

Analyzing Factors Affecting Manufacturing Defects in the Industry 4.0 Era Using the Fuzzy Analytic Hierarchy Process: A Case Study of Chang Shin Vietnam

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Abstract

Manufacturing defects pose significant challenges to product quality, operational efficiency, and customer satisfaction across various industries. Effectively identifying and mitigating these defects requires a robust understanding of their underlying causes and the complex interplay among contributing factors. This study addresses this critical need by thoroughly investigating the factors influencing manufacturing defects through the application of the Fuzzy Analytic Hierarchy Process (AHP). This study presents a focused case study on Chang Shin Vietnam, a prominent manufacturing entity, to provide a real-world context for our analysis. The primary objective of this research is to systematically identify and prioritize the root causes of manufacturing defects within Chang Shin Vietnam's operational framework. By leveraging the unique capabilities of the Fuzzy AHP method, which excels in handling vagueness and subjectivity inherent in expert judgments, this study illuminates the intricate relationships and hierarchical structure among various factors contributing to defects in the manufacturing process. This approach allows for a more nuanced and accurate assessment compared to traditional methods. The insights garnered from this comprehensive analysis go beyond mere identification, providing a clear prioritization of the most impactful factors. Ultimately, the robust findings of this research offer invaluable guidance for developing highly targeted and effective strategies to mitigate manufacturing defects, thereby enhancing overall product quality, reducing waste, and improving operational performance not only for Chang Shin Vietnam but also for similar industrial settings facing comparable quality challenges. This research contributes to the body of knowledge by demonstrating the practical utility of Fuzzy AHP in addressing complex industrial quality problems.

Keywords

AHP, fuzzy, IR 4.0, Root Causes of Manufacturing Defects, smart production.

Introduction

The global athletic footwear industry has experienced sustained growth over the past decade. According to [Grand View Research \(2022\)](#), the sports shoes market is projected to grow from USD 111.65 billion in 2023 to approximately USD 140 billion by 2028, at a compound annual growth rate (CAGR) of 4.63%. This expansion is driven by increased health awareness, rising disposable incomes, and a cultural shift toward active lifestyles accelerated by the COVID-19

pandemic. As demand intensifies, so does the competitive pressure on manufacturers to maintain consistent product quality while minimizing production costs.

In this context, manufacturing defects represent a critical operational challenge. Defects not only increase waste and rework costs, but also damage brand reputation and reduce customer satisfaction. The identification and prioritization of root causes behind these defects is therefore of significant strategic importance. Traditional quality tools such as the Pareto chart and the Ishikawa (fish-bone) diagram are commonly used to map causal relationships, but they do not inherently quantify the relative importance of identified causes. Multi-criteria decision-making (MCDM) methods, particularly the Analytic Hierarchy Process (AHP), offer a structured quantitative framework to address this limitation.

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However, expert judgments in manufacturing quality assessment are often characterized by vagueness and subjectivity, particularly when evaluating intangible factors such as worker skill level or management practices. Classical AHP cannot adequately handle this inherent uncertainty. The Fuzzy Analytic Hierarchy Process (Fuzzy AHP), which extends traditional AHP using fuzzy set theory, is particularly well-suited for such contexts because it accommodates linguistic imprecision in expert evaluations through triangular fuzzy numbers (Buckley, 1985; Chang, 1996).

Despite a growing body of literature on Fuzzy AHP applications in quality management (Boral et al., 2020; Büyüközkan & Çifçi, 2012; Pacana & Siwec, 2020), its application to manufacturing defect root cause analysis in the footwear industry remains limited. This study aims to address this gap by applying Fuzzy AHP integrated with the Ishikawa method to identify and prioritize the root causes of manufacturing defects at Chang Shin Vietnam, one of the largest footwear manufacturers in Southeast Asia.

The specific research objectives are: (1) to identify and structure the criteria and sub-criteria associated with quality failures in sewing line and bonding shoe production at Chang Shin Vietnam; (2) to quantitatively evaluate and rank these criteria and sub-criteria using the Fuzzy AHP method; and (3) to derive practical managerial implications and recommendations for quality improvement.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature on Fuzzy AHP, quality management in manufacturing, and footwear production defects. Section 3 presents the research methodology, including the Fuzzy AHP computational framework and describes the case company and data collection process. Section 4 reports the empirical results. Section 5 discusses the findings, implications, limitations, and future research directions. Section 6 concludes the paper.

Literature review

Quality Management in Manufacturing and the Footwear Industry

Product quality is a primary determinant of competitiveness in manufacturing industries. In athletic footwear production, quality is particularly critical due to the complex, multi-stage nature of the manufacturing process involving cutting, stitching, bonding, and finishing (Beatrix & Triana, 2019; Dhanapal et al., 2017). Common defect categories in footwear manufacturing include stitching irregularities, adhesive failure, material inconsistency, and dimensional non-

conformance (Chandra Paul et al., 2018). Identifying the root causes of these defects is a prerequisite for effective quality improvement.

The Ishikawa diagram, or cause-and-effect (fishbone) diagram, is widely used to systematically categorize the potential causes of a quality problem. In manufacturing, these causes are conventionally organized under the 5M framework: Material, Machine, Man (Human), Method, and Milieu (Environment) (Merk, 2008). This framework provides a structured basis for identifying the critical factors that may contribute to production defects.

Despite its widespread use in quality control literature, existing research on defect root cause analysis in footwear manufacturing is limited. Chandra Paul et al. (2018) applied Pareto analysis and Ishikawa diagrams to sewing complications in a footwear factory, identifying stitching tension and needle type as leading causes. Beatrix and Triana (2019) investigated bonding quality improvement using quality control circles at a shoe manufacturer. Dhanapal et al. (2017) analyzed bonding failure in footwear production and proposed process-based corrective measures. However, none of these studies applied a quantitative multi-criteria weighting method such as Fuzzy AHP to prioritize the identified root causes.

Analytic Hierarchy Process (AHP) and Fuzzy AHP

The Analytic Hierarchy Process (AHP), introduced by Saaty (1980), is a structured decision-making method that decomposes a complex problem into a hierarchy of criteria and alternatives, enabling systematic pairwise comparison and priority derivation. AHP has been widely applied across disciplines including manufacturing, engineering, healthcare, and public policy (Vaidya & Kumar, 2006). Its key advantages include its ability to measure decision consistency, handle both qualitative and quantitative criteria, and provide a transparent and auditable decision framework (Triantaphyllou & Lin, 1996; Durán & Aguilo, 2008).

A fundamental limitation of classical AHP is its use of crisp numerical values to represent expert judgments, which may not accurately reflect the inherent vagueness of human cognition. To overcome this, Zadeh (1965) introduced fuzzy set theory, which extends classical set theory by allowing partial membership in a set. Buckley (1985) subsequently formalized the Fuzzy AHP method, incorporating triangular fuzzy numbers into the pairwise comparison process. Chang (1996) later proposed an extent analysis method for Fuzzy AHP that simplified computation and is widely used in the literature.

Fuzzy AHP has been applied in numerous quality management and manufacturing contexts. Boral et al. (2020) used Fuzzy AHP integrated with MAIRCA for failure mode and effects analysis in engineering systems. Pacana and Siwec (2020) applied Fuzzy AHP to identify root causes of defects in soap production, combining it with the Ishikawa method. Büyüközkan and Çifçi (2012) evaluated e-service quality using a combined Fuzzy AHP and Fuzzy TOPSIS approach. Bakır & Atalık applied Fuzzy AHP and Fuzzy MARCOS for airline e-service quality assessment. These studies collectively demonstrate the robustness and versatility of Fuzzy AHP in prioritizing factors under conditions of expert uncertainty.

In the footwear sector, Chou et al. (2019) applied Fuzzy AHP and Fuzzy TOPSIS for human resource assessment in technology-intensive industries.

In the domain of digital business technology selection, Nguyen (2025) applied an integrated Fuzzy AHP-TOPSIS framework to evaluate and rank CRM platforms for digital marketing optimization, demonstrating that the two-stage approach – using Fuzzy AHP to weight evaluation criteria and TOPSIS to rank alternatives by proximity to the ideal solution. The methodological logic of Nguyen’s (2025) framework is directly analogous to the present study’s use of Fuzzy AHP for prioritizing manufacturing defect root causes under linguistic uncertainty, collectively reinforcing the broader applicability and transferability of fuzzy MCDM methods across diverse organizational decision-making contexts from technology procurement in digital marketing to quality management in industrial production. However, no prior study has applied Fuzzy AHP specifically to defect root cause analysis in athletic footwear manufacturing.

Research Gap and Contribution

Despite the growing application of Fuzzy AHP in manufacturing quality management, its use in the footwear industry – particularly for systematic root cause analysis – remains underexplored. Existing footwear quality studies rely predominantly on qualitative tools (Ishikawa diagrams, Pareto charts), which lack the quantitative rigor needed to prioritize causal factors. Moreover, the subjective nature of expert judgments in footwear quality assessment makes classical AHP inappropriate, as it cannot capture linguistic uncertainty.

This study contributes to the literature in three ways. First, it provides an empirical application of Fuzzy AHP to manufacturing defect analysis in the footwear industry that is a context not previously addressed in the literature. Second, it integrates the Ishikawa 5M framework with Fuzzy AHP to create

a structured, replicable methodology for quality root cause prioritization. Third, it demonstrates the broader transferability of this integrated approach to similar labor-intensive manufacturing settings.

Methodology

Fuzzy Set Theory

Fuzzy set theory, introduced by Zadeh (1965), extends classical set theory by allowing elements to belong to a set with a degree of membership in the interval $[0, 1]$. This enables the modeling of vague or imprecise information, which is characteristic of expert judgment in multi-criteria evaluation.

Fuzzy set theory is an element that can be part of a fuzzy set. Let X represent the set of items. The membership function $\mu_{A(x)}$ coupled with a real integer in the interval $[0; 1]$ for each element in X , to indicate the “membership” of in A , characterizes the fuzzy set A of the discourse set U . Triangular membership functions are frequently utilized to improve computing efficiency and data collecting. A triangular fuzzy number C determined by the membership function shown below (Wu et al., 2004).

$$\mu_{(x)} = \begin{cases} \frac{(x-a)}{b-a} \Rightarrow a \leq x \leq b \\ \frac{(x-c)}{b-c} \Rightarrow b \leq x \leq c \\ 0 \Rightarrow \text{otherwise} \end{cases} \quad (1)$$

which can be represent as triplet (abc) , with $a \leq b \leq c$.

Parameters a and c represent the lower and upper boundaries of the evaluation data availability region, respectively, while b represents the “average” of the fuzzy number C corresponding to the top of its membership function (i.e., $\mu_A(x) = 1$). As a result, the triangular fuzzy number $C(a, b, c)$ can be read as an “approximately b ” fuzzy quantity whose value cannot be less than a or greater than c (Fig. 1).

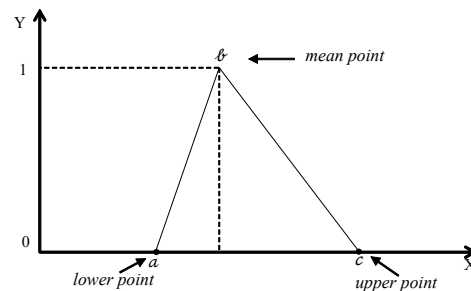


Fig. 1. A triangular membership function of the fuzzy number

There are many evaluation studies on quality management using different variations of fuzzy sets in the literature. In education, Lin (2010) developed an evolutionary model that integrates triangular fuzzy numbers and AHP to develop a fuzzy evaluation model.

The Fuzzy AHP Method

The Fuzzy AHP method adopted in this study follows the procedure proposed by Buckley (1985) with geometric mean aggregation. The method comprises eight sequential steps:

Step 1: Define the hierarchical structure: Establish the decision hierarchy consisting of the goal (minimize manufacturing defects), main criteria (5M factors), and sub-criteria derived from the Ishikawa analysis.

Step 2: Construct linguistic pairwise comparison matrices: Experts compare each pair of criteria using the linguistic scale in Tab. 1, which maps linguistic terms to triangular fuzzy numbers. Each expert provides an independent judgment matrix.

Table 1
Linguistic Scale for Fuzzy AHP Pairwise Comparison

Linguistic Term	Triangular Fuzzy Number (l, m, u)
Equally important	(1, 1, 1)
Weakly more important	(2, 3, 4)
Moderately more important	(4, 5, 6)
Strongly more important	(6, 7, 8)
Extremely more important	(8, 9, 10)
Intermediate values	Interpolated TFNs

Step 3: Check consistency: For each expert's crisp judgment matrix (using midpoint value b of each TFN), compute the Consistency Ratio (CR) per Saaty's (1980) procedure. A $CR \leq 0.10$ is acceptable; matrices with $CR > 0.10$ are returned to the expert for revision.

$$CR = \frac{CI}{RI} \quad (2)$$

where $CI = (\lambda_{\max} - n)/(n - 1)$ is the Consistency Index, $\lambda_{\max}$ is the principal eigenvalue, n is the matrix dimension, and RI is the Random Index (Saaty, 1980) (Tab. 2).

Step 4: Aggregate expert judgments using the geometric mean of corresponding fuzzy components, where k is the number of experts and $\otimes$ denotes fuzzy multiplication:

$$\tilde{a}_{ij} = (\tilde{a}_{ij1} \otimes \tilde{a}_{ij2} \otimes \dots \otimes \tilde{a}_{ijk})^{1/k} \quad (3)$$

Step 5: Compute fuzzy geometric mean for each criterion:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n} \quad (4)$$

Step 6: Compute fuzzy weights, normalize, and defuzzify. Fuzzy weights are computed by Eq. (5); defuzzification uses the centroid method; final crisp weights are normalized so that $\sum w_i = 1$:

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} \quad (5)$$

$$M_i = \frac{l_i + m_i + u_i}{3} \quad (6)$$

Global weights for sub-criteria are computed by multiplying each local sub-criterion weight by the weight of its parent criterion.

Step 7: Repeat Steps 4–6 for all sub-criteria levels.

Step 8: Rank all sub-criteria by global weight.

Saaty (2008) indicates that a consistency ratio (CR) less than or equal to 10% is acceptable. In other words, there is a 10% possibility that the experts answer the queries completely at random. If the CR is greater than 10% it indicates an inconsistency in the assessment and needs to be re-evaluated and recalculated.

The proposed method

The overall research process follows a sequential design. First, the problem context is defined and the decision hierarchy is established using the Ishikawa 5M framework applied to two production lines: sewing line quality failure and bonding shoes quality failure. Second, expert data are collected through structured interviews. Third, the Fuzzy AHP procedure is applied to compute criterion weights and rankings. Finally, results are interpreted and managerial recommendations are developed. The research process flowchart is shown in Figure 2.

Table 2
The random index corresponding to the number of selection criteria considered (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

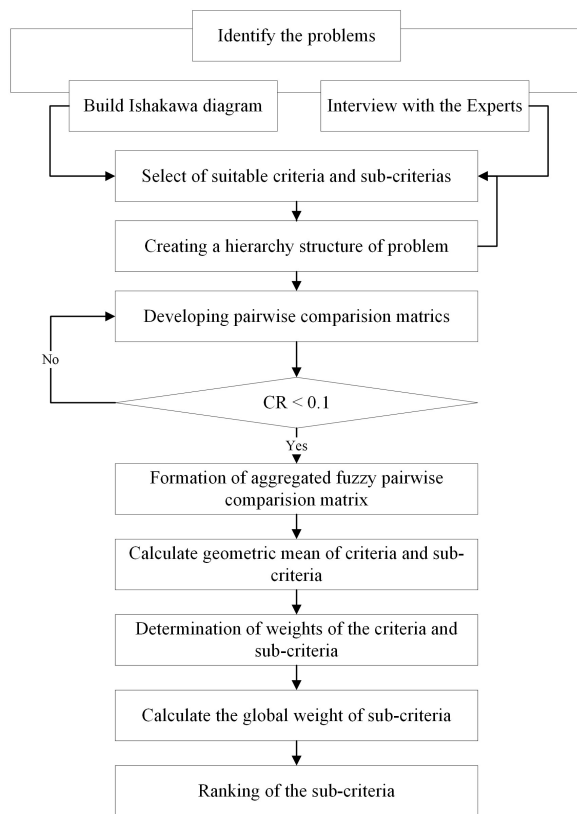


Fig. 2. Research process (Source: Author)

The problem is shown on the main bone and the cause of the problem is shown on its five primary branches, respectively. And the results are shown figures in Figure 3.

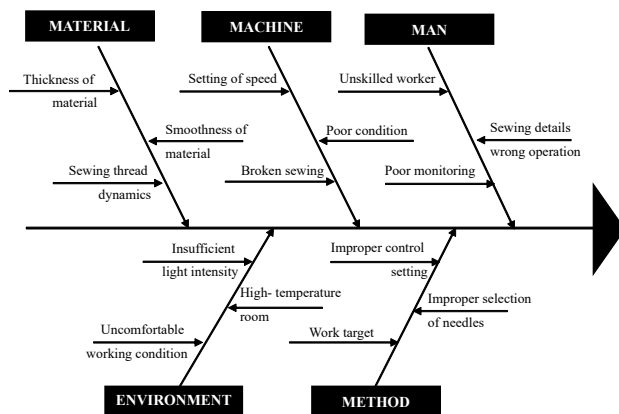


Fig. 3. Sewing Line Quality Failure (Source: Author)

Criteria Determination

The Ishikawa cause-and-effect (fishbone) diagram was employed to identify and categorize the root causes of manufacturing defects into the 5M framework. This

approach was selected because it provides a structured, visually intuitive mechanism for decomposing complex quality problems into their constituent causal categories, facilitating expert elicitation and subsequent AHP hierarchy construction (Pacana & Siwiec, 2020).

The five main factor categories (main criteria) are: (1) Material factor (A1/C1) – raw materials, components, and inputs used in production, including quality, consistency, and supplier reliability; (2) Equipment factor (A2/C2) – machinery and equipment, including mechanical performance, calibration, and maintenance status; (2) Human factor (A3/C3) – workers, operators, and supervisors, encompassing skill levels, training, and fatigue; (3) Method factor (A4/C4) – manufacturing processes, standard operating procedures, and quality control protocols; and (4) Environment factor (A5/C5) – physical workplace conditions, including temperature, humidity, lighting, and overall facility conditions.

The 5M framework was selected over 4M or 6M alternatives based on expert panel consensus. The Environment factor plays a non-trivial role in both sewing and bonding defects due to temperature sensitivity in adhesive application. A 6M model was rejected as Measurement issues are not a primary defect source at this facility. Sub-criteria for each main factor were identified through expert consultation and fishbone diagram analysis (Fig. 1). Table 3 summarizes the full criteria hierarchy.

Expert Selection and Data Collection

Data were collected through structured expert interviews using prepared pairwise comparison questionnaires. Expert selection followed purposive sampling criteria to ensure that respondents possess relevant domain knowledge and practical experience. All seven participating experts had a minimum of five years of experience in quality management within the athletic footwear industry and held roles including Quality Control Manager, Production Supervisor, Process Engineer, and Materials Specialist at Chang Shin Vietnam.

Experts were briefed on the research objectives, the Ishikawa framework, and the linguistic scale before completing the questionnaire. Interviews were conducted directly to minimize misunderstandings and ensure the quality of responses. All pairwise comparison matrices were completed individually by each expert. Post-interview, the consistency ratio (CR) for each expert's judgment matrix was computed; matrices with $CR > 0.10$ were returned to the respective expert for reconsideration and revision.

Table 3
Hierarchical Structure of Criteria and Sub-Criteria

Main Criterion	Code	Sub-Criterion	Code
Material	A1/C1	Thread/material quality inconsistency	A11/C11
		Supplier material variability	A12/C12
		Upper material quality	A13/C13
Equipment	A2/C2	Pressure machine instability	A21/C21
		Heating box temperature instability	A22/C22
		Machine calibration errors	A23/C23
Human	A3/C3	Inadequate worker training	A31/C31
		Worker fatigue	A32/C32
		Unskilled labor	A33/C33
Method	A4/C4	Incorrect stitching procedures	A41/C41
		Inadequate quality inspection	A42/C42
		Upper preparation process	A43/C43
Environment	A5/C5	Excessive ambient temperature	A51/C51
		High-temperature room conditions	A52/C52

Results

Chang Shin Vietnam Co., Ltd. is a subsidiary of Chang Shin Inc., a South Korean multinational corporation headquartered in Seoul, South Korea, and one of the world's largest manufacturers of athletic footwear. Chang Shin is a primary manufacturing partner of Nike, producing several million pairs of athletic shoes annually. The Vietnamese subsidiary is located in Dong Nai Province and employs tens of thousands of workers across multiple production buildings, making it one of the largest single-site footwear manufacturers in Southeast Asia (Changshin Inc., n.d.).

Chang Shin Vietnam operates under strict quality management requirements mandated by its principal client. Despite robust quality control systems, manufacturing defects in sewing and bonding processes remain a recurring concern. These two processes were selected for this study because they account for the highest proportion of rework and scrap in the facility, and because they involve complex interactions among material, human, equipment, method, and environmental factors.

Fuzzy AHP Results: Sewing Line Quality Failure

Following Steps 4–6 of the Fuzzy AHP procedure, the aggregated fuzzy pairwise comparison matrix for the five main criteria was computed using geometric mean aggregation across all seven expert judgments. Table 4 shows the resulting aggregated fuzzy matrix for main criteria.

Table 4
Aggregate Fuzzy Pairwise Comparison Matrix – Main Criteria (A1–A5) (Sewing Line)

	A1	A2	A3	A4	A5
A1	(1, 1, 1)	(0.73, 1.02, 1.48)	(0.34, 0.46, 0.62)	(0.51, 0.72, 1.03)	(1.23, 1.87, 2.73)
A2	(0.68, 0.98, 1.37)	(1, 1, 1)	(0.41, 0.56, 0.78)	(0.63, 0.89, 1.25)	(1.45, 2.14, 3.12)
A3	(1.61, 2.17, 2.94)	(1.28, 1.79, 2.44)	(1, 1, 1)	(1.34, 1.93, 2.76)	(3.21, 4.68, 6.34)
A4	(0.97, 1.39, 1.96)	(0.80, 1.12, 1.59)	(0.36, 0.52, 0.75)	(1, 1, 1)	(2.12, 3.05, 4.21)
A5	(0.37, 0.53, 0.81)	(0.32, 0.47, 0.69)	(0.16, 0.21, 0.31)	(0.24, 0.33, 0.47)	(1, 1, 1)

Table 5 presents the fuzzy geometric means, defuzzified weights, and normalized weights for main criteria.

The Human factor (A3) achieves the highest weight at 41.95%, indicating that human-related issues dominate the sewing line quality failure profile. The Method factor (A4) ranks second at 20.61%, followed by Equipment (A2) at 17.66%. At the sub-criterion level, unskilled labor (A33) emerges as the most critical sub-criterion with a global weight of 19.12%, reflecting the high impact of worker competency on stitching quality. This is followed by inadequate worker training (A31) at 14.57% and pressure machine instability (A21) at 11.24%.

Table 5
Fuzzy Weights and Final Priority Weights – Main Criteria (A1–A5) (Sewing Line)

Criterion	Fuzzy Geom. Mean (l,m,u)	Defuzz. Weight	Norm. Weight (%)
A1: Material	(0.62, 0.88, 1.27)	0.257	14.83%
A2: Equipment	(0.71, 1.01, 1.45)	0.306	17.66%
A3: Human	(1.58, 2.21, 3.02)	0.727	41.95%
A4: Method	(0.84, 1.19, 1.68)	0.357	20.61%
A5: Environment	(0.23, 0.33, 0.48)	0.080	4.62%
Total	–	1.727	100%

Fuzzy AHP Results: Bonding Shoes Quality Failure

The same procedure was applied to the bonding shoes production line. Table 6 presents the final normalized weights for main criteria in the bonding process.

Table 6
Final Priority Weights – Main Criteria (C1–C5) (Bonding Shoes)

Criterion	Defuzzified Weight	Normalized Weight (%)
C1: Material	0.281	16.24%
C2: Equipment	0.394	22.77%
C3: Human	0.298	17.22%
C4: Method	0.634	36.63%
C5: Environment	0.124	7.16%
Total	1.731	100%

For bonding shoes defects, the Method factor (C4) ranks highest at 36.63%, highlighting the critical role of process execution quality – particularly upper preparation procedures – in determining adhesive bonding outcomes. Equipment (C2) ranks second at 22.77%. Table 7 presents the global ranking of sub-criteria for bonding shoes quality failure.

Upper preparation (C43) ranks first with a global weight of 14.78%, confirming that the preparation of the upper material surface prior to adhesive application is the most influential factor in bonding defect occurrence. Pressure machine instability (C21) and heating box temperature instability (C22) follow closely at 13.37% and 13.31%, respectively, reflecting the machine-dependence of the bonding process.

Table 7
Global Priority Ranking – Sub-Criteria (Bonding Shoes Quality Failure)

Rank	Sub-Criterion	Code	Global Weight (%)
1	Upper preparation process	C43	14.78%
2	Pressure machine instability	C21	13.37%
3	Heating box temperature instability	C22	13.31%
4	Inadequate quality inspection	C42	11.89%
5	Unskilled labor	C33	10.54%
6	Machine calibration errors	C23	9.40%
7	Inadequate worker training	C31	7.12%
8	Supplier material variability	C12	5.83%
9	Upper material quality	C13	1.10%
10	High-temperature room conditions	C52	0.57%

Priority factors were identified, such as unskilled worker (A33) at 19.12% highlighting the urgent importance of investing in employee training. Similarly, in the context of bonding shoes quality failures, the most important sub-criteria of upper preparation (C43) with a rate of 14.78% signals the important role of this stage. By addressing these root causes, the company can significantly reduce errors and improve overall product quality.

Discussion and implications

The results of this study yield several important insights into the nature of manufacturing defects at Chang Shin Vietnam. For the sewing line, the dominance of the Human factor (A3, 41.95%) and the sub-criterion of unskilled labor (A33, 19.12%) underscores the central role of worker competency in determining stitching quality. This finding is consistent with [Chandra Paul et al. \(2018\)](#), who identified operator skill and training as key determinants of sewing complications in footwear production, and with [Ali Asghar and Mohtsham Saeed \(2012\)](#), who demonstrated that person-job fit and worker training are critical drivers of production performance.

For the bonding process, the primacy of the Method factor (C4, 36.63%) and specifically the upper preparation sub-criterion (C43, 14.78%) aligns with the findings of [Beatrix and Triana \(2019\)](#) and [Dhanapal et al. \(2017\)](#), who both identified improper surface preparation as a leading cause of adhesive failure in footwear bonding. The high weights assigned to Equipment sub-criteria (C21, C22) also reflect the temperature-sensitive nature of polyurethane and polychloroprene adhesives, which require precise machine calibration for optimal performance ([Broughton & Lodeiro, 2002](#); [Paiva et al., 2016](#)).

Notably, the Environment factor received the lowest weight in both analyses (A5: 4.62%; C5: 7.16%), suggesting that while environmental conditions are relevant, they are secondary to human, method, and equipment factors in driving defects at this facility. This may partly reflect the company's existing climate control measures for production areas.

This study extends prior applications of Fuzzy AHP in manufacturing quality management in several respects. [Pacana and Siwec \(2020\)](#) demonstrated the combined utility of Ishikawa diagrams and Fuzzy AHP for defect root cause prioritization in soap production, finding that material and method factors were dominant. Our findings for the bonding line partially corroborate this pattern, although the Human factor is comparatively more prominent at Chang Shin Vietnam, likely due to the higher labor intensity and lower automation level of athletic footwear assembly relative to soap production.

Compared to [Boral et al. \(2020\)](#), who applied Fuzzy AHP-MAIRCA for failure mode analysis in engineering systems, the present study demonstrates that Fuzzy AHP alone provides sufficient discriminatory power for root cause prioritization in this context, given the relatively small number of criteria and the high quality of expert judgments (all CR < 0.08).

Managerial Implications

The findings carry direct and actionable implications for quality managers and production supervisors at Chang Shin Vietnam and in similar labor-intensive footwear manufacturing settings. First, and most urgently, the high weight of unskilled labor (A33) in sewing line defects calls for a systematic workforce development program. This includes structured onboarding training for new operators, periodic competency assessments, and targeted skill refresher programs aligned with product-specific stitching requirements.

Second, for the bonding process, the prioritization of upper preparation (C43) suggests that standardized surface treatment protocols should be established and

strictly enforced. These should specify sanding techniques, adhesive compatibility requirements, and surface inspection checklists prior to bonding operations. Quality checkpoints at the pre-bonding stage should be embedded in the standard operating procedure.

Third, the high rankings of equipment instability sub-criteria (C21, C22) highlight the need for a preventive maintenance regime for pressure machines and heating boxes. Regular calibration schedules, real-time temperature monitoring, and machine performance logs should be implemented to detect and correct deviations before they translate into product defects.

From a broader perspective, the Fuzzy AHP framework developed in this study can be adapted for use in other manufacturing contexts where multiple interdependent quality factors must be prioritized under expert uncertainty. The 5M-Fuzzy AHP integration offers a replicable, cost-effective methodology that does not require large-scale quantitative data collection, making it particularly suitable for medium-sized manufacturers and those operating in resource-constrained settings.

Conclusions

This study applied the Fuzzy Analytic Hierarchy Process (Fuzzy AHP), integrated with the Ishikawa cause-and-effect framework, to systematically identify and prioritize the root causes of manufacturing defects in two production lines – sewing and bonding – at Chang Shin Vietnam, a major athletic footwear manufacturer. Seven quality management experts participated in structured pairwise comparison interviews, and their judgments were processed through a rigorous Fuzzy AHP procedure incorporating consistency checking, fuzzy geometric mean aggregation, defuzzification, and global weight computation.

The results demonstrate that for sewing line quality failures, the Human factor, particularly unskilled labor (A33, 19.12%), represents the most critical root cause, followed by the Method and Equipment factors. For bonding shoe defects, the Method factor dominates, with upper preparation (C43, 14.78%) and equipment instabilities (C21, C22) ranking as the highest-priority sub-criteria. These findings provide a clear, evidence-based foundation for targeted quality improvement interventions.

Beyond the single-case context, this study demonstrates the broad applicability and methodological value of the Fuzzy AHP framework for manufacturing defect root cause analysis. The approach is particularly well-suited for contexts involving expert-based evaluation under linguistic uncertainty, limited quantitative

data, and multiple interdependent quality factors. Its replicability across different manufacturing settings is a key contribution of this work. Future research should extend this framework to other industry contexts, explore multi-method integrations, and validate the recommended interventions through longitudinal quality performance studies.

Several limitations of this study should be acknowledged. First, the expert panel comprised seven individuals, all from Chang Shin Vietnam. While this provides rich insider knowledge, it may introduce organizational bias and limits the diversity of perspectives. Second, the study was conducted at a single manufacturing facility; the generalizability of the specific weight rankings to other manufacturers or production contexts cannot be assumed without further validation. Third, the Fuzzy AHP method does not explicitly model interdependencies among criteria; methods such as FANP or DEMATEL could be explored to capture such interdependencies. Fourth, as with all expert-based methods, the quality of results is contingent on the accuracy and honesty of expert judgments; the CR check provides a partial but not complete safeguard against systematic bias.

Future research could extend this work in several directions. First, the integrated Ishikawa-Fuzzy AHP framework could be applied to other footwear manufacturers or to different production stages (e.g., cutting, finishing) to build a more comprehensive quality knowledge base for the industry. Second, the framework could be combined with other MCDM methods, such as TOPSIS or VIKOR, to not only prioritize root causes but also rank proposed corrective actions. Third, longitudinal studies tracking defect rates before and after implementing the recommended interventions would provide valuable empirical evidence. Finally, future research could explore the integration of Industry 4.0 data streams (e.g., IoT sensor data from production machines) with the Fuzzy AHP framework to enable dynamic, real-time quality root cause monitoring.

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