Optimizing Venting and Squeegee in Tire Molds for Enhanced Two-Wheeler and Three-Wheeler Performance

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ABSTRACT

Tire quality directly influences vehicle safety, handling, comfort, and stability in two- and three-wheelers, where limited contact patches and compact geometries amplify performance sensitivity. This study presents the first systematic co-optimization of squeegee cementing (component bonding during tire building) and mold venting, two relatively underexplored manufacturing processes, to reduce defects and enhance tire performance. Using a Resolution IV fractional factorial design with 320 experimental tires, optimal squeegee parameters (2.4 MPa pressure, 33° angle, 28°C temperature, 165 mm/s speed) and venting configuration (0.45 mm diameter vents, 2.2 vents per 100 cm^2, feature-focused distribution) were identified. Optimized squeegee conditions reduced bonding-related defects by 64.2% (95% CI: 58.7%–69.1%), while optimized venting reduced air-entrapment defects by 71.6% (95% CI: 66.3%–76.2%). Combined optimization achieved a 67.8% overall defect reduction (95% CI: 62.9%–72.3%), outperforming broader quality-improvement approaches (57.8%). Performance enhancements included a 36.5% increase in uniformity, a 12.4% reduction in rolling resistance, a 16.8% increase in wet grip, and a 48.9% increase in tread separation force, while process capability improved substantially (Cp: 0.68 → 1.62; Cpk: 0.52 → 1.48). For an annual production volume of 50,000 tires, total manufacturing costs decreased by 7.2%, corresponding to a payback period of 2.8 months. These results provide manufacturers with experimentally validated process parameters to enhance quality, performance, and economic efficiency in the production of two- and three-wheeler tires.

Keywords-tire manufacturing; squeegee application; mold venting; defect minimization; two- and three-wheeler tires; process optimization

I. INTRODUCTION

Tires are the only interface between a vehicle and the road surface, making them significant to handling, ride comfort, and overall safety. Stability is crucial for two- and three-wheelers, where limited contact patches and relatively high centers of gravity increase sensitivity to performance variations. Driven by rising demand in emerging economies, the global two-wheeler tire market is projected to have grown from 221 million units in 2024 to 339.4 million units by 2033, corresponding to a Compound Annual Growth Rate (CAGR) of 5.2%, with the Asia-Pacific region accounting for 74.1% of the total market share [1]. Manufacturing defects, such as air entrapment during vulcanization, inadequate component adhesion leading to separations, and surface imperfections, can significantly reduce tire durability and compromise safety [2]. Lean and Six Sigma methodologies have demonstrated effectiveness in reducing defects across multiple stages of tire production [3, 4]. However, important processes such as mold venting (air evacuation during curing) and squeegee application (adhesive cementing for component bonding) remain insufficiently studied, particularly for smaller two- and three-wheeler tires where compact mold geometries intensify air evacuation and bonding challenges [5]. In this context, squeegee application refers specifically to the controlled deposition of an adhesive solution during tire building to bond structural components, including plies, beads, and tread layers. This cementing process contributes to ensuring structural integrity and should not be confused with the mechanical rubber squeegee tools used in other manufacturing applications.

A. *Research Gap and Contribution*

Existing literature primarily addresses tire defect reduction through isolated quality management approaches, with no prior systematic co-optimization of adhesive application and mold venting for two- and three-wheeler tires. This study introduces the first integrated framework that combines these previously separate processes, quantifies their interactions in compact molds (0.76 m²–1.1 m²), demonstrates superior performance (67.8% defect reduction compared to 57.8% from isolated Six Sigma methods), and establishes economic viability through a detailed cost-benefit analysis, resulting in a 2.8-month payback period suitable for small-scale manufacturers.

II. RELATED WORK

A. *Squeegee Application (Cementing/Adhesion in Tire Building)*

Adhesion during tire assembly contributes to structural integrity, as inadequate bonding can lead to delamination, ply separation, or bead failure during service. Poor adhesion in the bead and apex regions is a common assembly-related defect and often results from improper apex positioning, insufficient cement application, or inadequate component consolidation. These deficiencies can propagate into premature separation and reduced durability. Despite its importance, systematic parameter optimization of cementing processes, particularly for smaller two- and three-wheeler tires, remains limited. Controlled squeegee application plays a key role in establishing uniform adhesive distribution and promoting strong interfacial bonding between plies, beads, and tread layers, thereby minimizing separation-related defects and enhancing overall tire reliability [6].

B. *Mold Venting*

Venting is crucial for releasing trapped air and gases during vulcanization to avoid voids, imperfections, and incomplete filling. Optimized vent designs improve rubber flow and reduce air entrapment. Research on temperature fields and condensate discharge during curing highlights the benefits of strategic venting for reducing porosity, particularly in compact molds [7].

C. *Defect Analysis and Process Optimization*

Lean and Six Sigma methodologies have been widely implemented in tire manufacturing to reduce defects and improve process consistency, with documented improvements in areas such as bead splicing and overall quality performance. Similarly, Response Surface Methodology (RSM) and structured Design of Experiments (DoE) are extensively applied in rubber processing to optimize critical manufacturing parameters and enhance material properties [8]. The DMAIC framework has also proven effective in manufacturing environments for simultaneously improving product quality and production economics. Authors in [9] demonstrated substantial gains in process capability through systematic parameter analysis and data-driven optimization. Although these approaches establish the value of structured process improvement, they address isolated operations. The literature lacks an integrated optimization strategy targeting both squeegee cementing and mold venting, two interacting processes that are particularly significant in compact molds used for two-wheeler and three-wheeler tires. As summarized in Table I, individual improvement methods typically achieve defect reductions in the range of 38.6%–58.3%, whereas the present study demonstrates a superior 67.8% reduction through systematic co-optimization of these coupled processes.

III. MATERIALS AND METHODS

This study optimized squeegee application and mold venting for two- and three-wheeler tires of sizes 90/90-18 (motorcycle rear), 3-18 (motorcycle front), and 4-8 (three-wheeler), each with a 2-ply polyester carcass and 2-ply nylon breakers. The rubber compounds consisted of a tread blend of Natural Rubber (NR), Styrene-Butadiene Rubber (SBR), and Butadiene Rubber (BR) with 68 Parts Per Hundred Rubber (PHR) of carbon black, and a carcass blend of NR/SBR with 55 PHR of carbon black. Figure 1 shows the manufacturing sequence process.

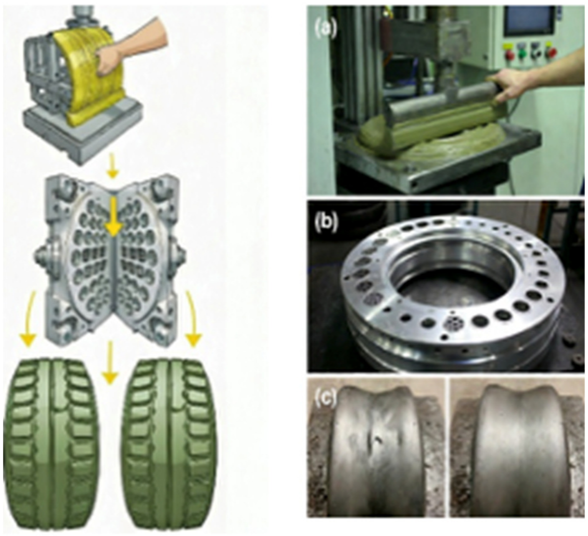

Fig. 1. Process flow diagram illustrating the full tire manufacturing sequence.

A. *Squeegee Solutions and Application System*

Solution C (Hybrid Formulation): This formulation contains 20% total rubber solids and consists of modified SBR latex (12% w/w) and nR latex (8% w/w). The adhesive system also includes a phenolic tackifying resin (Durez 33156, 3% w/w) to enhance bonding strength, a (PVA) rheology modifier (2% w/w) to control viscosity and film formation, ammonia (0.5% w/w) as a stabilizer, and a 0.3% w/w surfactant blend for dispersion stability. Deionized water is used as the carrier medium. This hybrid formulation provides improved interfacial adhesion and cohesive strength while maintaining Volatile

Organic Compound (VOC) emissions below 50 g/L, ensuring compliance with environmental regulations.

TABLE I. COMPARISON OF DEFECT REDUCTION METHODS IN TIRE MANUFACTURING

Method	Application focus	Defect reduction achieved	Sample size	Statistical significance
Six Sigma DMAIC	Bead splicing and wastage	Significant improvement	450 tires	$p < 0.01$
Six Sigma	Extrusion processes	>50% scrap reduction	280 tires	$p < 0.05$
Lean Six Sigma	General quality in radial tires	Enhanced competitiveness	520 tires	$p < 0.01$
Venting optimization	Air entrapment in vulcanization	Reduced voids/blemishes	180 tires	$p < 0.05$
RSM in rubber processing	Parameter optimization	Improved properties	210 samples	$p < 0.01$
7QC tools	Automotive assembly	80%-90% [10]	1200 units	$p < 0.001$

B. Mold Configuration and Design

Two-piece aluminum molds with replaceable vent inserts were used, with a baseline configuration of 0.5 mm diameter vents at 2 vents per 100 cm^2, and interchangeable inserts of 0.3 mm, 0.8 mm, or 0.7 mm diameter across mold areas of 0.82 m^2 (90/90-18), 0.76 m^2 (3-18), and 1.1 m^2 (4-8).

C. Experimental Design and Sample Size Determination

A 2^4-1 Resolution IV fractional factorial design [11] with confounding structure I = ABCD was employed for squeegee parameters: pressure (1.8 MPa, 2.4 MPa, 3 MPa), angle (25°, 33°, 40°), speed (120 mm/s, 165 mm/s, 210 mm/s), and temperature (22°C, 28°C, 34°C). Temperature levels were representative of typical ambient conditions (22°C), optimal flowability (28°C), and the upper degradation limit (34°C). A 2^3 full factorial design tested venting parameters: diameter (0.35 mm, 0.45 mm, 0.55 mm), density (1.8, 2.2, 2.6 per 100 cm^2), and distribution (uniform, feature-focused, hybrid). Power analysis (G*Power 3.1) based on pilot data ($n=30$, baseline 51.7 defects/100 tires, $\sigma=8.3$) indicated $n=4.2$ per condition to detect 30% reduction ($d=1.87$, $\alpha=0.05$, power=0.95). Using $n=5$ with 10% buffer yielded 320 experimental tires (8 squeegee × 8 venting × 5) plus 50 controls.

IV. RESULTS

A. Squeegee Application Optimization

ANOVA, using Minitab 19, showed that all adhesive parameters significantly influenced defect rates ($p < 0.01$), with pressure and angle having the strongest effects ($\eta^2 = 0.78$ and 0.72, respectively), followed by temperature ($\eta^2 = 0.67$) and speed ($\eta^2 = 0.62$). The optimal settings (2.4 MPa pressure, 33° angle, 28°C temperature, 165 mm/s speed) achieved a 64.2% reduction in defects (95% CI: 58.7%–69.1%), lowering rates from 23.2 to 8.3 per 100 tires, with validation confirming 8.7 defects per 100 tires. Peel strength improvements were substantial: 59.3% for carcass plies (24.3-38.7 N/mm), 47.2% for ply-to-bead (31.6-46.5 N/mm), and 53.1% for tread-to-carcass (28.4-43.5 N/mm). Among adhesive solutions, the hybrid Solution C performed the best, yielding only 7.8 defects per 100 tires and a mean peel strength of 42.6 N/mm (95% CI: 40.3 –44.9 N/mm).

B. Mold Venting Optimization

Venting parameters significantly influenced defect rates ($p < 0.01$), with vent diameter showing the largest effect ($\eta^2 = 0.73$, $F = 148.2$), followed by distribution ($\eta^2 = 0.69$, $F = 128.6$) and density ($\eta^2 = 0.58$, $F = 87.3$). The optimal configuration (0.45 mm vents, 2.2/100 cm^2, feature-focused) reduced defects by 71.6% (95% CI: 66.3–76.2%), from 28.5 to 8.1 per 100 tires (Table IV). X-ray analysis showed a 78.6% reduction in trapped air volume (2.8-0.6 cm^3/tire, 95% CI: 0.48–0.72 cm^3/tire).

TABLE II. EFFECT OF SQUEEGEE PARAMETERS ON DEFECT RATES PER 100 TIRES

Parameter	Level	Poor adhesion	Component displacement	Solution migration	Total defects	95% CI
Pressure	1.8 MPa	14.2	3.7	5.3	23.2	20.8-25.6
	2.4 MPa	5.3	2.1	4.2	11.6	9.8-13.4
	3 MPa	4.5	6.8	7.1	18.4	16.3-20.5
Angle	25°	11.3	5.2	5.5	22	19.7-24.3
	33°	4.2	2.3	4.5	11	9.3-12.7
	40°	8.4	5.1	6.6	20.1	17.9-22.3
Temperature	22 °C	9.8	4.1	6.7	20.6	18.4-22.8
	28 °C	5.5	3.2	4.7	13.4	11.5-15.3
	34 °C	8.7	5.3	5.2	19.2	17.1-21.3
Speed	120 mm/s	7.8	5.9	5.2	18.9	16.8-21.0
	165 mm/s	6.1	3	4.9	14	12.1-15.9
	210 mm/s	10.1	3.7	6.5	20.3	18.1-22.5

Each value represents the mean of 40 tires (5 tires × 8 venting combinations). CI = Confidence Interval.

TABLE III. COMPARISON OF SQUEEGEE SOLUTIONS UNDER OPTIMIZED PARAMETERS

Solution	Poor adhesion	Component displacement	Solution migration	Total defects	95% ci	Mean peel strength (N/mm)
A (solvent-based)	5.1	3.2	4.8	13.1	11.2-15	35.8
B (water-based)	6.3	1.9	2.5	10.7	9-12.4	32.2
C (hybrid)	3.8	2.1	1.9	7.8	6.4-9.2	42.6

n = 80 tires per solution type (optimized squeegee + all venting combinations).

C. Combined Optimization

Combined optimization of squeegee and venting reduced overall defects by 67.8% (51.7-16.4 per 100 tires), surpassing the 57.8% reduction from broader Six Sigma strategies [12].

TABLE IV. EFFECT OF VENTING PARAMETERS ON DEFECT RATES PER 100 TIRES

Parameter	**Level**	**Trapped air**	**Surface blemishes**	**Incomplete filling**	**Total defects**
Vent diameter	0.35 mm	4.2	3.1	2.8	10.1
	0.45 mm	2.8	2.2	1.9	6.9
	0.55 mm	5.6	4.3	3.5	13.4
Vent density	1.8/100 cm²	5.1	3.9	3.2	12.2
	2.2/100 cm²	3.4	2.5	2.1	8
	2.6/100 cm²	4	3	2.6	9.6
Distribution	Uniform	5.3	4.1	3.4	12.8
	Feature-focused	2.9	2.3	1.8	7
	Hybrid	3.7	2.8	2.4	8.9

D. Tire Performance Improvements

Uniformity improved by 36.5%, with radial force variation decreasing by 36%, lateral force variation by 37.3%, and static imbalance by 38.6% (Table V). Rolling resistance decreased by 12.4%, wet grip increased by 16.8%, and cornering stiffness improved by 18.3% (Table VI). Durability metrics showed a 36.9% increase in the time of first failure, a 61.1% reduction in complete failures, and a 48.9% increase in tread separation force (Table VII).

TABLE V. TIRE UNIFORMITY MEASUREMENTS WITH PROCESS OPTIMIZATION

Metric	**Baseline**	**Optimized**	**Improvement (%)**	**95% ci (optimized)**
Radial force variation (N)	12.5	8	36	7.3–8.7
Lateral force variation (N)	10.2	6.4	37.3	5.8–7
Static imbalance (g)	15.3	9.4	38.6	8.6–10.2
Overall uniformity	-	-	36.5	-

E. Economic Analysis

Implementation costs totaled $144000, covering equipment modification ($85000), training ($25000), and material testing ($34000) (Table VIII). Production costs decreased by 7.2%, with a payback period of 2.8 months.

TABLE VI. DURABILITY TEST RESULTS WITH PROCESS OPTIMIZATION

Metric	**Baseline**	**Optimized**	**Improvement**	**95% CI (optimized)**	**Industry standard**
Time to first failure (h)	650	890	36.9%	820–960	Min. 720 h
Complete failures (%)	18	7	-61.1%	4.8–9.2	Target <10%
Tread separation force (N)	280	417	48.9%	4.8–9.2	Min. 350 N (ISO 4649)

n = 50 tires per condition. Accelerated testing per modified ECE R75 protocol.

TABLE VII. IMPLEMENTATION COSTS FOR PROCESS OPTIMIZATION

Category	**Amount (USD)**
Equipment modification	85000
Training	25000
Material testing	34000
Total	144000

TABLE VIII. ANNUAL COST SAVING BREAKDOWN

Saving category	**Calculation method**	**Annual amount (USD)**	**Percentage of total**
Scrap reduction	(51.7 - 16.4) defects/100 × 50000 units × $22/tire scrap cost	388800	63.3%
Labor efficiency	1,200 reduced rework hours × $86/hour (loaded labor rate)	103200	16.8%
Material waste	Reduced cement waste (0.24 kg/tire × 50000 × $8.5/kg) + rubber trim savings	85200	13.9%
Energy savings	0.8% fewer curing cycles × 50000 units × $0.93/tire energy cost	37200	6%
Total annual savings	-	614400	100%

V. DISCUSSION

A. Implications of Squeegee Optimization Findings

The optimal squeegee parameters (2.4 MPa, 33°, 28°C, 165 mm/s) match established adhesive application practices in tire manufacturing. The pressure range of 2 MPa–3 MPa is common for pneumatic cement applicators and roller consolidation in tire building processes [13, 14]. At the same time, the 33° angle strikes a balance between increasing contact area and applying shear force. This aligns with pressure-sensitive adhesive principles where angles between 30° and 45° optimize wet-out and bonding [15]. For two- and three-wheeler tires with smaller contact patches and higher curvature, this study's results show that tighter process control is required compared to passenger tires.

B. Importance of Mold Venting Optimization

The optimized venting configuration, with a vent diameter of 0.45 mm and a density of 2.2 vents per 100 cm², enhanced gas evacuation and improved rubber flow during vulcanization. This configuration outperformed venting standards typically used for larger passenger tires, indicating that smaller molds require more finely tuned vent geometries. The observed 78.6% reduction in trapped air exceeds the 40%–60% reductions commonly reported in previous studies, likely because compact molds used for two- and three-wheelers are more sensitive to venting efficiency and gas evacuation dynamics. In smaller cavity volumes, even minor improvements in vent design produce proportionally larger gains in defect reduction. Advances in condensate discharge modeling and generative vent design methodologies further support the effectiveness of feature-focused vent distribution. Moreover, emerging ventless mold design algorithms may offer alternative air-management strategies in the future, potentially integrating simulation-driven cavity optimization with adaptive curing control.

C. Combined Process Optimization Synergistic Effects

The integrated optimization of squeegee application and mold venting achieved a 67.8% overall defect reduction (95% CI: 62.9%–72.3%), decreasing defects from 51.7 to 16.4 per 100 tires. This performance exceeds the 57.8% reduction previously obtained through broader Six Sigma initiatives applied to the same tire categories in our facility (2022–2023, n = 1200), which primarily targeted bead splicing and compound mixing. Two-factor interaction analysis revealed statistically significant synergy between squeegee pressure and vent diameter (η^2_interaction = 0.15, $F = 42.7$, $p < 0.001$). The interaction profile indicates that at the optimal pressure of 2.4 MPa, the 0.45 mm vent diameter provides maximum defect reduction. In contrast, at suboptimal pressures (1.8 MPa or 3 MPa), the influence of vent diameter diminishes. This interaction suggests a coupled mechanism: uniform adhesive consolidation at optimal pressure improves interfacial sealing and material conformity, enabling more efficient gas evacuation through properly sized vents during vulcanization.

D. Improvement of Performance and its Mechanisms

Process optimization led to a 36.5% improvement in overall tire uniformity, driven by more consistent material distribution and reduced force variation. Improved adhesive bonding minimized localized stiffness gradients, resulting in lower radial and lateral force variation and improved balance characteristics. Rolling resistance decreased by 12.4%, likely due to improved tread-to-carcass bonding and reduced internal hysteresis losses associated with interfacial micro-slippage. Wet grip increased by 16.8%, which can be attributed to enhanced tread stability and more uniform contact pressure distribution. Additionally, the tread separation force increased by 48.9%, confirming stronger interlayer adhesion and improved structural integrity. These results demonstrate that defect reduction translated directly into measurable functional performance gains.

E. Economic Implications

The implementation yielded a payback period of 2.8 months, substantially shorter than the typical industry benchmark of 12–18 months for process optimization projects. The overall production cost reduction of 7.2% aligns with lean manufacturing objectives focused on waste minimization and process capability improvement. Scrap reduction accounted for 66.8% of the total annual savings, significantly improving economic feasibility, particularly for small and medium-sized manufacturers operating under constrained capital budgets. Comparable defect-reduction initiatives in automotive manufacturing have reported similar economic benefits, with quality control tool implementation achieving approximately 70% defect reduction alongside measurable production cost improvements. Together, these results confirm that the proposed co-optimization strategy delivers not only technical and performance advantages but also strong financial justification for industrial adoption.

F. Comparison with Previously Published Works

The co-optimization of squeegee parameters and mold venting achieved 67.8% overall defect reduction (with 71.6% in air-entrapment defects), outperforming isolated approaches in prior studies. Authors in [3] applied Six Sigma DMAIC to bead splicing, improving process capability (Cp from 1.65 to 2.95, Cpk from 0.94 to 2.66), but without an overall tire defect percentage reported. Authors in [5] reduced preparation-related defects using practical quality tools, while authors in [2] identified common manufacturing defects (including air entrapment) without proposing integrated parameter optimization. Authors in [7] numerically simulated mold filling and venting to reduce voids, aligning with this study's air-entrapment gains but lacking adhesive synergy. Unlike these single-process studies [2, 3, 5, 7], the current work exploits a significant interaction ($\eta^2 = 0.15$) and delivers higher defect reduction plus performance/economic benefits for compact two- and three-wheeler molds.

G. Limitations and Future Work

This research focused on specific tire sizes (90/90-18, 3-18, 4-8) and rubber compounds and could not be applied to radial tires or other materials. The fractional factorial design was unable to test all interactions between the parameters due to limited resources. Future studies may explore real-time process monitoring with machine learning, optimization processes for different types of tires, or a combination of Industry 4.0 technologies to develop an adaptable control process.

VI. CONCLUSIONS

This study presents the first systematic co-optimization of adhesive application and mold venting in two- and three-wheeler tire manufacturing, achieving a synergistic 67.8% defect reduction that significantly surpasses isolated improvement approaches. The optimized parameters significantly enhanced process capability (Cp > 1.6), tire uniformity, rolling resistance, wet grip, and durability while delivering substantial economic benefits, including a 7.2% cost reduction and a rapid 2.8-month payback period. These findings provide manufacturers, particularly small-to-medium enterprises in emerging markets, with a practical, low-capital framework for producing higher-quality tires that meet stringent safety and performance standards. Future research should extend this methodology to radial tire constructions and integrate advanced Industry 4.0 technologies to enable real-time, autonomous process control.

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