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MCDM Solutions for Complex SMT Process Optimization: A Comprehensive Approach

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ABSTRACT

This study examines the application of Multi-Criteria Decision-Making (MCDM) methodologies to enhance the Solder Paste Printing (SPP) process within the electronics sector. SPP is a vital stage in manufacturing that profoundly affects the quality of the finished product and overall production efficiency. Refining the setup of this process can result in significant improvements in performance and product dependability. All of the characteristics that were chosen are modifiable in an actual production setting. The study utilizes methodologies, including the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to determine the optimal design. It is demonstrated by simulating weight change situations that the rankings of the configurations (A > B > C) are maintained even when significant elements like Print Pressure, Printing Speed, and Separation Speed fluctuate somewhat. This supports the TOPSIS model's strong stability and dependability, which boosts confidence when using the decision-making outcomes in the production process.

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1. Introduction

The electronics industry plays a central role in driving technological advancements and societal development in the modern era. As electronic devices become increasingly compact yet functionally complex, their integration into daily life has grown exponentially. However, the pursuit of miniaturization and enhanced processing speed-key demands of the digital age has introduced challenges, particularly in managing densely packed circuit components. This issue significantly impacts manufacturing efficiency and innovation within technology-related sectors [1].

To address these obstacles, Surface Mount Technology (SMT) emerged as a groundbreaking solution, enabling the production of smaller, multifunctional devices without compromising performance. From a manufacturing perspective, SMT implementation involves meticulous processes, with the solder paste printing (SPP) phase being especially critical. During this stage, the precise application of solder material onto copper pads directly determines the reliability of electrical connections in printed circuit boards (PCBs). Even minor deviations in solder quantity or placement can lead to defects in subsequent stages, such as weak joints or component misalignment, ultimately risking product failure [2].

Notably, the component attachment phase- often termed the "core" of SMT- demands exceptional precision. This step involves mounting micro-components directly onto PCBs, which serve as both structural frameworks and conductive pathways for electronic circuits [3]. Given its pivotal role, errors during this phase can propagate through later production stages, including soldering and quality testing, potentially undermining product durability and end-user satisfaction. Consequently, optimizing this process through advanced automation and AI-driven calibration has become a priority for manufacturers aiming to balance cost-efficiency with high-quality outputs.

Research findings [3] highlight that squeegee pressure, squeegee velocity, and separation rate exert substantial influence on three critical solder paste metrics: filled volume, paste height, and paste area. However, inconsistencies in detection accuracy were observed when printing PCBs across multiple machines, underscoring the variability introduced by differing operational conditions [4]. This reinforces the necessity of machine-specific calibration and adaptive threshold adjustments to maintain precision in classification systems.

A recurring challenge in component mounting involves defects such as misalignment (e.g., positional inaccuracies, rotational errors, or inverted placements) and solder paste irregularities (e.g., uneven distribution or excessive application), particularly in high-density assemblies [5]. These flaws can compromise solder joint integrity, leading to electrical failures (e.g., short or open circuits) that degrade circuit functionality and complicate downstream processes like soldering [6].

To address these complexities, this study adopts a novel two-phase optimization framework. Initially, a Design of Experiments (DOE) identifies permissible variation ranges for key parameters—print speed, pressure, standoff distance, and detachment rate—establishing a systematic framework for subsequent analysis. Building on this, Multi-Criteria Decision-Making (MCDM) techniques, including the Analytic Hierarchy Process (AHP) and TOPSIS, are employed to evaluate trade-offs between conflicting objectives (e.g., cost vs. reliability) and determine optimal solder paste printing (SPP) configurations. While current conclusions are based on preliminary DOE data, this approach lays the foundation for future large-scale experimental validation [7].

Context & Scope:

Conducted at Global Corporation X (2023–2024), the research focuses on optimizing SMT parameters for passive components (resistors, capacitors, inductors) using 2.8-mil-thick stencils. Key variables analyzed include:

- Stencil properties (material, aperture design)
- Process parameters (print angle, pressure, speed)
- Solder paste characteristics (type, alloy composition)

The AHP-TOPSIS hybrid model was utilized to prioritize criteria weights, though external factors such as environmental conditions were excluded from the analysis.

1.1. Basic SMT Process

A standard Surface Mount Technology (SMT) production line comprises five core stages: solder paste printing (SPP), solder paste inspection (SPI), component placement, reflow soldering, and automated optical inspection (AOI). Among these, the initial three phases—printing, component assembly, and reflow soldering—are universally recognized as the backbone of SMT manufacturing [5].

Solder Paste Printing (SPP), the foundational stage, involves depositing solder paste onto designated PCB pads through a laser-cut stencil, as illustrated in Figure 1.

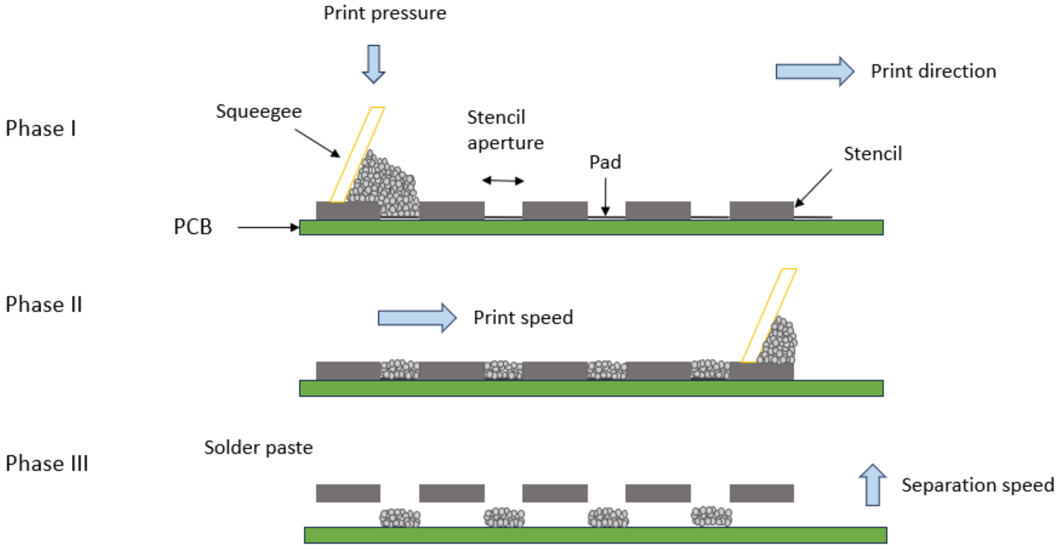

Figure 1. *Illustration of the three phases in the solder paste printing process*

Phase I – Paste Application: The squeegee moves across the stencil, applying solder paste with a controlled print pressure. The paste fills the stencil apertures aligned with the pads on the PCB.

Phase II – Rolling and Spreading: While the squeegee continues its movement at a set print speed, solder paste maintains contact and fills apertures uniformly as it rolls forward.

Phase III – Stencil Separation: The stencil is lifted vertically at a defined separation speed, allowing the paste to transfer to the PCB pads. Residual paste may remain on the stencil if conditions are not optimal.

1.2. Compare the importance of the stages.

The precision of this step is paramount, as misalignment or inconsistent paste volume directly compromises solder joint integrity in subsequent stages [8], [9]. Notably, SPP accounts for 60–70% of SMT defects [10], including insufficient/excessive paste deposition or positional inaccuracies, which often propagate irreversibly through later processes. Consequently, stringent process control during SPP is critical to minimizing yield loss and ensuring end-product reliability [11]. The complexity of SPP arises from non-linear interactions among variables such as stencil design, paste rheology, and machine parameters. These factors, combined with inherent process variability, necessitate advanced statistical modeling (e.g., Six Sigma frameworks) to optimize outcomes. [10]

Table 1. *Comparing the importance of the stages*

Stage	Importance	Impact on yield loss
Paste Printing	Most important	Direct and most potent, insufficient solder paste, excess solder paste,…
Pick and Place	Important	Component misalignment, component rotation,…
Reflow	Important	Cold solder joints, lead particles,..
Inspection	Important (to detect and prevent defects)	Does not directly cause yield loss

2. Materials and Methods

2.1. Keys to the Success of Solder Paste Printing

2.1.1. The size of the metal powder particles in the solder paste.

Solder powder particle size, quantified in micrometers (µm), critically influences both the printability of solder paste and the mechanical integrity of solder joints. Under the IPC J-STD-005 standard, these particles are categorized into Types 3 to 7, where higher type numbers indicate finer particle dimensions [12].

Industry guidelines often recommend IPC Type 4 or 5 solder pastes for stencils with aperture area ratios below the IPC-recommended threshold of 0.66, as these formulations balance printability with reduced defect propensity [12].

2.1.2. Solder alloy powder: The main component that determines the properties of the solder joint.

The solder alloy selection significantly impacts thermal properties (e.g., melting range), mechanical strength, and corrosion resistance. Thus, aligning alloy composition with operational demands, such as thermal cycling tolerance or regulatory compliance, remains imperative for optimal performance.

2.1.3. Stencil Printing

Stencil printing in Surface Mount Technology (SMT) remains inherently complex due to non-linear interactions between process variables and unavoidable stochastic variations, particularly in high-volume manufacturing environments. To mitigate these challenges, the meticulous optimization of stencil design and process parameters is critical.

2.1.4. Aperture design

Stencil Design Considerations: Stencil design plays a critical role in print quality. Stainless steel is commonly used for its durability and stability, while nickel electroformed stencils are ideal for ultra-fine-pitch components (<0.4 mm) due to their precision. Square apertures are cost-effective but may cause tombstoning, whereas rounded corners help ensure uniform paste release and reduce that risk. Additionally, maintaining an aspect ratio above 0.66 is crucial [13]; lower ratios require finer solder powder (Type 4–5) to avoid stencil clogging.

2.1.5. Paste Printing Tool

Solder paste printing quality is influenced by key factors: excessive squeegee pressure can cause stencil deformation or paste bleeding, while too little leads to voids due to poor aperture filling. High print speed risks skipping printing, whereas low speed increases smearing, especially with thick pastes. Maintaining an optimal separation distance ensures clean paste release. A squeegee angle of 45–60° provides a good balance between stencil wiping and paste rolling, which is critical for fine-pitch printing. [11]

2.1.6. Solder Paste Printing Equipment

ProFlow: The solder paste cartridge (solder paste tube) is housed inside a transfer head attached directly to the printer's cartridge (instead of a squeegee).

Squeegee: During stencil printing, the squeegee moves in one direction when force is applied to it. This force causes micro-bending on the stencil, affecting the amount of solder paste printed. [1]

2.1.7. Other factors

PCB (Printed Circuit Board): PCB surface quality, flatness, and cleanliness affect solder paste adhesion. Environment: Ambient temperature and humidity affect solder paste viscosity and print quality.

2.1.8. Evaluation criteria and options

Parameter combinations are determined based on the Expert Opinion Method. Objective: Select the optimal solder paste printing configuration.

Table 2. *Defining Parameter Ranges Based on Scientific Standards*

Parameter	Scientific Basis
Stencil Thickness	IPC-7525 recommends 70–150µm for standard PCBs.
Solder Paste Type	[2] proved that Type 4 suits fine-pitch components (≤0.3mm pads). [3]
Stencil Material	Nickel stencils reduce wear by 12–18% after 10,000 print cycles [4]
Separation Distance	DEK guidelines suggest 2 mm to prevent paste from sticking to the stencil.
Squeegee Angle	IPC-7525 recommends 45–60° to reduce solder bridging.
Print Pressure	IPC-7525: Stencil Design Guidelines
Print Speed	[5] Speed >40 mm/s reduces the cream amount on the pad by 20%.
Separation Speed	IPC-7525 advises 1–2 mm/s to avoid paste peaking.

2.2. *MCDM Methods*

Multi-criteria decision-making (MCDM) is a set of mathematical and computational methods designed to support decision-making in complex situations where multiple, conflicting criteria need to be considered. In reality, very few decisions are based on just one criterion. For example, when buying a car, you may be concerned with price, fuel economy, safety, design, and many other factors. MCDM provides tools to evaluate and compare alternatives based on all of these criteria.

AHP: Chosen because it allows for a systematic, easy-to-understand analysis of the problem and easy collection of expert opinions through pairwise comparisons. However, AHP does not directly rank options based on the distance to the ideal solution.

TOPSIS: Strong in ranking options based on the distance between the ideal (best) solution and the worst solution. It allows for an intuitive and easy-to-understand evaluation of the performance of each option. However, TOPSIS requires the weights of the criteria to be determined in advance.

Combining these two methods allows us to take full advantage of the strengths of each method: AHP provides weights to TOPSIS, and TOPSIS uses those weights to rank the options.

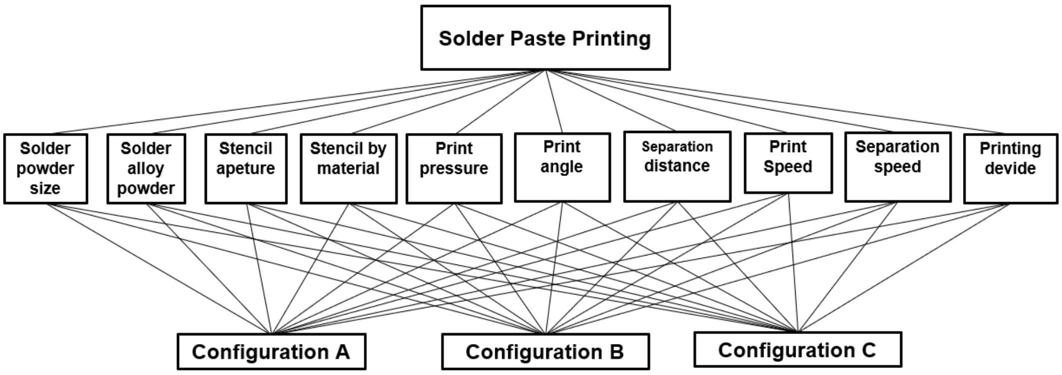

Figure 2. *Factors affecting SPP*

2.3. Comparison with Related Studies and Industry Trends

To contextualize our approach and emphasize its practical relevance, a comparison with recent academic and industrial advancements is presented below:

In recent years, stencil printing research has progressed toward hybrid methods combining empirical modeling, data analytics, and mechanical simulation. Farrag et al. (2024) utilized Random Forest combined with a Genetic Algorithm to identify optimal printing directions from SPI data, achieving a 94 % detection accuracy and highlighting the influence of separation speed and path control on print consistency [6]. Meanwhile, Mohammad demonstrated that applying a stopper load of 170 N reduced PCB warpage by 60 %, leading to a more uniform solder paste deposition [7].

These studies focus primarily on data-driven modeling or board mechanics. In contrast, our framework adds a structured decision-making layer using AHP to screen key factors before conducting a Central Composite Design (CCD) experiment for validation. This two-phase approach balances interpretability and empirical testing.

Additionally, industry trends toward intelligent stencil systems—such as stencils with nano-coatings, real-time feedback from smart SPI, and precision-designed aperture patterns—support the significance of our selected variables: Separation Speed, Print Pressure, and Print Speed. Unlike purely algorithmic or simulation-driven methods, our approach remains grounded in expert judgment while achieving robust, experimentally validated outcomes.

3. Results and Discussion

3.1. AHP Construct a pairwise comparison matrix

In essence, it is a table in which we compare each item, one pair at a time, to every other item. Attempting to determine which is more significant, desired, or whatever we're measuring.

Pairwise Comparison Matrix: When we have *n* criteria, construct a square matrix $A=[a_{ij}]$, where:

- a_{ij} = how much more important criterion *i* is over criterion *j*
- $a_{ji}=1/a_{ij}$, and $a_{ii}=1$

To establish a comprehensive yet focused parameter set for stencil printing process optimization, a list of potential influencing factors was compiled. These included: Pressure, Printing Speed, Separation

Speed, Separation Distance, Printing Angle, Printing Device, Stencil Aperture, Alloy Powder, Powder Size, and Stencil Material. This list was derived from standard guidelines (e.g., IPC-7525), DEK application notes, and expert industrial experience.

To objectively screen and prioritize these factors, the Analytic Hierarchy Process (AHP) was adopted as a multi-criteria decision-making (MCDM) technique. Expert judgments were collected through structured interviews with twenty senior SMT engineers. The resulting pairwise comparison matrix (Table 4) produced a priority weight vector, highlighting Print Pressure, Print Speed, and Separation Speed as the top-ranked criteria.

These three parameters were then selected for experimental validation via Design of Experiments (DOE), employing a Central Composite Design (CCD) on a representative product - a fine-pitch, double-sided PCB with C01005 components and 0.3 mm pads. Preliminary DOE results indicated that separation speed significantly affected cycle time, while print pressure and print speed influenced print quality. These trends supported the prioritization outcome of the AHP analysis.

This integrative approach - merging expert insight, MCDM-based factor screening, and DOE-based validation - ensures that both theoretical relevance and practical effectiveness are embedded in the optimization framework.

Table 3. *Construct a pairwise comparison matrix*

Criteria	Pressure	Printing speed	Separation speed	Separation distance	Printing angle	Printing device	Stencil aperture	Alloy Powder	Powder size	Stencil material
Pressure	**1**	3	5	7	7	7	9	9	9	9
Printing speed	1/3	**1**	3	5	5	5	7	7	7	7
Separation speed	1/5	1/3	**1**	3	3	3	5	5	5	5
Separation distance	1/7	1/5	1/3	**1**	1	1	3	3	3	3
Printing angle	1/7	1/5	1/3	1	**1**	1	3	3	3	3
Printing device	1/7	1/5	1/3	1	1	**1**	3	3	3	3
Stencil aperture	1/9	1/7	1/5	1/3	1/3	1/3	**1**	1	1	1
Alloy Powder	1/9	1/7	1/5	1/3	1/3	1/3	1	**1**	1	1
Powder size	1/9	1/7	1/5	1/3	1/3	1/3	1	1	**1**	1
Stencil material	1/9	1/7	1/5	1/3	1/3	1/3	1	1	1	**1**

Normalize a matrix: Divide each element by the sum of the corresponding column. The priority vector (criteria weight) is an important concept in the AHP method. It represents the relative importance of each criterion in achieving the overall goal. The sum of all the weights in the priority vector is always 1 (or 100%). Take the average of the values in each row in the normalized matrix.

Table 4. *Weight of indicators*

Weight of indicators	Criteria
0.357	Pressure
0.220	Printing speed
0.129	Separation speed
0.063	Separation distance
0.063	Printing angle
0.063	Printing device
0.026	Stencil aperture
0.026	Alloy Powder
0.026	Powder size
0.026	Stencil material

CI is compared to a random index (RI) using the Relative Consistency Index (CR), also known as the Consistency Ratio. A random pairwise comparison matrix is used to obtain the average value of CI, or RI. The number of criteria or possibilities (n) determines the RI value.

λ_{max} (The average of these ratios)

$$\boldsymbol{CI} = \frac{\lambda\,\text{max} - n}{n - 1} \tag{1}$$

RI value is determined based on the following table:

Table 5. *The RI value*

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

With n =10, RI = 1.49, we calculate

$$CR = \frac{CI}{RI} \tag{2}$$

CR = 0.026 < 0.1. The matrix is consistent, and the findings are regarded as credible since CR is less than 0.1. This is a highly significant finding in AHP analysis. It shows how important each criterion is to the overall objective (choosing the best solder paste printing setup).

3.2. TOPSIS analysis results

3.2.1. Building a decision matrix

Weights of the criteria used from the AHP results.

Table 6. *Normalize the decision matrix*

Criteria	Configuration A	Configuration B	Configuration C
Solder Powder Size (µm)	0.696	0.597	0.398
Solder Alloy Powder	SAC305	SAC405	SAC505
Stencil Aperture (mm)	0.424	0.565	0.707
Stencil Material	Stainless	Eform Ni	Stainless
Print Pressure (kg)	0.491	0.573	0.655

Squeegee Angle (degree)	0.384	0.512	0.768
Separation Distance (mm)	0.371	0.557	0.742
Print Speed (mm/s)	0.667	0.572	0.476
Separation Speed (mm/s)	0.455	0.569	0.683
Printing device	Squeegee	ProFlow	Squeegee

Standardize the values of each criterion by dividing each value by the square root of the sum of the squares of the values in that column.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\Sigma_{i=1}^{m} x_{ij}^{2}}} \tag{3}$$

Where,

- x_{ij}: the score of alternative i on criterion j
- r_{ij}: normalized score

Table 7. *Normalized weight matrix*

Criteria	**Configuration A**	**Configuration B**	**Configuration C**
Solder Powder Size (μm)	0.018	0.015	0.01
Solder Alloy Powder	SAC305	SAC405	SAC505
Stencil Aperture (mm)	0.011	0.014	0.018
Stencil Material	Stainless	Eform Ni	Stainless
Print Pressure (kg)	0.175	0.204	0.233
Squeegee Angle (degree)	0.024	0.032	0.048
Separation Distance (mm)	0.023	0.035	0.047
Print Speed (mm/s)	0.146	0.125	0.104
Separation Speed (mm/s)	0.058	0.073	0.088
Printing device	Squeegee	ProFlow	Squeegee

Multiply by Criteria Weights: Apply the weights from AHP or expert judgment

$$v_{ij} = \omega_j \cdot r_{ij} \tag{4}$$

Where:

- ω_j: weight of criterion j
- v_{ij}: weighted normalized score

Identify Ideal Solutions

- Positive Ideal Solution (PIS) A+: best value for each criterion.
- Negative Ideal Solution (NIS) A−: worst value for each criterion.

Note:

- For benefit criteria → best = max, worst = min.
- For cost criteria → best = min, worst = max.

Table 8. *Distance to Ideal Solutions*

	D_i^+	D_i^-
Configuration A	0.024	0.057
Configuration B	0.044	0.042
Configuration C	0.082	0.064

Calculate the Distance to Ideal Solutions

Use Euclidean distance:

$$Di^{+} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - A_j^{+}\right)^2} \tag{5}$$

$$Di^{-} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - A_j^{-}\right)^2} \tag{6}$$

Table 9. *Rank the options*

Configuration	Score
A	0.699
B	0.486
C	0.437

Calculate the Closeness Coefficient (CC): The closer CC is to 1, the better the alternative.

$$CC_i = \frac{Di^{-}}{Di^{+} + D_i^{-}} \tag{7}$$

Rank alternatives based on CC_i: higher is better.

3.2.2. Sensitivity analysis

Sensitivity analysis is an important step to evaluate the stability and reliability of the results. Configuration A is nearer the optimal solution than B and C, with a score of 0.7. This demonstrates that A tends to hold its top spot even when weights or input data are slightly altered (based on the sensitivity analysis scenarios). For this arrangement, the model thus exhibits good stability.

Simulation Scenario 1: Increase the weight of “Print Pressure” by 10%

Configuration A: from 0.699 to ≈ 0.710

Configuration B: from 0.486 to ≈ 0.49

Configuration C: from 0.437 to ≈ 0.445

Although the scores of all configurations increased slightly, the rankings remained: A > B > C.

Simulate Scenario 2: Adjust for "Separation Speed" and reduce the weight of "Printing Speed" by 10%.

Configuration A: from 0.699 to ≈ 0.705

Configuration B: from 0.4865 to ≈ 0.485

Configuration C: from 0.4379 to ≈ 0.435

The score is little impacted by this weighting change, but the overall ranking stays the same: A > B > C.

The rankings of the configurations (A > B > C) are maintained when weight change scenarios are simulated, even when significant variables like Print Pressure, Printing Speed, and Separation Speed fluctuate somewhat. This adds to the trust in using the decision-making outcomes in the manufacturing process by confirming the TOPSIS model's high stability and dependability.

4. Conclusions

To determine the most influential settings for solder paste deposition, this study employed a structured MCDM framework. The analysis focused on variables such as applied print pressure, squeegee speed, stencil separation speed, and gap distance during separation. Among these, print pressure emerged as a key factor, strongly affecting aperture fill quality and paste transfer consistency - especially critical in fine-pitch applications.

The robustness of the prioritization was confirmed through sensitivity analysis and cross-method validation using the TOPSIS approach. Both expert consensus and method triangulation supported the technical validity of the selected parameters.

Preliminary results from the Design of Experiments (DOE) further reinforced the AHP-based selection: Print pressure had the most substantial impact on cycle time, while print speed and separation speed primarily affected print quality. These insights provide a practical foundation for optimizing stencil printing in surface mount technology (SMT), helping engineers improve yield and reduce operational costs.

For future research, it is recommended to incorporate real-time production data, explore adaptive control strategies, and extend the analysis to include additional factors such as stencil wear, solder paste aging, and environmental conditions. These directions would enhance the generalizability, robustness, and industrial applicability of the proposed optimization framework.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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