The conceptual framework posits that improvements or deficiencies in any of these domains can significantly impact the rate of defects observed in the production process. By empirically testing these relationships, the study aims to provide a deeper understanding of how 4M factors contribute to quality outcomes in plastic mat manufacturing. Figure 1 presents the conceptual framework guiding this research.

Based on the conceptual framework and literature review, the following research hypotheses are proposed:

H1: Manpower factors have a significant impact on defect rates in the plastic mat manufacturing process.

H2: Machine factors have a significant impact on defect rates in the plastic mat manufacturing process.

H3: Material factors have a significant impact on defect rates in the plastic mat manufacturing process.

H4: Method factors have a significant impact on defect rates in the plastic mat manufacturing process.

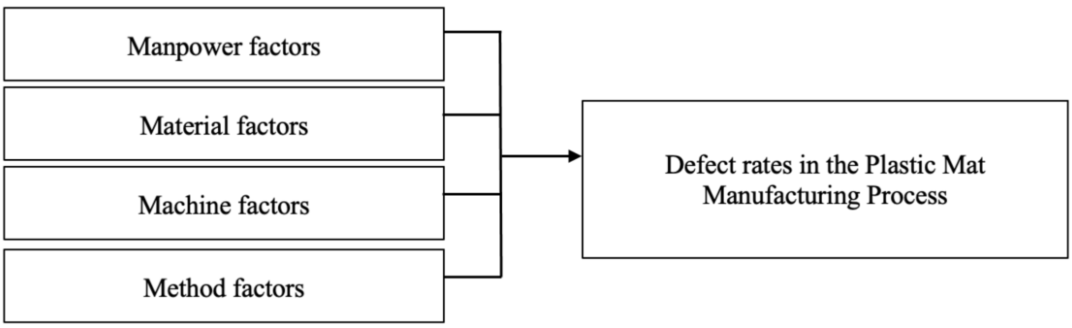

Figure 1 Conceptual Framework

METHODS

This study employed a quantitative research approach to investigate the impact of four key production factors - Manpower, Machine, Material, and Method (4M) on defect rates in plastic mat manufacturing. The research design was structured to facilitate empirical testing of the proposed hypotheses through statistical analysis.

Data were collected from XYZ Plastic Mat Factory, located in Khon Kaen Province, Thailand. The target population comprised production staff and quality control personnel directly involved in the manufacturing process. A purposive sampling method was used to select respondents with relevant operational knowledge and experience. In total, 100 valid responses were obtained through structured, self-administered questionnaires.

The questionnaire was developed based on established literature and prior studies related to Lean Manufacturing, Zero Defect Manufacturing, and 4M factors (Gruszka & Gašpar, 2018; Psarommatis et al., 2021). It consisted of five sections: demographic information and four sections measuring perceptions of Manpower, Machine, Material, and

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Method factors using a 5-point Likert scale. The dependent variable, defect rate, was operationalized based on reported defect occurrence within production processes.

The reliability and validity of the instrument were assessed prior to full deployment. Cronbach's alpha coefficients for all 4M factors exceeded the 0.70 threshold, indicating acceptable internal consistency. Descriptive statistics and multiple regression analysis were employed to test the hypotheses at a significance level of 0.05, using SPSS statistical software version 29 (KhonKaen University's Copyright). This methodological approach enabled the identification and quantification of the relative contributions of 4M factors to defect rates, providing actionable insights for quality improvement in plastic mat manufacturing.

RESULTS

This section presents the findings of the study based on data collected from 100 production staff and quality control personnel at XYZ Plastic Mat Factory. Descriptive statistics were first computed to summarize respondent characteristics and perceptions of the 4M production factors. Subsequently, multiple regression analysis was conducted to test the research hypotheses and to quantify the relative impact of each 4M factor on defect rates in the plastic mat manufacturing process.

Descriptive Statistics

Table 1 presents the operation staff's perceptions of the contribution of four major production factors - Manpower, Material, Machine, and Method to defect occurrence in the plastic mat manufacturing process.

The descriptive analysis revealed that **Material factors** were perceived as the most significant contributor to defects, with the highest mean score (M = 3.81, SD = 0.96). Respondents highlighted issues such as inconsistent raw material quality and insufficient quality inspection of materials prior to production as key sources of defects. **Manpower factors** were also viewed as highly influential (M = 3.81, SD = 1.04), with concerns centered on employees' lack of proficiency in task execution.

Method factors followed (M = 3.65, SD = 0.90), with respondents citing unclear work procedures as a notable cause of process variation and defects. Finally, **Machine factors** received the lowest mean score (M = 3.46, SD = 0.97), with aging equipment and machinery exceeding its optimal service life identified as relevant issues.

These findings suggest that quality management efforts in the plastic mat manufacturing process should prioritize improvements in material quality and workforce competency, followed by enhancements in process standardization and equipment maintenance.

Table 1 Perceived Defect Factors in the plastic mat manufacturing process

Defect Factor	Mean Score	S.D.	Interpretation
MANPOWER	3.70	1.04	Agree
MATERIAL	3.81	0.96	Agree
MACHINE	3.46	0.97	Agree
METHOD	3.65	0.90	Agree

Further Analysis of Key Items within Each Factor

Table 2 provides deeper insights into specific sub-issues within each 4M factor that were perceived to contribute significantly to defect occurrence in the plastic mat manufacturing process.

Among Material factors, inconsistent raw material quality received the highest mean score, reinforcing the critical importance of material consistency in achieving product quality. Other key material-related issues included insufficient quality inspection of raw materials prior to production and improper storage of materials, which may lead to damage and quality degradation.

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Within the Manpower factor, the highest rated defect-related issue was employees' lack of proficiency in performing their assigned tasks. This finding highlights the need for enhanced workforce training and competency development to reduce operator-related variability in the production process.

For Method factors, unclear work procedures were identified as a significant contributor to defects, indicating opportunities for improving process documentation and standardization.

Regarding Machine factors, aging equipment specifically machinery that had exceeded its optimal service life was perceived as a notable source of process instability and defects.

These results underscore the multifaceted nature of defect generation in plastic mat manufacturing and suggest that effective quality improvement initiatives must address both technical (Material, Machine) and human/process-related (Manpower, Method) factors in an integrated manner.

Table 2 High-Impact Items within Each 4M Factor Based on Mean Scores

Items Description	Mean	S.D.
Employees lack proficiency in performing their tasks (Manpower)	3.79	1.05
Inconsistent raw material quality (Material)	3.89	0.93
The machinery has exceeded its optimal service life (Machine)	3.57	0.90
The work procedures lack clarity (Method)	3.68	0.97

Specific Causes of Defect

Furthermore, respondents were asked to identify specific causes contributing to defects in the plastic mat manufacturing process. As shown in Table 3, inconsistent raw material quality emerged as the top cause (M = 4.91), followed by inadequate employee proficiency (M = 4.72) and unclear work procedures (M = 4.37). These results align with the earlier findings on the relative importance of Material, Manpower, and Method factors in driving defect occurrence. The results highlight the importance of strengthening material quality control, enhancing workforce training, and improving process standardization to effectively reduce defect rates and improve overall production efficiency.

Table 3 Specific Causes of Defect

Specific Causes of Defect	Mean	S.D.
Decrease in the company's revenue	4.91	0.28
Loss of quantity of standard-quality mats	4.72	0.47
Higher production costs	4.37	0.64

Inferential Statistics - Pearson Correlation Analysis

Table 4 presents the Pearson product-moment correlation coefficients among the four independent variables (Manpower, Machine, Material, and Method) and the dependent variable (Defect rates) in the plastic mat manufacturing process. The analysis revealed that all independent variables were positively correlated with defect rates, and intercorrelations among the independent variables were within acceptable limits. Specifically, all pairwise correlation coefficients were below 0.800, indicating no multicollinearity concerns. These results suggest that the

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four independent variables exhibit normal correlation patterns and are suitable for inclusion in subsequent multiple regression analysis to model their collective impact on defect rates.

Table 4 Pearson Correlation Coefficients among 4M Factors and Defect Rates

Variables	Defect	Manpower	Material	Machine	Method
Defect	1	0.005	-0.035	-0.049	0.695**
Manpower	0.005	1			
Material	-0.035		1		
Machine	-0.049			1	
Method	0.695**				1

**. Correlation is significant at the 0.01 level (2-tailed).

Regression Analysis – Hypothesis Testing

Multiple regression analysis using the Enter method was conducted to test the proposed research hypotheses (Table 5). The overall regression model demonstrated a relatively strong level of association ($R = 0.736$) and explained approximately 54.20% of the variance in defect rates ($R^2 = 0.542$). Variance Inflation Factor (VIF) values for all independent variables were below 10.00, and Tolerance values exceeded 0.20, indicating no multicollinearity concerns (O'Brien, 2007). These results support the suitability of the data for multiple regression analysis.

Table 5 Multiple Regression Results: Impact of 4M Factors on Defect Rates

Variable	B	Std. Error	β	t	Sig.	Tolerance	VIF
Constant	1.64	0.422		3.891	I. .000	II.	III.
Manpower	0.102	0.053	0.706	10.139	IV. .000	V. .996	VI. 1.004
Material	0.108	0.108	0.144	VII. 2.070	VIII. .041	IX. .996	X. 1.004
Machine	0.024	0.024	0.024	XI. .413	XII. .680	XIII. .983	XIV. 1.018
Method	0.163	0.163	0.163	XV. 2.905	XVI. .005	XVII. .980	XVIII. 1.021

Remarks: $R= 0.736^a$, $R^2=0.542$, Adjusted $R^2= 0.523$, SEE=0.28537,

$F=28.099$, $Sig=0.000^b$

Significance levels: $*p < 0.05$, $**p<0.01$

The regression results indicated that three independent variables - Manpower, Material, and Method factors had statistically significant positive effects on defect rates in the plastic mat manufacturing process. Manpower factors emerged as the strongest predictor ($\beta = 0.706$, $p < 0.01$), suggesting that increased deficiencies in manpower-related aspects, such as employee proficiency and adherence to procedures, are associated with higher defect rates.

$$Waste = 1.643 + 0.523Manpower + 0.108Material + 0.163Method$$

The unstandardized regression coefficient for Manpower was 0.523, meaning that a one-unit increase in perceived manpower-related deficiencies is associated with a 0.523 unit increase in defect rates, holding other factors constant.

Method factors also had a significant positive impact ($\beta = 0.204$, $p < 0.01$), with an unstandardized coefficient of 0.163. This finding indicates that issues related to process design and standardization contribute meaningfully to defect generation.

Material factors exhibited a statistically significant positive effect as well ($\beta = 0.144$, $p < 0.05$), with an unstandardized coefficient of 0.108. Inconsistent material quality and inadequate material handling practices were key drivers of this relationship.

Conversely, Machine factors did not show a statistically significant effect on defect rates ($p > 0.05$), suggesting that equipment-related issues may not be a primary driver of defects in the studied context.

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Hypothesis Testing Summary

H1: Manpower factors have a significant positive impact on defect rates. Hypothesis supported ($p < 0.01$).

H2: Material factors have a significant positive impact on defect rates. Hypothesis supported ($p < 0.05$).

H3: Machine factors do not have a significant impact on defect rates. Hypothesis not supported ($p > 0.05$).

H4: Method factors have a significant positive impact on defect rates. Hypothesis supported ($p < 0.01$).

These findings underscore the critical influence of manpower, material, and method factors on defect rates, highlighting priority areas for quality improvement interventions in plastic mat manufacturing.

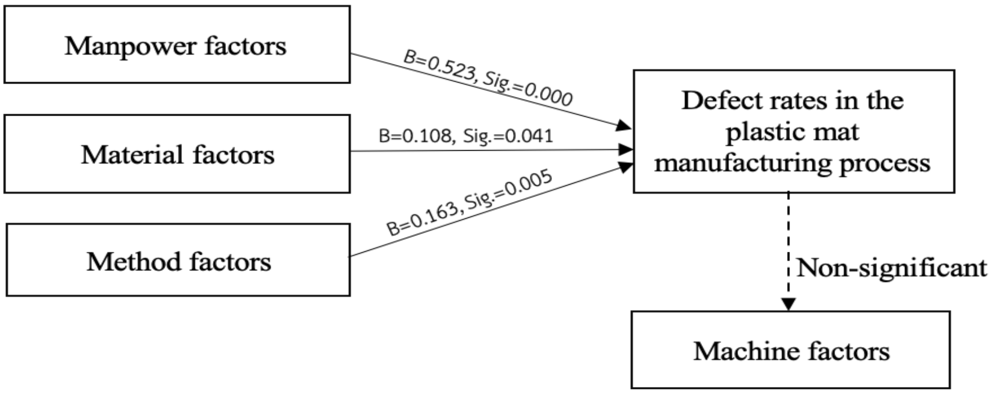

Figure 2: 4M Production Factors Influencing Defect Rates in Plastic Mat Manufacturing

Statistical Summary and Interpretation

The multiple regression analysis results indicate that Manpower factors are the strongest positive predictors of defect rates ($\beta = 0.706$, $p < 0.01$) in the plastic mat manufacturing process. Both Method and Material factors also emerged as significant predictors, with $\beta = 0.204$ ($p < 0.01$) and $\beta = 0.144$ ($p < 0.05$), respectively (Table 6). These findings suggest that deficiencies in workforce proficiency, process design, and material quality are key contributors to defect generation.

In contrast, the Machine factor did not exhibit a statistically significant effect on defect-related waste at the 0.05 significance level, thereby failing to support the corresponding research hypothesis. This result implies that equipment-related issues may not play a primary role in influencing defect rates within the studied manufacturing context.

Table 6 Summary of Multiple Regression Analysis Results

Predictor	β (Beta)	B (Under standardized)	t-value	Sig.	VIF
Manpower	0.706	0.523	10.139	0.000**	1.004
Method	0.204	0.163	2.905	0.005**	1.021
Material	0.144	0.108	2.070	0.041*	1.004
Machine	0.029	0.024	0.413	0.680	1.018

Remarks: R= 0.736[a], R^2=0.542, Adjusted R^2= 0.523, SEE=0.28537,

F=28.099, Sig=0.000[b]

Significance levels: *$p < 0.05$, **$p<0.01$

DISCUSSION

This study advances empirical knowledge on defect-related waste in plastic-mat manufacturing by quantifying the relative weight of the classical "4M" production factors - Manpower, Method, Material, and Machine within a single, integrated regression framework. The model's explanatory strength (R = 0.736; adjusted R^2 = 0.542) indicates that slightly

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more than half of the variation in defect incidence is predictable from these variables, a level of statistical power rarely reported in comparable shop-floor studies. This section interprets the findings in light of extant literature, assesses their practical salience, and delineates avenues for continued inquiry.

Manpower as the Predominant Leverage Point

Manpower demonstrated the highest standardized coefficient, underscoring its pivotal role in driving quality outcomes. This result corroborates earlier observations that human-factor deficiencies - insufficient training, ambiguous role expectations, and limited tacit knowledge are primary antecedents of process variability (Gruszka & Gašpar, 2018; Psarommatis et al., n.d.; Simaremare & Tarigan, 2024). In the present context, operator errors frequently manifested as improper mold alignment, inconsistent heating cycles, and sub-optimal finishing, each directly traceable to knowledge gaps or fatigue-induced attentional lapses. Therefore, the evidence supports prioritising structured capacity-building programmes: competency-based training modules, periodic skill audits, and continuous feedback loops anchored in statistical process control (SPC) data. Notably, "human capital maturity" must be viewed as dynamic; without systematic reinforcement, earlier gains may erode due to workforce turnover or task reconfiguration (Janapiraganit & Namwat, 2024).

Method Factors and the Imperative of Procedural Discipline

Method effects ranked second in magnitude, aligning with the argument that robust standard operating procedures (SOPs) and real-time process governance are indispensable for defect prevention (Hakeem, 2022; Youngyuen & Ruangchoengchum, 2018). The plant under investigation exhibited gaps in documented work instructions, limited use of poka-yoke (mistake-proofing) devices, and sporadic adherence to first-article inspection protocols. These deficiencies significantly raise the entropy of the production system, creating multiple pathways for non-conformities to arise. Embedding lean tools such as value-stream mapping and line-balancing, complemented by digital dashboards that visualize critical-to-quality parameters, can reduce process opacity and enable proactive intervention.

Material Quality as a Determinant of Defect Propagation

The positive relationship between material variability and defect rates confirms that upstream supply risk propagates downstream quality losses (Febianti et al., 2022). Key pain points included inconsistent polymer viscosity, moisture contamination, and sub-standard colour masterbatches. While incoming-quality control existed, sampling plans were neither statistically rigorous nor consistently executed. Transitioning to supplier-certification schemes coupled with near-infrared (NIR) on-line spectroscopy could tighten material specification windows and attenuate defect propagation. Furthermore, improved storage—temperature- and humidity-controlled warehouses and FIFO (first-in, first-out) rotation—would mitigate material degradation.

Non-significance of Machine Factors

Contrary to conventional expectations in repetitive manufacturing, the Machine variable did not achieve statistical significance. Root-cause analysis revealed that the facility recently completed a preventive-maintenance overhaul, resulting in above-benchmark overall equipment effectiveness (OEE > 85 %). The residual impact of equipment malfunction on defect creation is consequently muted. This finding suggests diminishing marginal returns from additional capital outlay in machinery relative to human- and process-centric investments, at least in contexts where baseline mechanical reliability is already high. Nonetheless, predictive-maintenance analytics may still offer cost-avoidance benefits not directly captured in defect metrics.

Managerial Implications and Strategic Priorities

Taken together, the results delineate a clear hierarchy for resource allocation: 1) elevate operator capability and engagement; 2) institutionalise method rigour via documented standards and digital monitoring; 3) fortify material quality assurance through tighter supplier integration and in-process sensing; and 4) maintain, rather than expand, the current equipment base. Aligning these priorities with continuous-improvement frameworks, Lean Six Sigma's

DMAIC cycle or Total Productive Maintenance pillars can maximise defect-reduction ROI and support broader sustainability goals by curbing material waste.

In sum, the study substantiates the primacy of human and procedural dimensions in defect mitigation within plastic-mat manufacturing and offers a data-driven blueprint for targeted operational excellence initiatives.

CONCLUSION

The results of this study provide valuable insights into the influence of 4M production factors (Manpower, Method, Material, and Machine) on defect-related waste in the plastic mat manufacturing process. The regression model demonstrated a relatively strong relationship ($R = 0.736$), explaining approximately 54.20% of the variance in defect rates (Adjusted $R^2 = 0.542$). Among the four factors, Manpower emerged as the most influential predictor of defect-related waste, followed by Method and Material factors. The Machine factor, however, did not exhibit a statistically significant effect in this context.

This study offers a significant contribution to the body of knowledge by empirically examining the effects of 4M production factors on defect-related waste within the plastic mat manufacturing industry, a sector that has been underrepresented in academic research. The results reveal that Manpower, Method, and Material factors have a statistically significant impact on defect rates, whereas Machine factors do not. These findings underscore the critical importance of prioritizing workforce development, procedural standardization, and rigorous material quality control in waste reduction strategies. The study provides actionable insights for production managers aiming to improve process reliability and operational efficiency. Furthermore, it advocates for a holistic quality management framework that simultaneously addresses human performance, process discipline, and input quality to achieve sustainable manufacturing excellence.

SUGGESTIONS

Suggestions for This Research

Based on the findings of this study, several practical recommendations can be proposed to support quality improvement initiatives in the plastic mat manufacturing process:

Enhance Workforce Competency and Engagement

Given that Manpower factors emerged as the strongest predictor of defect rates, it is recommended that manufacturing organizations invest in comprehensive training programs aimed at enhancing employee skills, process knowledge, and adherence to standard operating procedures. In addition, fostering a culture of quality awareness and encouraging employee engagement in continuous improvement activities can further reduce operator-related defects.

Strengthen Process Standardization and Control

The significant influence of Method factors highlights the need for well-defined and standardized work procedures. Organizations should prioritize the development and implementation of clear process documentation, supported by regular audits and process control measures. Providing frontline employees with accessible and comprehensible work instructions can help ensure consistent process execution and minimize variability.

Improve Material Quality Management

As Material factors also significantly contribute to defect rates, strengthening material quality control processes is essential. This includes implementing stringent material inspection protocols, establishing robust supplier quality management practices, and ensuring proper storage and handling of raw materials. Such measures can help mitigate material-related defects and improve overall product quality.

Sustain Equipment Maintenance Practices

Although Machine factors did not exhibit a significant impact in this study, it is important to maintain current levels of equipment reliability and performance. Continued adherence to preventive maintenance schedules and equipment monitoring practices can help sustain process stability and prevent future equipment-related defects.

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By addressing these key areas - workforce competency, process standardization, and material quality management - manufacturing organizations can enhance their operational performance, reduce defect-related waste, and improve competitiveness in the plastic mat industry.

Limitations

Two limitations merit acknowledgment. First, the cross-sectional design constrains causal inference; longitudinal data capturing seasonal load variations and technology upgrades would enrich model robustness. Second, the study's scope excluded environmental and organisational-culture variables, both of which may interact with the 4M factors.

Suggestions for Future Research

Building on the findings of this study, future research could adopt a qualitative approach to gain deeper insights into the mechanisms through which Manpower factors influence defect generation. For example, focus group discussions with production staff could facilitate the exchange of ideas and practical solutions for reducing defect-related waste.

Furthermore, future studies could employ participant observation combined with in-depth interviews to explore operational practices in greater detail. This approach would enable researchers to observe actual production activities, identify process bottlenecks, and gather rich qualitative data to inform targeted quality improvement strategies. In addition, future research should employ mixed-method approaches combining real-time sensor analytics with ethnographic assessments to unravel these complex interdependencies.

Competing interests

The authors declare that they have no competing interests.

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