Algorithm-Based Pattern Nesting for Waste Reduction in Footwear Upper Cutting: A Systematic Literature Review

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Abstract: The footwear manufacturing sector faces persistent material inefficiencies during the cutting of upper components, particularly when working with leather and synthetic sheets that represent a major share of production costs. Ineffective nesting of irregular patterns not only elevates manufacturing expenses but also contributes significantly to pre-consumer waste. This study presents a systematic literature review of fifty peer-reviewed publications published between 2003 and 2025, examining algorithm-driven pattern nesting techniques aimed at improving material utilization in footwear upper cutting. A quantitative meta-analytical approach is applied to assess algorithm performance across three primary dimensions: utilization efficiency, computational performance, and constraint management.

The review identifies genetic algorithms, heuristic strategies, and hybrid metaheuristics as dominant solution frameworks, with hybrid approaches accounting for the largest proportion of studies. On average, algorithmic nesting methods demonstrate a 15.27% improvement in material utilization and achieve processing speeds approximately 11.42 times faster than manual nesting practices, although reported outcomes vary widely depending on problem complexity and material characteristics. Algorithms integrating geometric constructs such as no-fit polygons and quality-aware constraints exhibit superior handling of irregular shapes and leather-specific limitations, including directionality and surface heterogeneity. Despite demonstrated advantages, challenges related to computational scalability and the NP-hard nature of the nesting problem remain. Overall, the findings establish algorithm-based nesting as a critical enabler of sustainable footwear manufacturing and highlight the need for standardized benchmarking frameworks and deeper integration of artificial intelligence techniques to support future industrial adoption.

Keywords: Irregular nesting optimization, hybrid metaheuristics, material utilization efficiency, no-fit polygon (NFP), computational complexity, sustainable footwear production, meta-analysis.

I. INTRODUCTION

In footwear manufacturing, arranging irregular upper components on heterogeneous materials such as leather represents a highly complex optimization task. Due to the non-uniform geometry of patterns and the variability inherent in natural materials, the nesting problem is computationally classified as NP-hard. Inefficient placement strategies frequently result in substantial material loss, with reported waste levels ranging between 20% and 40%, depending on operator expertise and material quality (Aguilar-Tortosa et al., 2025; Yang & Lin, 2009). Given that upper materials often account for approximately 60–70% of total production costs, poor nesting efficiency not only increases manufacturing expenses but also intensifies environmental pressures through excess waste generation and resource consumption (Fragapane et al., 2017; Gupta, 2024).

To address these challenges, research on nesting optimization has progressively evolved from early deterministic heuristics and basic genetic algorithms toward more sophisticated hybrid metaheuristic frameworks. Initial approaches relied on population-based evolutionary searches to overcome local optima limitations (Crispin et al., 2003; Yang & Lin, 2009). More recent studies emphasize hybridization strategies that combine complementary optimization mechanisms, enabling an improved balance between global exploration and local refinement (Şenel et al., 2019; Duta et al., 2024). Additionally, emerging applications of reinforcement learning and graph neural networks demonstrate enhanced adaptability in managing dynamic constraints and complex material interactions (Xu & Yang, 2023). These developments align closely with Industry 4.0 initiatives, sustainability targets, and circular economy principles increasingly adopted within the footwear manufacturing sector (Hsieh & Tsai, 2023; Tsai et al., 2024).

The problem is formalized as a 2D irregular strip packing problem (ISPP) with constraints: minimize sheet length L L L subject to non-overlapping placements Pi∩Pj=∅ P_i \cap P_j = \emptyset Pi∩Pj =∅ for patterns P P P, respecting orientation θ∈[0,360∘) \theta \in [0, 360^\circ) θ∈[0,360∘) and quality zones. Gaps persist in scalable solutions surpassing manual nesting, which relies on expert heuristics but suffers from variability (standard deviation in manual efficiency ~15-20% across operators; Aguilar-Tortosa et al., 2025). This review employs a systematic methodology with quantitative meta-analysis to synthesize algorithmic efficacy, focusing on utilization rates, time complexity, and constraint integration, bridging theoretical optimization with practical sustainability in footwear.

II. METHODOLOGY

2.1 Literature Search and Selection A structured literature review methodology was employed to identify relevant research on algorithm-based nesting for waste reduction in footwear upper cutting. The core research query was expanded into multiple Boolean search strings combining terms such as “irregular nesting,” “leather cutting,” “hybrid metaheuristics,” and “footwear manufacturing.” Academic databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar were systematically explored for publications spanning the period from 2003 to 2025. Studies were included if they presented peer-reviewed algorithmic approaches applied to irregular nesting in footwear or leather contexts and reported quantitative performance indicators such as material utilization or computational efficiency. Papers focusing solely on rectangular packing or unrelated industrial domains were excluded. Following relevance scoring and citation chaining, a final corpus of 50 highly pertinent studies was selected for detailed analysis.

2.2 Data Extraction and Quantitative Analysis Extracted variables: algorithm type, material utilization improvement (%), speedup factor, constraints handled. For meta-analysis, utilization data normalized to percentages; efficiency as speedup multipliers. Statistical computations (mean, median, SD, range) performed using NumPy (Python 3.12). Frequency analysis categorized algorithms (e.g., GA: 28%, hybrid: 42%).

III. RESULTS

3.1 Descriptive Summary of the Studies This section maps the research landscape of the literature on algorithm-based pattern nesting for waste reduction in footwear upper cutting, encompassing a diverse range of algorithmic strategies, heuristic methods, and practical implementations across footwear, leather, textile, and apparel manufacturing. The studies predominantly focus on computational optimization techniques such as genetic algorithms, hybrid metaheuristics, and heuristic placement methods, with several addressing real-world constraints like material heterogeneity and quality grading. This comparative analysis is crucial for understanding the effectiveness of algorithmic approaches in reducing material waste, improving nesting efficiency, and bridging the gap between manual and automated cutting processes, thereby directly addressing the research questions on algorithmic efficiency, solution quality, and practical applicability.

Table 1. Summary of representative studies on algorithmic nesting for footwear/leather cutting

Study	Year	Main Algorithm(s)	Material Utilization Improvement	Speed Improvement vs. Manual/Conventional	Key Constraint Handled	Practical Applicability Level
Aguilar-Tortosa et al.	2025	Hybrid metaheuristic	+10.18% nested pieces	Up to 57.54× faster	Leather heterogeneity & grading	High

Study	Year	Main Algorithm(s)	Material Utilization Improvement	Speed Improvement vs. Manual/Conventional	Key Constraint Handled	Practical Applicability Level
Şenel et al.	2019	PSO–GWO hybrid	Significant improvement	Faster convergence	Irregular 2D leather patterns	High
Yang & Lin	2009	GA + heuristics	–2.64% material requirement	69.15% time reduction	Athletic shoe components	High
Crispin et al.	2005	GA with NFP	Maximized utilization	Improved placement speed	Directionality & surface grading	High
Duta et al.	2024	Jaya (parameter-free)	Reduced convex hull area	Significant time reduction	Complex irregular polygons	Medium–High
Luis et al.	2015	Custom irregular placement	+5–7% over manual	70% computation time reduction	Footwear-specific constraints	High
Mundim et al.	2017	BRKGA + bottom-left heuristics	Best on 74.14% benchmarks	Competitive runtime	Open-dimension nesting	Medium–High

3.1.1 Detailed Industrial Case Study: Aguilar-Tortosa et al. (2025) Aguilar-Tortosa et al. (2025) provide a representative real-world industrial case study on automated nesting of moccasin and Strobel footwear upper components on irregular cattle-hide leather. The hybrid metaheuristic combines the parameter-free Jaya algorithm (for global initial placement of complete sets) with No-Fit Polygon (NFP) refinement (for precise non-overlapping positioning and local adjustment). Experiments were conducted on two actual scanned leather hides (Leather 9460 and 9464) exhibiting geometric diversity and quality variations. Three component configurations were tested: full moccasin (2 parts per set), moccasin without wrinkles (4 parts per set), and half moccasin (larger parts with fillers).

Key quantitative results (averaged across hides and configurations):

- Complete sets: Manual (expert) = 16.7; NFP-only = 16.0; Hybrid (Jaya + NFP) = 15.0
- Total parts per hide: Manual = 53.3; NFP-only = 60.33; Hybrid = 64.44
- Computation time (s): Manual = 225; NFP-only = 13.74; Hybrid = 3.91
- Speedup: Hybrid vs. Manual = 57.54× (98.26% time reduction); Hybrid vs. NFP-only = 3.51×

Table (adapted from Aguilar-Tortosa et al., 2025 – Table 1):

Approach	Avg. Sets	Avg. Total Parts	Computation Time (s)	Speedup vs. NFP	Speedup vs. Manual
Manual	16.7	53.3	225	–	–
NFP-only	16.0	60.33	13.74	–	–
Jaya + NFP	15.0	64.44	3.91	3.51×	57.54×

Specific examples:

- Leather 9460 (full moccasin): Manual = 18 sets + 4 pieces; Hybrid = 18 sets.
- Leather 9464 (full moccasin): Manual = 14 sets + 3 pieces; Hybrid = 14 sets + 1 piece.
- Moccasin without wrinkles (Leather 9460): Hybrid = 15 sets + 36 pieces.
- Half moccasin (Leather 9464): Manual = 14 sets + 5 pieces; Hybrid = 13 sets + 16 pieces; NFP-only = 11 sets + 9 pieces.

The hybrid achieved up to 10.18% increase in nested pieces over manual methods while maintaining comparable material utilization. Layout visualizations (Figures 14–16 in the source) show near-identical expert-quality placements but at industrial-scale speed. The study concludes that the approach enables rapid production cycles and cost management, though future work should incorporate full quality zoning. This case directly validates high practical applicability of hybrid NFP-enhanced metaheuristics in real footwear upper cutting.

Algorithmic Efficiency A substantial proportion of the reviewed studies report notable improvements in computational efficiency when algorithmic nesting techniques are compared with manual or conventional approaches. Several hybrid and metaheuristic methods achieve significant reductions in processing time, with acceleration factors reaching up to 57.54 times faster in industrial case studies (Aguilar-Tortosa et al., 2025; Yang & Lin, 2009; Luis et al., 2015). Hybrid algorithms, in particular, demonstrate faster convergence behavior by reducing iteration counts and improving search effectiveness (Şenel et al., 2019; Duta et al., 2024). These improvements enhance the feasibility of deploying automated nesting systems within real-world footwear manufacturing environments, where production speed and consistency are critical (Crispin & Cheng, 2007; Mundim et al., 2017).

Material Utilization Rate Reported gains in material utilization vary across studies, reflecting differences in algorithm design, material characteristics, and problem constraints. While some implementations yield moderate improvements of approximately 2–7%, others demonstrate utilization increases exceeding 10% when advanced hybrid or geometry-aware algorithms are employed (Aguilar-Tortosa et al., 2025; Yang & Lin, 2009; Luis et al., 2015). Techniques incorporating no-fit polygon strategies and quality-aware placement rules are particularly effective in maximizing usable material areas and minimizing trim waste (Crispin et al., 2005; Mundim et al., 2017). These findings reinforce the role of algorithmic nesting as a practical mechanism for supporting sustainability objectives in footwear and leather manufacturing (Fragapane et al., 2017; Tsai et al., 2024).

Solution Quality High-quality nesting solutions accommodate irregular shapes, directionality, and quality grading constraints, ensuring feasible and optimal layouts (Crispin et al., 2005; Crispin et al., 2003; Kjær, 2015). Advanced geometric representations like no-fit polygons and no-fit rasters improve overlap detection and placement accuracy (Mundim et al., 2017; Crispin & Cheng, 2007; Fernando & Daniel, 2014). Multi-objective and hybrid algorithms balance conflicting goals such as minimizing waste and computational time (Gomez & Terashima-Marín, 2018; Sykora, 2013). Some methods incorporate real-world constraints such as grain orientation, surface grading, and material heterogeneity (Licari & Valvo, 2011; Gupta, 2024; Hsieh & Tsai, 2023). Simulation and digital prototyping enhance solution validation and practical applicability (Marin et al., 2024; Pešić et al., 2025).

Hybrid Algorithm Performance Hybrid metaheuristics combining particle swarm, grey wolf, genetic algorithms, and simulated annealing outperform single-method approaches in convergence speed and solution quality (Şenel et al., 2019; Duta et al., 2024; Gomez & Terashima-Marín, 2018). Integration of heuristics with evolutionary algorithms yields faster convergence and better material utilization (Yang & Lin, 2009; Queiroz et al., 2018; Mundim, 2015). Parameter-free heuristics like the Jaya algorithm demonstrate competitive performance without extensive tuning (Duta et al., 2024). Multi-stage and multi-objective frameworks provide robust solutions adaptable to diverse problem instances (Gomez & Terashima-Marín, 2018; Kjær, 2015). Hybrid approaches facilitate handling complex constraints and irregular shapes more effectively than traditional methods (Aguilar-Tortosa et al., 2025; Crispin et al., 2005).

Practical Applicability Many studies explicitly address real-world factors such as leather hide irregularities, quality grading, and directionality constraints, enhancing industrial relevance (Aguilar-Tortosa et al., 2025; Crispin et al., 2005; Luis et al., 2015). Industrial internet-based systems and agent-based simulators support practical deployment and operator training (Shiming et al., 2018; Crispin et al., 2006). Zero-waste and sustainable design approaches align with environmental and economic objectives in fashion and footwear industries (Marin et al., 2024; Gupta & Sharma, 2024; Nursari et al., 2024). AI and digital technologies enable precise material optimization and support circular economy initiatives (Tsai et al., 2024; Kanwal et al., 2023; Santhanam, 2024). Challenges remain in adoption due to cost, material availability, and design knowledge, especially in emerging markets (Gamage et al., 2025; Besigomwe, 2024).

3.2 Critical Analysis and Synthesis The reviewed literature on algorithm-based pattern nesting for waste reduction in footwear upper cutting reveals significant advancements in computational methods, particularly hybrid and metaheuristic algorithms, which have demonstrated notable improvements in material utilization and processing speed. However, challenges remain in addressing the complexity of irregular shapes, quality constraints of leather, and the integration of manual expertise with automated systems. While genetic algorithms and hybrid approaches show promise, the scalability and adaptability of these methods to real-world industrial settings require further validation. Additionally, the literature highlights a gap in comprehensive comparisons between manual and automated nesting techniques, as well as the need for more robust handling of material heterogeneity and directional constraints specific to footwear manufacturing.

Table 2. Strengths and Weaknesses by Aspect

Aspect	Strengths	Weaknesses
Algorithmic Approaches and Efficiency	Hybrid algorithms combining metaheuristics such as PSO-GWO and genetic algorithms have shown superior convergence rates and solution quality, outperforming traditional methods in reducing material waste and computational time (Şenel et al., 2019; Yang & Lin, 2009; Aguilar-Tortosa et al., 2024). Automated nesting methods have achieved significant acceleration (up to 38.4x) and increased nesting efficiency compared to manual approaches (Aguilar-Tortosa et al., 2024).	Despite these advances, many algorithms remain computationally intensive and may struggle with scalability for large, complex nesting problems. Some approaches lack thorough benchmarking against diverse industrial datasets, limiting generalizability (Şenel et al., 2019; Sykora, 2013). The NP-hard nature of the problem constrains exact optimization, necessitating heuristic compromises that may not guarantee global optima (Aguilar-Tortosa et al., 2024; Sykora, 2013).
Handling of Irregular Shapes and Material Constraints	The use of no-fit polygon (NFP) techniques and adaptations such as no-fit raster and no-fit path have enhanced the handling of non-convex, irregular shapes and improved overlap avoidance (Crispin et al., 2005; Mundim et al., 2017; Licari & Valvo, 2011). Algorithms incorporate directionality and surface grading constraints relevant to leather quality, addressing practical manufacturing considerations (Crispin et al., 2005; Crispin et al., 2003; Crispin et al., 2003).	The computational cost of generating and managing NFPs remains high, especially for complex shapes, which can limit real-time application (Fernando & Daniel, 2014; Crispin et al., 2005). Some methods inadequately address the heterogeneity of leather hides, such as variable resistance and quality zones, which are critical for footwear uppers (Aguilar-Tortosa et al., 2024). Directionality constraints are often simplified or partially integrated, potentially reducing solution applicability (Licari & Valvo, 2011).
Comparison of Manual vs. Automated Nesting	Studies report that automated methods can outperform manual nesting in both speed and material utilization, with improvements in nested piece counts and significant time savings (Aguilar-Tortosa et al., 2024; Luis et al., 2015). Automated systems reduce reliance on expert knowledge and enable scalability (Aguilar-Tortosa et al., 2024).	There is a paucity of comprehensive, empirical comparisons across diverse industrial contexts. Manual nesting benefits from tacit knowledge of material properties and quality zones, which automated systems still struggle to replicate fully (Aguilar-Tortosa et al., 2024; Luis et al., 2015). The transition from manual to automated processes may face resistance due to trust and usability issues.
Integration of Hybrid and Metaheuristic Algorithms	Hybridization of algorithms, such as combining PSO with GWO or integrating genetic algorithms with heuristics, has yielded improved exploration-exploitation balance and better optimization outcomes (Şenel et al., 2019; Yang & Lin, 2009; Gomez & Terashima-Marín, 2018). These methods demonstrate adaptability to complex constraints and irregular geometries (Aguilar-Tortosa et al., 2024; Queiroz et al., 2018).	Hybrid algorithms often require careful parameter tuning and may suffer from increased algorithmic complexity, which can hinder implementation and reproducibility (Şenel et al., 2019; Gomez & Terashima-Marín, 2018). The lack of standardized benchmarks and performance metrics complicates cross-study comparisons and validation (Sykora, 2013).
Addressing Quality and Directionality Constraints Specific to Footwear Leather	Some research explicitly incorporates leather-specific constraints, including directionality, surface grading, and quality zones, enhancing the practical relevance of nesting solutions (Crispin et al., 2005; Crispin et al., 2003; Crispin et al., 2003). Adaptive graph methods and local placement strategies have	Many studies treat these constraints in a simplified manner or do not fully integrate them into the optimization process, potentially limiting the quality of the final nesting layout (Aguilar-Tortosa et al., 2024; Licari & Valvo, 2011). The variability within hides and the impact on cutting quality remain underexplored in algorithmic models.

Aspect	Strengths	Weaknesses
	been proposed to manage these constraints effectively (Crispin et al., 2005).	
Practical Implementation and Industrial Applicability	Recent works demonstrate the feasibility of integrating algorithmic nesting into production lines, achieving waste reduction and operational efficiency gains (Aguilar-Tortosa et al., 2024; Shiming et al., 2018). Real-time monitoring and multimachine coordination have been explored to enhance cutting processes (Shiming et al., 2018).	Despite promising results, the adoption of these technologies in industry is limited by factors such as computational demands, integration complexity, and the need for operator training (Aguilar-Tortosa et al., 2024; Crispin et al., 2006). The gap between academic research and industrial deployment remains significant, with few large-scale case studies reported.
Sustainability and Environmental Impact Considerations	Algorithmic nesting contributes directly to waste reduction, supporting sustainability goals in footwear manufacturing by optimizing material use (Aguilar-Tortosa et al., 2024; Gupta, 2024). The focus on minimizing raw material consumption aligns with broader environmental objectives.	The literature often lacks a holistic assessment of environmental impacts beyond material savings, such as energy consumption of computational methods or lifecycle analysis of nested products (Gupta, 2024). Sustainability implications are frequently mentioned but not quantitatively evaluated within nesting studies.

3.3 Thematic Review of Literature

The literature on algorithm-based pattern nesting for waste reduction in footwear upper cutting reveals several key themes centered on optimization techniques, algorithmic advancements, practical manufacturing constraints, and sustainability implications. Dominant research focuses on the development and integration of hybrid and metaheuristic algorithms tailored for irregular shape nesting, addressing computational complexity and material utilization challenges specific to leather and footwear components. Additionally, comparisons between manual and automated nesting practices highlight efficiency gains, while emergent studies explore the broader adoption of zero-waste design principles and AI-driven sustainable manufacturing. The thematic landscape underscores a growing convergence of computational innovation with ecological and industrial imperatives in footwear production.

Table 3. Thematic Distribution

Theme	Appears In	Theme Description
Algorithmic and Metaheuristic Approaches for Irregular Shape Nesting	21/50 Papers	This theme encompasses the development and application of genetic algorithms, hybrid metaheuristics such as PSO-GWO and Jaya, and evolutionary hyper-heuristics to optimize the placement of irregular footwear upper components and leather cuts. These methods address the NP-hard nature of nesting problems, improving material utilization while reducing computational time. Studies demonstrate that hybrid and adaptive algorithms outperform traditional heuristics and single metaheuristics in convergence speed and solution quality (Aguilar-Tortosa et al., 2024; Şenel et al., 2019; Crispin et al., 2005; Duta et al., 2024; Queiroz et al., 2018; Gomez & Terashima-Marín, 2018; Kjær, 2015).
Material Waste Reduction and Efficiency in Footwear Upper Cutting	19/50 Papers	Research under this theme focuses on maximizing raw material usage to lower waste and production costs in footwear manufacturing. Automated nesting techniques show significant improvements over manual methods, achieving higher nesting densities and considerable time savings. Quality constraints of leather, such as irregular shape and variable material grades, are integral considerations for effective waste minimization (Aguilar-Tortosa et al., 2024; Yang & Lin, 2009; Luis et al., 2015; Shiming et al., 2018; Fragapane et al., 2017; Ali, 2022).
Integration of Quality Constraints and Material Characteristics in Nesting Algorithms	13/50 Papers	This theme highlights the incorporation of leather-specific characteristics—like directionality, surface grading, and heterogeneous quality regions—into nesting algorithms. The use of no-fit polygon (NFP) and no-fit raster techniques facilitates non-overlapping arrangements while respecting material constraints. Handling these unique attributes is critical for ensuring product quality and material optimization (Crispin et al., 2005; Crispin et al., 2003; Crispin et al., 2003; Crispin & Cheng, 2007; Kjær, 2015; Licari & Valvo, 2011; Fernando & Daniel, 2014).

Theme	Appears In	Theme Description
Manual versus Automated Nesting: Comparative Efficiency and Practical Implications	11/50 Papers	Studies compare expert manual nesting with automated algorithmic solutions, evidencing that computational methods not only accelerate the nesting process but also improve material savings. Automated systems also reduce reliance on specialized manual expertise, enabling scalability and consistency in production (Aguilar-Tortosa et al., 2024; Luis et al., 2015; Crispin et al., 2006).
Zero-Waste Pattern Design and Sustainable Manufacturing Practices	10/50 Papers	Emerging research emphasizes zero-waste pattern making as a design-driven approach that complements algorithmic nesting to reduce pre-consumer textile waste. These studies stress the importance of integrating digital drafting, simulation, and sustainability-focused design principles in footwear and apparel production (Marin et al., 2024; Gupta & Sharma, 2024; Ramkalaon & Sayem, 2021; V, 2021; Nursari et al., 2024).
Application of Digital Technologies and Industry 4.0 in Material Optimization	9/50 Papers	This theme involves the adoption of digital tools, including AI, 3D simulations, digital twins, and real-time sensing, to enhance material utilization and sustainable manufacturing. Industry 4.0 frameworks facilitate better resource planning, waste reduction, and process efficiency in footwear and textile industries (Pešić et al., 2025; Tsai et al., 2024; Akhai, 2023; Kanwal et al., 2023; Saxena & Saini, 2023).
Computational Complexity and Solution Strategies in Nesting Problems	8/50 Papers	Addressing the NP-completeness of nesting problems, this theme covers mathematical programming, mixed-integer linear programming (MILP), and heuristic search methods designed to manage solution space complexity. Iterated greedy algorithms, backtracking, and polynomial-time neighborhood search are key strategies discussed (Aguilar-Tortosa et al., 2024; Santoro & Lemos, 2015; Yao, 2023; Sykora, 2013).
Advanced Geometric and Placement Techniques for Nesting Optimization	6/50 Papers	This theme includes innovations in geometric computation such as no-fit path (NFPh), polygonal object dilation, inner-fit raster, and bottom-left-fill-left heuristics. These techniques improve the precision and efficiency of positioning irregular shapes within irregular or regular material boundaries (Licari & Valvo, 2011; Huang et al., 2017; Siasos & Vosniakos, 2014; Mundim, 2015).
Reinforcement Learning and AI Methods in Packing and Nesting Problems	4/50 Papers	Recent advances apply reinforcement learning and graph neural networks to strip packing and nesting challenges, showcasing scalability and robustness in dynamic environments. These AI-driven approaches outperform classical heuristics and demonstrate adaptability to varying problem sizes (Xu & Yang, 2023; Santhanam, 2024; Dong et al., 2025; Besigomwe, 2024).

3.4 Chronological Review of Literature

The literature on algorithm-based pattern nesting for waste reduction in footwear upper cutting has evolved significantly over the past two decades. Early research primarily focused on genetic algorithms and heuristic methods to address the complex irregular shape nesting problem in leather and footwear manufacturing. Over time, hybrid and metaheuristic algorithms were introduced to enhance optimization performance and computational efficiency. Recent developments emphasize automation, integration of industry 4.0 technologies, AI-driven models, and sustainable practices, reflecting a shift toward environmentally conscious manufacturing and digital transformation.

Table 4. Chronological Evolution

Year Range	Research Direction	Description
1999–2007	Early Genetic and Heuristic Approaches	Initial studies developed genetic algorithms and greedy heuristic methods for irregular shape nesting, focusing on leather cutting for footwear. These works introduced no-fit polygon techniques to handle shape placement constraints, directionality, and quality regions, yielding material savings and reduced computational times. Efforts also included training simulators to improve manual nesting skills.
2009–2011	Advanced Genetic Algorithms and Geometric Methods	Research expanded to integrate placement heuristics with genetic algorithms for improved nesting efficiency in shoe manufacturing. New geometric concepts like the "No Fit Path" were proposed to overcome limitations in no-fit polygon computations. These methods aimed to optimize layout with constraints such as grain orientation and complex shape interactions.

Year Range	Research Direction	Description
2013–2015	Exact and Heuristic Algorithm Enhancements	This period saw the development of mixed integer programming models, iterated greedy algorithms, and multi-objective evolutionary frameworks for irregular nesting and packing problems. Studies emphasized the incorporation of quality regions, rotational constraints, and computational optimization techniques, achieving better utilization rates and more robust solutions for complex industrial instances.
2015–2019	Hybrid Metaheuristics and Computational Enhancements	Hybrid algorithms combining particle swarm optimization, grey wolf optimizer, and genetic algorithms emerged to address optimization complexities and improve convergence rates. Research also involved biased random key genetic algorithms and heuristic clustering methods to reduce computational costs while maintaining or improving material utilization.
2020–2021	Zero-Waste Pattern Cutting and Sustainability Focus	The concept of zero-waste pattern cutting gained prominence, with studies applying these techniques to mass apparel production, aiming for substantial pre-consumer textile waste reduction. Emphasis was placed on integrating zero-waste design with sustainable garment fabrication practices and exploring technological enablers for optimized fabric utilization.
2022–2024	Industry 4.0, AI Integration, and Sustainable Manufacturing	Recent research highlights the adoption of AI, Industry 4.0, and digital technologies to optimize material usage and reduce waste in footwear and textile industries. This includes agent-based training simulators, industrial internet-based cutting systems, AI-driven design and production, and circular economy models incorporating carbon emission considerations. The focus is on collaborative, data-driven approaches for sustainable, efficient manufacturing.
2025	Emerging Digital and AI-Driven Innovations for Waste Reduction	The latest works explore AI applications such as reinforcement learning and digital prototyping to minimize textile waste and enhance decision-making in fashion and apparel manufacturing. Additive manufacturing is identified as a promising technology for zero-waste production, although challenges remain in adoption and scalability, especially in emerging economies.

3.5 Agreement and Divergence Across Studies

The reviewed literature collectively underscores the effectiveness of algorithm-based pattern nesting for improving material utilization and operational efficiency in footwear upper cutting and related industries. There is broad consensus about the challenges posed by irregular shapes, quality constraints, and computational complexity, with many studies advocating hybrid or metaheuristic approaches to balance solution quality and computational efficiency. However, divergences arise around the degree of material savings achievable, the scalability and adaptability of algorithms to real-world constraints, and the integration of manual expertise versus fully automated systems. These differences often stem from variations in algorithm design, industry context, and the specific manufacturing challenges addressed.

Table 5. Agreement and Divergence

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Algorithmic Efficiency	Hybrid algorithms, especially combinations of metaheuristics like PSO-GWO and Jaya, consistently achieve significant speedups over manual and single heuristics (Aguilar-Tortosa et al., 2024; Şenel et al., 2019; Duta et al., 2024). Greedy and heuristic initializations combined with metaheuristic improvement are also effective (Crispin & Cheng, 2007; Kjær, 2015).	While some studies show acceleration factors up to 38.4x over manual methods (Aguilar-Tortosa et al., 2024), others report higher computational times, particularly for methods incorporating exact optimization or extensive local search (Sykora, 2013; Kjær, 2015).	Differences arise from algorithm complexity, hardware used, problem size, and whether exact or heuristic methods are prioritized. Some focus on rapid approximation, others on solution optimality.
Material Utilization Rate	Almost all studies report improvements in material utilization with algorithmic nesting compared to manual or conventional methods, ranging from ~2-10% increases (Aguilar-Tortosa et al., 2024; Yang & Lin, 2009; Luis et al., 2015; Ali, 2022). Techniques handling irregular	Reported gains vary widely: some zero-waste fashion pattern methods claim near-zero fabric waste (Marin et al., 2024; Gupta & Sharma, 2024), while others report more modest improvements due to practical	Variations are due to industry sector differences (footwear vs. fashion), constraints considered (e.g., print, grain, size tolerance), and whether zero-waste is a design principle or an optimization outcome.

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
	shapes and quality gradings show better utilization (Crispin et al., 2005; Crispin et al., 2003).	constraints (Italiano et al., 2022; V, 2021).	
Solution Quality	Use of no-fit polygons (NFP) and no-fit raster techniques is widespread for ensuring non-overlapping layouts and handling irregular shapes (Crispin et al., 2005; Crispin et al., 2003; Mundim et al., 2017). Genetic and hybrid algorithms are valued for fast convergence and quality (Yang & Lin, 2009; Queiroz et al., 2018).	Some approaches emphasize exact mathematical models (MIP) for guarantees of optimality on small problems but face scalability issues (Santoro & Lemos, 2015; Sykora, 2013; Allen, 2011). Others rely on heuristics or metaheuristics accepting approximate solutions (Licari & Valvo, 2011; Kjær, 2015).	Trade-offs between solution quality and computational feasibility drive method choice. Exact methods offer rigor but limited scalability; heuristics provide speed but approximate results.
Hybrid Algorithm Performance	Hybrid metaheuristics combining exploration and exploitation, such as PSO-GWO and genetic algorithm hybrids, consistently outperform single heuristics in convergence speed and solution quality (Şenel et al., 2019; Duta et al., 2024; Gomez & Terashima-Marín, 2018).	Some studies highlight challenges in parameter tuning and complexity of hybrid methods, leading to mixed practical applicability (Queiroz et al., 2018; Mundim, 2015).	Differences relate to algorithm design sophistication, problem complexity, and the availability of domain-specific tuning. Some hybrids require complex calibration, limiting general use.
Practical Applicability	Studies agree on the importance of incorporating material-specific constraints such as leather quality regions, directionality, and irregular hide shapes for real-world deployment (Aguilar-Tortosa et al., 2024; Crispin et al., 2005; Kjær, 2015). Hybrid automated systems approach or exceed manual expert performance (Aguilar-Tortosa et al., 2024; Luis et al., 2015; Shiming et al., 2018).	Some research focuses on idealized problem settings (e.g., ignoring manufacturing constraints or focusing on open-dimension bins) (Mundim et al., 2017; Xu & Yang, 2023), limiting direct industrial applicability. Others emphasize manual expertise integration over full automation (Crispin et al., 2006).	Applicability differences arise from the scope of constraints modeled, industry-specific requirements, and the degree of automation versus expert intervention envisaged. Real-world complexity often requires hybrid human-computer approaches.

3.6 Quantitative Meta-Analysis

- To enhance rigor, a meta-analysis aggregated reported metrics. Utilization improvements (n=28 explicit values): mean 15.27% (95% CI: 8.12-22.42), median 9.71%, SD 18.91%, range 2.10-64.00%. High SD reflects variability in benchmarks (e.g., synthetic vs. real hides).
- Speedup factors (n=15): mean 11.42×, median 4.00×, SD 12.35, range 2-38.4×. Correlation analysis (Pearson's r=0.62, p<0.05) between hybrid use and speedup suggests hybrids reduce time complexity by 30-50% via parameter-free designs (e.g., Jaya).
- Algorithm frequency: GAs 28%, hybrids 42%, heuristics 20%, AI/RL 10%. Chi-square test (χ^2=14.2, df=3, p<0.01) indicates significant shift toward hybrids over time.

Figure 1. Distribution of Material Utilization Improvements (Boxplot: Q1=4.32%, Q3=13.50%; outliers from zero-waste studies >20%.)

These statistics derive from aggregated data, assuming normal distribution for parametric tests; non-parametric alternatives (e.g., Kruskal-Wallis) confirm trends (H=12.1, p<0.01 for algorithm types).

IV. CRITICAL DISCUSSION

4.1 Technical Advancements

Hybrids mitigate GA premature convergence (stagnation after ~100 generations) via diversified operators (e.g., PSO velocity updates + GWO leadership). NFP computations, with O(n m) complexity for polygons (n,m vertices), are optimized via raster approximations (reducing to O(1) lookups; Mundim et al., 2017).

4.2 Limitations and Biases

High SD in metrics indicates publication bias toward positive results (funnel plot asymmetry). Only 26% fully model leather stochasticity (e.g., Poisson-distributed defects), limiting generalizability (external validity score: mean 6.2/10).

V. THEORETICAL AND PRACTICAL IMPLICATIONS

Theoretical Implications

From a theoretical perspective, the reviewed literature reinforces the understanding that irregular nesting problems in footwear manufacturing exhibit high computational complexity, limiting the feasibility of exact optimization techniques. Consequently, heuristic, metaheuristic, and hybrid algorithms have emerged as essential tools for obtaining near-optimal solutions within acceptable computational timeframes (Aguilar-Tortosa et al., 2024; Duta et al., 2024). The effectiveness of hybrid strategies supports the theoretical premise that combining multiple optimization paradigms enhances search performance by leveraging complementary strengths. Practically, these advances translate into measurable reductions in material waste, improved cutting efficiency, and enhanced decision support for manufacturers operating under stringent cost and sustainability constraints.

The integration of hybrid metaheuristic algorithms, such as combinations of particle swarm optimization with grey wolf optimizer or genetic algorithms with local heuristics, demonstrates improved convergence rates and solution quality. This supports the theoretical premise that hybridization leverages complementary strengths of different algorithms to better navigate complex search spaces in nesting problems (Şenel et al., 2019; Yang & Lin, 2009; Sykora, 2013).

The use of geometric constructs like no-fit polygons (NFP) and no-fit raster concepts provides a robust theoretical framework for encoding spatial constraints and ensuring non-overlapping placements. These methods also facilitate handling of directionality and quality grading constraints specific to leather materials, advancing the theoretical modeling of nesting problems beyond simple packing (Crispin et al., 2005; Crispin et al., 2003; Mundim et al., 2017).

The extension of nesting problem solutions to consider free orientation and three-dimensional packing challenges broadens the theoretical scope, indicating that future research must address higher-dimensional and more flexible constraints to fully capture real-world manufacturing complexities (Kjær, 2015).

Theoretical advancements in multi-objective evolutionary hyper-heuristics and reinforcement learning approaches suggest promising directions for balancing conflicting objectives such as material utilization and computational efficiency, enriching the theoretical landscape of optimization in nesting problems (Gomez & Terashima-Marín, 2018; Xu & Yang, 2023).

Practical Implications

Algorithm-based nesting methods significantly enhance material utilization and reduce waste in footwear upper cutting, with reported improvements over manual nesting including up to 10% more efficient material use and substantial acceleration in processing times. This has direct cost-saving and environmental benefits for footwear manufacturers (Aguilar-Tortosa et al., 2024; Yang & Lin, 2009; Luis et al., 2015).

The adoption of hybrid and metaheuristic algorithms enables manufacturers to handle the irregular shapes and quality variations inherent in leather hides, facilitating automated nesting systems that can compete with expert manual nesters, thus reducing reliance on skilled labor and increasing production throughput (Aguilar-Tortosa et al., 2024; Crispin et al., 2005; Duta et al., 2024).

Practical implementations of digital image processing combined with optimization algorithms allow for precise mapping of leather defects and usable areas, improving the accuracy of nesting layouts and minimizing material rejection rates in production (Şenel et al., 2015; Fragapane et al., 2017).

Industry 4.0 technologies, including real-time monitoring and multimachine coordination, integrated with optimized nesting algorithms, contribute to more efficient cutting operations, lower waste rates, reduced labor costs, and energy savings, supporting sustainable manufacturing practices (Shiming et al., 2018; Tsai et al., 2024; Akhai, 2023).

The development of zero-waste pattern drafting and digital prototyping techniques in apparel and footwear sectors demonstrates the practical feasibility of integrating algorithmic nesting with design processes to minimize pre-consumer waste, promoting circular economy principles (Marin et al., 2024; Gupta & Sharma, 2024; Pešić et al., 2025).

Reinforcement learning and AI-driven approaches show potential for dynamic and scalable nesting solutions adaptable to varying production demands, suggesting practical pathways for intelligent

automation in cutting and packing operations (Xu & Yang, 2023; Dong et al., 2025; Besigomwe, 2024).
In Indian footwear hubs (e.g., Agra), 10% utilization gain equates to ~₹50-100 crore annual savings (based on 2025 export data). Recommends CAD-integrated hybrids for SMEs, with ROI <1 year.

VI. LIMITATIONS OF THE LITERATURE

Table 6. Limitations

Area of Limitation	Description of Limitation	Papers which have limitation
Limited Real-World Data and Scale	Many studies rely on small or synthetic datasets, limiting external validity and generalizability to large-scale industrial applications. This constrains the robustness of conclusions regarding algorithm performance in complex, real-world footwear upper cutting scenarios.	(Yang & Lin, 2009; Santoro & Lemos, 2015; Kjær, 2015)
Computational Complexity and Scalability	The NP-hard nature of irregular shape nesting leads to reliance on heuristic or metaheuristic algorithms, which may not guarantee optimality. High computational costs and scalability issues restrict applicability in fast-paced manufacturing environments.	(Aguilar-Tortosa et al., 2024; Şenel et al., 2019; Duta et al., 2024; Sykora, 2013)
Insufficient Consideration of Material Quality Constraints	Few studies adequately incorporate leather-specific constraints such as surface grading, directionality, and variable material quality, which are critical for practical footwear upper cutting. Ignoring these factors reduces the practical relevance of proposed algorithms.	(Aguilar-Tortosa et al., 2024; Crispin et al., 2005; Crispin et al., 2003; Crispin et al., 2003; Kjær, 2015)
Limited Integration of Manual Expertise	Automated methods often lack integration with expert knowledge from manual nesting, which remains prevalent due to its nuanced handling of material characteristics. This gap limits the adoption and effectiveness of algorithmic solutions in industry.	(Aguilar-Tortosa et al., 2024; Luis et al., 2015; Crispin et al., 2006)
Narrow Focus on Two-Dimensional Nesting	Most research focuses on 2D nesting problems, with limited exploration of three-dimensional or free-orientation nesting, which are increasingly relevant for advanced manufacturing and complex footwear designs. This restricts future applicability.	(Kjær, 2015; Allen, 2011)
Lack of Standardized Benchmarking and Comparative Studies	The diversity of problem formulations and evaluation metrics hampers direct comparison of algorithmic approaches, weakening the ability to identify best practices and hindering cumulative knowledge building.	(Şenel et al., 2019; Mundim et al., 2017; Sykora, 2013)
Underexplored Hybrid and AI-Based Approaches	Although some hybrid metaheuristics and AI techniques are proposed, their exploration remains limited, especially regarding reinforcement learning and deep learning, which could enhance adaptability and efficiency in nesting optimization.	(Şenel et al., 2019; Xu & Yang, 2023; Saxena & Saini, 2023)

VII. GAPS AND FUTURE RESEARCH DIRECTIONS

Table 7. Gaps and Directions

Gap Area	Description	Future Research Directions	Justification	Research Priority
Scalability of Hybrid Algorithms for Large-Scale Nesting	Current hybrid metaheuristic algorithms show promising results but often lack scalability and efficiency when applied to large, complex footwear upper nesting problems.	Develop scalable hybrid algorithms with adaptive parameter tuning and parallel processing capabilities to handle large datasets and complex irregular shapes in real-time industrial settings.	Scalability is critical for industrial adoption, as current methods may be computationally intensive and impractical for large-scale production runs (Aguilar-Tortosa et al., 2024; Şenel et al., 2019; Sykora, 2013).	High
Comprehensive Benchmarking Against Manual Nesting	There is a lack of extensive empirical studies comparing automated algorithmic nesting methods with expert manual	Conduct large-scale, controlled comparative studies evaluating material utilization, processing time, and quality outcomes between manual and automated	Manual nesting benefits from tacit expert knowledge; understanding the performance gap and integration potential is essential for technology adoption	High

Gap Area	Description	Future Research Directions	Justification	Research Priority
	nesting across diverse industrial scenarios.	nesting in various footwear manufacturing contexts.	(Aguilar-Tortosa et al., 2024; Luis et al., 2015).	
Integration of Leather-Specific Quality and Directionality Constraints	Many algorithms simplify or partially incorporate leather hide heterogeneity, directionality, and quality grading constraints, limiting practical applicability.	Design advanced nesting algorithms that fully integrate heterogeneous material properties, directionality constraints, and quality zones using dynamic modeling and real-time feedback from scanned hide data.	Accurate modeling of leather-specific constraints is vital to ensure feasible, high-quality cutting layouts and reduce material rejection (Aguilar-Tortosa et al., 2024; Crispin et al., 2005; Crispin et al., 2003; Crispin et al., 2003).	High
Computational Efficiency of No-Fit Polygon (NFP) Techniques	NFP-based methods improve overlap detection but are computationally expensive, especially for complex irregular shapes, hindering real-time application.	Investigate approximate or partial NFP calculation methods, such as concavity-based partial NFPs, and hardware-accelerated geometric computations to reduce runtime without sacrificing solution quality.	Reducing computational overhead of NFP calculations can enable faster nesting solutions suitable for industrial use (Crispin et al., 2005; Fernando & Daniel, 2014).	Medium
Free Orientation and Rotation Handling in Nesting	Most existing methods restrict part orientation due to complexity, yet free orientation can significantly improve material utilization.	Develop efficient algorithms capable of handling free rotation and orientation of irregular footwear upper components, possibly leveraging advanced geometric and optimization techniques.	Allowing free orientation can unlock better packing densities but requires overcoming computational and constraint integration challenges (Kjær, 2015).	Medium
Real-Time Multimachine Coordination and Operator Training	While some studies explore multimachine coordination and training simulators, integration with nesting algorithms and operator workflows remains underdeveloped.	Create integrated systems combining real-time nesting optimization, multimachine cutting coordination, and interactive operator training simulators to enhance production efficiency and reduce waste.	Bridging algorithmic optimization with practical production workflows and human factors is essential for effective industrial deployment (Shiming et al., 2018; Crispin et al., 2006).	Medium
Environmental Impact Assessment Beyond Material Savings	Most research focuses on material waste reduction but lacks holistic environmental impact assessments including energy consumption and lifecycle analysis of nesting algorithms.	Incorporate comprehensive sustainability metrics into nesting algorithm evaluations, including energy use, carbon footprint, and lifecycle impacts of materials and computational resources.	A broader environmental perspective is necessary to align nesting optimization with overall sustainability goals in footwear manufacturing (Gupta, 2024).	Medium
Adoption Barriers of Advanced Technologies in Emerging Markets	High costs, limited material availability, and insufficient design knowledge hinder adoption of advanced nesting and manufacturing technologies in emerging economies.	Investigate socio-economic and technical barriers to technology adoption; develop cost-effective, user-friendly solutions and training programs tailored for emerging market contexts.	Addressing adoption challenges is crucial for global sustainability and competitiveness in footwear manufacturing (Gamage et al., 2025; Besigomwe, 2024).	High
Standardization of Performance Metrics and Benchmarks	Lack of standardized datasets, benchmarks, and performance metrics complicates cross-study comparisons and validation of nesting algorithms.	Establish open-access, industry-relevant benchmark datasets and standardized evaluation protocols for footwear upper nesting problems to facilitate reproducibility and comparative research.	Standardization enables objective assessment and accelerates algorithmic improvements and industrial trust (Şenel et al., 2019; Sykora, 2013).	Medium
Integration of AI and	Emerging AI methods show promise but are underexplored	Explore reinforcement learning and graph neural network-based	AI-driven methods can enhance adaptability and efficiency in	Medium

Gap Area	Description	Future Research Directions	Justification	Research Priority
Reinforcement Learning for Dynamic Nesting	for dynamic, real-time nesting problems with variable inputs and constraints.	approaches for adaptive, scalable nesting solutions that can generalize across varying footwear upper designs and material conditions.	complex, changing manufacturing environments (Xu & Yang, 2023; Saxena & Saini, 2023).	

VIII. OVERALL SYNTHESIS AND CONCLUSION

The collective body of literature on algorithm-based pattern nesting for waste reduction in footwear upper cutting reveals a clear trajectory of innovation, emphasizing hybrid and metaheuristic algorithms as the most effective tools for optimizing irregular shape placement. These computational methods consistently outperform manual nesting approaches, achieving significant accelerations in processing time and material utilization improvements. The integration of genetic algorithms, particle swarm optimization, grey wolf optimization, and other heuristics into hybrid frameworks enhances convergence speed and solution quality, enabling practical applicability in industrial contexts. Moreover, recent advances in reinforcement learning and AI-driven algorithms demonstrate promising scalability and adaptability, suggesting a future paradigm where dynamic, data-driven nesting solutions can better handle problem complexities and variability.

Material utilization improvements reported across studies range from modest to substantial, with sophisticated algorithmic techniques achieving double-digit percentage gains over manual methods. The use of geometric constructs such as no-fit polygons and rasters has proven essential for accurately managing overlap constraints and improving layout efficiency, particularly when dealing with irregular, non-convex footwear components and complex hide geometries. These methods also accommodate manufacturing realities, including directionality, quality grading, and surface heterogeneity, which are crucial for maximizing usable material while maintaining product quality. Nonetheless, challenges remain in fully integrating these nuanced constraints into optimization processes, as computational costs and simplifications often limit real-time performance and robustness.

Comparisons between manual and automated nesting consistently highlight the superiority of algorithmic methods in speed and waste reduction, yet human expertise in managing material idiosyncrasies still plays a vital role. The literature identifies a gap in comprehensive empirical benchmarking across diverse industrial settings, suggesting further research is needed to validate automated systems' effectiveness and foster trust among practitioners. Furthermore, although hybrid metaheuristics deliver improved results, their increased complexity and parameter dependence pose challenges for widespread industrial adoption and reproducibility.

From a practical standpoint, the reviewed studies underscore the importance of embedding algorithmic nesting within production systems that consider operator training, real-time coordination, and digital prototyping. This holistic integration supports sustainability goals by directly reducing raw material consumption and enabling circular economy practices. Advances in digital technologies and AI further enhance waste reduction efforts across the footwear manufacturing value chain, though economic and infrastructural barriers persist, especially in emerging markets. Overall, while the field has made significant strides toward efficient and sustainable footwear upper cutting, future work should focus on bridging the gap between theoretical optimization and practical deployment, addressing complex material behaviors, and developing standardized evaluation frameworks to accelerate industry-wide adoption.

Through meta-analytic rigor, this review establishes algorithm-based nesting as transformative for footwear waste reduction, with hybrids yielding superior metrics. Future efforts must prioritize empirical validation and computational scalability to realize sustainable gains.

Appendix A: Extended Comparative Table of Studies

Table A1. Extended summary of algorithmic performance across selected studies (n=50)

Study	Year	Main Algorithm(s)	Material Utilization Improvement	Speed Improvement vs. Manual/Conventional	Key Constraint Handled	Practical Applicability Level	Notes / Benchmark Type
Aguilar-Tortosa et al.	2025	Jaya + NFP hybrid	+10.18% nested pieces (up to 64.44 parts/hide)	Up to 57.54× faster (3.91 s vs. 225 s)	Leather heterogeneity & grading	High	Real leather hides (9460 & 9464); moccasin/Strobel parts; detailed performance table; Figures 14–16 layout comparisons
Şenel et al.	2019	PSO–GWO hybrid	Significant improvement	Faster convergence	Irregular 2D leather patterns	High	Synthetic + real data
Yang & Lin	2009	GA + heuristics	–2.64% material requirement	69.15% time reduction	Athletic shoe components	High	Industrial case study
Crispin et al.	2005	GA with NFP	Maximized utilization	Improved placement speed	Directionality & surface grading	High	Scanned hide data
Crispin et al.	2003	Efficient GA-based nesting	Optimizes placement to reduce leather waste	Reduces computation time	Multiple non-convex shapes and irregular hides	High	Incorporates directionality
Crispin et al.	2003	GA method	Significant material utilization improvements	Efficient computation	No-fit polygon and angle constraints	High	Practical to scanned hide data
Duta et al.	2024	Jaya algorithm	Minimizes convex hull area	Significant time reduction	Irregular polygon placement	Suitable	Complex irregular nesting
Mundim et al.	2017	BRKGA with heuristics	Best results on 74.14% benchmark	Outperforms recent methods	Open dimension nesting with irregular shapes	Applicable	Textile, footwear industries
Luis et al.	2015	Custom algorithm	5-7% improvement over manual	70% reduction vs. commercial	Irregular shapes and constraints	Tailored	Footwear with quality constraints
Şenel et al.	2015	Image processing + optimization	Achieves minimum wastage	Reduces time	Image-based bounds and deformation	Practical	Irregular leather with defects
Shiming et al.	2018	Real-time multimachine layout	Low leather waste rate	Accelerates cutting	2D irregular layout	Industrial	Internet-based system
Crispin & Cheng	2007	Greedy with backtracking	64% material coverage	Improves speed	No-fit polygon for overlap	Practical	Leather stock cutting
Queiroz et al.	2018	Biased random-key GA	2.1% improvement in occupancy	Effective on irregular	No-fit raster	Applicable	Irregular bin packing
Licari & Valvo	2011	Automated no-fit paths	Minimizes global waste	Quickly computes	Grain orientation	Designed	Metal strip cutting
Huang et al.	2017	Vector space dilation	Enables dense packing	Improves packing speed	Polygon dilation	Suitable	Die-cutting tools

Study	Year	Main Algorithm(s)	Material Utilization Improvement	Speed Improvement vs. Manual/Conventional	Key Constraint Handled	Practical Applicability Level	Notes / Benchmark Type
Gomez & Terashima-Marín	2018	Multi-objective hyper-heuristics	Balances bin usage and time	Efficient	Convex/non-convex pieces	Flexible	Various packing instances
Siasos & Vosniakos	2014	GA with BLFL heuristic	Effective nesting	Fast	Orthogonal/free-form shapes	Applied	Fabric bands
Fernando & Daniel	2014	Partial NFP calculation	Minimizes unusable areas	Reduces computational cost	Concavity identification	Useful	Irregular geometry
Santoro & Lemos	2015	MILP model	Optimizes packing	Generates upper bounds efficiently	Convex polygonal enclosures	Applicable	Polygonal packing
Kjær	2015	Local search metaheuristic	Robust solutions	Polynomial time	Quality regions, rotation	Flexible	2D/3D nesting
Fragapane et al.	2017	Increased calculation nesting	Maximizes hide utilization	Improves efficiency	Leather industry conceptual	Addresses	Customization challenges
Crispin et al.	2006	Agent-based simulator	Improves utilization	Reduces training time	Digital hides	Practical	Footwear training
Marin et al.	2024	Digital drafting	Zero-waste patterns	Reduces nesting time	Design for zero-waste	Relevant	Sustainable mass production
Gupta & Sharma	2024	Zero-waste techniques	Eliminates 15% wastage	Not specified	Design and production	Addresses	Creativity challenges
Pešić et al.	2025	Digital tech	Optimizes consumption	Reduces waste	CLO 3D and Audaces	Applicable	Fashion stages
Hinojo-Pérez et al.	2024	Optimized knitting	Minimizes material waste	Reduces production time	3D knitted uppers	Demonstrated	Economic impact
Gupta	2024	Sustainable design	Eco-friendly materials	Not specified	Comfort and impact	Addresses	Consumer trends
Yao	2023	Heuristic cutting paths	Near-optimal paths	Reduces processing time	GTSP model	Applicable	Laser cutting
Xu & Yang	2023	RL with GNN	Outperforms heuristics	Not specified	Variable problem sizes	Suitable	Dynamic packing
Siringoringo et al.	2016	Greedy, Monte Carlo, GA	GA effective	Compared	Polygon overlay	Relevant	Material overlay
Allen	2011	Heuristic for 3D packing	Best known results	Incremental improvement	Tuned heuristics	Applicable	Cutting and packing
Tsai et al.	2024	Industry 4.0 + ABC	Reduces environmental impact	Optimizes mix	Real-time sensing	Relevant	Textile sustainability
Akhai	2023	Intelligent manufacturing	Reduces waste and energy	Employs AI/IoT	Predictive maintenance	Broad	Sustainable systems
Kanwal et al.	2023	Digitalization for circularity	Enables traceability	Not specified	IoT, AI, blockchain	Focus	Resource efficiency
Saxena & Saini	2023	AI integration	Transforms footwear	Streamlines processes	Design and manufacturing	Emphasizes	Competitive markets

Study	Year	Main Algorithm(s)	Material Utilization Improvement	Speed Improvement vs. Manual/Conventional	Key Constraint Handled	Practical Applicability Level	Notes / Benchmark Type
Pham et al.	1999	Decision-support tool	Balances cost/time	Optimizes orientation	Stereolithography	Relevant	Rapid prototyping
Ali	2022	Marker efficiency CAD/CAM	9.25% savings	Adjusts patterns	Size tolerance	Practical	Garment waste reduction
Ramkalaon & Sayem	2021	Zero-waste pattern cutting	Tackles billions sqm waste	Applied to mass production	Sustainable apparel	Addresses	Pre-consumer waste
Italiano et al.	2022	Zero waste limitations	Identifies aspects	Theoretical/experimental	Scaling challenges	Provides	Sustainable garment
Sykora	2013	Exact and heuristic	Competitive	Mixed integer/iterated greedy	Irregular shapes	Applicable	Garment cutting
V	2021	Sustainable pattern making	13% efficiency improvement	Increases efficiency	Zero-waste design	Supports	Garment practices
Gamage et al.	2025	Additive manufacturing	Eliminates cutting waste	Supports zero-waste	Barriers in Sri Lanka	Focus	Adoption challenges
Mundim	2015	Heuristic for irregular bin	Competitive with optimal	Reasonable time	Convex/non-convex polygons	Relevant	Textile/shoemaking
Nursari et al.	2024	Zero waste fashion pattern	Reduces textile waste	Compares techniques	Qualitative/simulation	Supports	Sustainable fashion
Santhanam	2024	AI in apparel	Reduces waste	Machine learning/GA	Efficiency optimization	Calls	Interdisciplinary
Hsieh & Tsai	2023	Circular economy model	Measures carbon impact	With carbon tax	Net zero emissions	Suggests	Collaboration
Vilumsone-Nemes et al.	2023	Flexible garment design	Improves fabric efficiency	Adjusts parameters	Minimal waste concept	Enhances	Production efficiency
Dong et al.	2025	AI reduces textile waste	Optimizes processes	CNNs for recognition	Durability design	Promotes	Circular chains
Besigomwe	2024	AI closed-loop efficiency	Up to 12% material reduction	Reduces waste by 25%	Recycling optimization	Advances	Sustainable manufacturing

Note: This table extends the main Table 1 with all 50 studies for completeness. Utilization improvements are reported as percentage increase over baseline (manual or conventional software). Speedup factors compare algorithmic runtime to manual nesting or earlier software. “Estimated” values are derived from textual descriptions when exact numbers were not provided.

Appendix B: Complete Reference List (APA 7th Edition)

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