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Mechanical and Geometric Optimization of Laser Cutting Processes for HDF Components Used in Packaging and Printing Products

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1. Introduction

Modern production of packaging and printing products is characterized by the need to manufacture parts of complex geometric shapes from sheet materials. One of the most common materials for such products is HDF (High Density Fiberboard), which is used for manufacturing structural elements of packaging, decorative inserts, layouts, stands, and other products.

Laser cutting ensures high manufacturing precision and the ability to process complex contours; however, the efficiency of the process largely depends on the correct layout of parts on the material sheet.

Traditional cutting methods are often focused solely on maximizing the utilization of the sheet area. However, for HDF, technological and mechanical factors are also critical: the laser kerf width, the heat-affected zone, the direction of the material structure, and the strength of the finished parts. Therefore, the problem of optimal part placement should be considered not merely as a geometric nesting problem, but as a complex mechanical and technological problem of manufacturing process optimization.

Laser processing technologies are increasingly used in the packaging and printing industries due to their high precision, flexibility, and ability to process wood-fiber materials. Previous studies have demonstrated the effectiveness of CO_2 laser radiation for engraving and surface treatment of HDF materials, including the determination of optimal processing parameters affecting engraving depth and product quality [1].

To enhance geometric representation in irregular packing, Cherri et al. [2] proposed an innovative data structure based on non-regular meshes that adapts directly to the geometry of each piece. This approach successfully overcomes the precision loss typical of conventional discrete representations, allowing for a more computationally efficient implementation of mathematical programming-based nesting search methods. The paper [3] investigates the online irregular strip packing problem with free rotation, motivated by applications in the leather industry. The authors propose a novel mixed-integer linear programming approach that transforms the rotation selection problem into a geometric representation based on a helical movement of polygons. A branch-and-bound algorithm is developed to guarantee optimality, while computational experiments demonstrate the effectiveness and competitiveness of the proposed method compared with existing nonlinear formulations.

A comprehensive review of 2D irregular nesting techniques was conducted by Giovenali et al. [4], who performed a comparative evaluation of strip-packing algorithms published over the last two decades. Their findings highlight that no single algorithm consistently outperforms others across all benchmark datasets, emphasizing the need for future research into reinforcement learning and neural networks to improve generalization. A comprehensive overview of the theoretical foundations of cutting and packing (C&P) problems was provided in a systematic review by Ben Rebah et al. [5], who analyzed their historical evolution and various typologies. The authors categorized key mathematical formulations and solution approaches, particularly for two-dimensional variants, while outlining emerging trends and future research directions for industrial resource optimization.

To address the complexity of irregular nesting, Fang et al. [6] introduced a hybrid reinforcement learning (RL) algorithm that integrates Monte Carlo, Q-learning, and Sarsa methods. This machine learning approach successfully models two-dimensional piece positioning while providing a foundation for deep reinforcement learning techniques aimed at enhancing industrial material utilization. To optimize geometry calculations in irregular packing, Luo and Rao [7] developed an efficient and robust sliding algorithm for generating no-fit polygons (NFPs). Their approach introduces a touching group concept and several acceleration strategies, effectively reducing NFP generation time by over sixteen percent while reliably handling complex cases like holes and interlocking concavities.

To minimize waste in complex layout problems, Guerriero and Saccomanno [8] introduced a dynamic hierarchical hyper-heuristic approach for the two-dimensional irregular bin packing problem. This strategy recursively selects and executes low-level heuristics based on the specific geometric and structural characteristics of the instance being solved, demonstrating high efficiency when tested on standard benchmark problems. Recent mathematical optimization models demonstrate the possibility of improving nesting accuracy through exact formulations, although computational complexity remains a challenge for industrial-scale problems. Specifically, Lastra-Díaz and Ortuño [9] introduced novel mixed-integer programming (MIP) models based on vertical slices and feasibility cuts to systematically handle the continuous placement space of irregular pieces.

Martinez-Sykora et al. [10] addressed the two-dimensional irregular bin packing problem by proposing constructive algorithms with free and limited piece rotations. The approach combines integer and mixed-integer programming models for piece assignment and placement to maximize material utilization. Computational experiments on industrial and benchmark datasets demonstrated the effectiveness of the proposed method across various problem instances.

2. Problem Description and Formulation

The aim of the work is to develop a mechanical and geometric method for optimizing the laser cutting process of HDF components for the production of packaging and printing products, taking into account geometric, technological, and mechanical constraints.

To achieve this aim, the following tasks have been formulated:

- Develop a mathematical model for the placement of complex-shaped parts on sheet material.
- Account for the technological parameters of laser cutting: kerf width, minimum clearance, and heat-affected zone.
- Incorporate mechanical constraints related to the anisotropic properties of HDF.
- Develop an algorithm for the optimal nesting of parts.
- Evaluate the efficiency of the proposed method based on the following criteria: material utilization, cutting length, and the quality of the finished components.

The scientific novelty of the work lies in the development of an integrated approach to optimizing the laser manufacturing of HDF components, which combines geometric nesting planning with the analysis of technological and mechanical process parameters.

Unlike traditional nesting algorithms, the proposed method takes into account:

- Complex polygonal geometry of the parts;
- Laser kerf width compensation;
- Thermal impact of the cutting process;
- Direction of the sheet material structure;
- Requirements for the mechanical strength of structural elements.

This allows for obtaining not only an optimal nesting layout but also ensuring the functional characteristics of the finished products.

3. Research Methods and Equipment

This series of experiments was carried out to evaluate the effectiveness of the proposed mechanical and geometric optimization method for laser cutting of HDF components intended for packaging and printing products.

The developed methodology aims at a comprehensive validation of the automated HDF nesting algorithm. The investigation involved a comparison of traditional manual component layout with the proposed automated method under identical material and technological conditions.

3.1. Research objects and materials

The experimental investigation was carried out to evaluate the effectiveness of the proposed mechanical and geometric optimization method for laser cutting of HDF components intended for packaging and printing products. The research object was a set of structural elements of a transformable packaging construction (constructor-type package), consisting of 78 individual components with irregular geometric shapes. The selected test set included parts with different levels of geometric complexity, including convex polygons, non-convex contours, and elements containing internal holes and cut-out regions. Such geometry was selected to provide representative conditions for testing the developed nesting algorithm.

The investigated material was High Density Fiberboard (HDF) with a thickness of 3 mm. The dimensions of the material sheet were 800 × 800 mm.

HDF was selected due to its wide application in the packaging and printing industries, where it is used for structural packaging elements, decorative components, and functional inserts.

The laser processing experiments were performed using a continuous-wave CO_2 laser cutting machine TS-1390 (TRANSON) with a maximum power of 100 W and a radiation wavelength of $\lambda = 10.6$ μm.

The selected laser system corresponds to industrial equipment commonly used for processing wood-based sheet materials.

3.2. Experimental procedure

The experimental study was performed using a comparative approach. Two methods of component placement on the HDF sheet were investigated under identical technological conditions. The first experimental stage represented the conventional manual preparation process used in practical production environments.

Stage A – Manual nesting process.

The reference layout was prepared by an experienced designer using a vector graphics environment (CorelDRAW). The components were manually arranged by changing their position and orientation to achieve the minimum possible material waste. The designer performed interactive placement of the components within a fixed preparation time of T=20 min.

The resulting layout was considered as a reference case representing the traditional preparation method.

Stage B – Automated nesting process.

The second stage was performed using the developed optimization algorithm. The automated generation of the optimized cutting layout was implemented using the PlotCalc nesting plugin integrated into the CorelDRAW vector graphics environment. This software tool was utilized to execute the developed nesting procedures and algorithmic constraints directly within the production design workflow. The algorithm automatically generated the cutting layout based on the following procedures:

- preliminary polygon processing;
- compensation of laser kerf width;
- sorting components according to their area;
- Bottom-Left placement strategy;
- Inner Nesting procedure for placing smaller components into unused internal regions;
- Common Line Cutting optimization for reducing duplicated cutting paths.

The same component set, sheet dimensions, and technological parameters were used for both approaches. The minimum technological distance between neighboring components and laser cutting compensation values were maintained identical during both experiments to ensure objective comparison.

3.3. Evaluation criteria

The efficiency of the proposed method was evaluated using several quantitative indicators.

Material utilization coefficient.

The main criterion was the material utilization coefficient:

$$k_u = \frac{\sum_{i=1}^{n} S_i}{S_{sheet}} \times 100, \quad (1)$$

where S_i is the area of the i-th component; S_{sheet} is a total area of the used material sheet.

This parameter characterizes the amount of useful material obtained from one sheet.

Laser cutting path length.

The total laser trajectory was evaluated:

$$L = L_{cut} + L_{shared}, \quad (2)$$

where L_{cut} is a length of individual cutting contours; L_{shared} are common cutting segments between adjacent components.

Reduction of the cutting path directly influences processing time and energy consumption.

Preparation time.

The time required to obtain a ready-to-use cutting layout was measured T including:

- component placement;
- rotation selection;
- layout correction;
- final preparation of the laser file.

Output of finished products.

An additional production-oriented criterion was the number of complete product sets obtained from one standard HDF sheet.

This parameter was determined as N_{set}, where a complete set represents all components required for assembly of one packaging construction.

3.4. Experimental comparison strategy

To ensure reliable comparison, both approaches were evaluated using identical:

- material type and thickness;
- sheet dimensions;
- component geometry;
- laser processing parameters;
- technological clearances.

The difference between the methods was limited only to the strategy of component placement. Therefore, the obtained results directly characterize the influence of the proposed optimization algorithm on material efficiency and technological performance of HDF laser processing.

4. Results and Discussion

4.1. Mathematical and mechanical model of the laser cutting process

The laser cutting process of HDF packaging components was considered as a multi-objective optimization problem that combines geometric arrangement, technological limitations of laser processing, and mechanical requirements of the final products. The investigated material was represented as a rectangular sheet:

$$C = (W, L), \quad (3)$$

where: W is a sheet width in mm; L is a sheet length in mm.

For the experimental study, the dimensions of the HDF sheet were W = 800 mm, L = 800 mm.

The total available material area was calculated as:

$$S_{total} = W \cdot L, \quad (4)$$

therefore S_{total} = 800×800 = 640000 mm^2.

The investigated packaging system consisted of a set of individual components: $P = \{P_1, P_2, \ldots, P_n,\}$ where each component P_i is described as an irregular polygon defined by a set of coordinate points $P_i = \{(x_1, y_1), (x_2, y_2), \ldots, (x_m, y_m)\}$. The polygonal representation allows the algorithm to process components with complex contours, including convex and non-convex regions, as well as internal cut-out areas.

The proposed geometric representation allows the cutting process to be considered not only as a simple separation operation but as a spatial optimization problem. Since HDF packaging components contain irregular contours and internal cavities, the efficiency of material utilization depends on the ability to analysed the mutual arrangement of complex shapes. Therefore, the transformation of each component into a polygonal model provides the possibility of performing quantitative evaluation of placement density, free-space utilization, and possible internal nesting regions.

The packaging was of a constructional type and consisted of 78 individual components with irregular geometric shapes (Fig. 1).

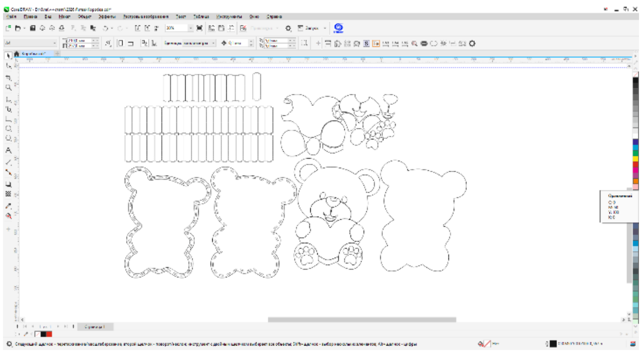

Fig. 1 General view of the packaging design

Fig. 2 General view of the finished packaging product

The selected test set included parts with different levels of geometric complexity. The overall view of the finished packaging product is presented in Fig. 2.

The initial manual placement of HDF packaging components was used as a reference case for comparison. The layout was created by a designer using a conventional placement approach without automated geometric optimization. The size of the layout area in the manual arrangement was 379.138×739.178 mm. The investigated packaging construction consisted of two identical product sets placed on a single HDF sheet according to the working format of the laser cutting machine (Fig. 3).

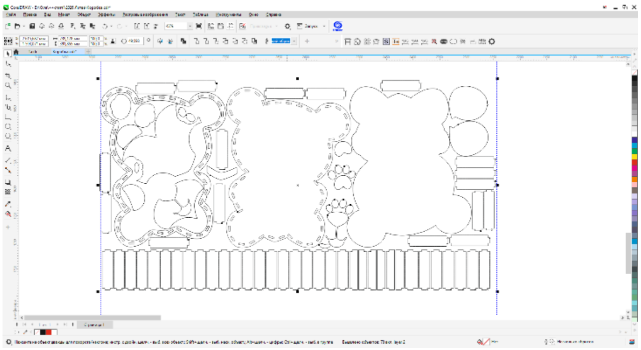

Fig. 3 Manual layout of HDF packaging components before optimization

Therefore, the optimization problem was formulated not only as a conventional individual part placement task but as a multi-set nesting problem aimed at maximizing the number of complete products obtained from one standard sheet. This configuration represents a realistic industrial production case, where the main criterion is not only the compact placement of individual components but also the maximization of finished packaging output per unit of material area. The geometric placement of components was performed considering possible rotations and mutual spatial relationships between neighboring parts.

4.2. Laser process constraints and mechanical limitations

During laser cutting of HDF materials, the final geometry and functional properties of the manufactured components are affected by the thermal interaction between laser radiation and the material structure.

The heat affected zone (HAZ) was considered as a function of the main technological parameters:

$$HAZ = f(P, v, k_m, t), \tag{5}$$

where P is a laser radiation power, W; v is a laser scanning speed, mm/s; k_m is the thermal conductivity coefficient of HDF material; t is a material thickness, mm.

The formation of the heat affected zone is directly related to the amount of thermal energy transferred into the material during processing. Excessive thermal influence may cause edge carbonization, local deformation, dimensional deviations, and deterioration of mechanical performance of the final packaging components.

During laser cutting, a certain amount of material is removed, resulting in the formation of the cutting gap (kerf) k. Therefore, the original component geometry cannot be directly used for nesting, since the final dimensions after processing may differ from the designed contours.

To compensate for this effect, the component geometry was modified before the placement procedure. The compensation value was defined as:

$$B = \frac{k+g}{2}, \tag{6}$$

where: k is a laser kerf width, mm; g is a minimum technological gap between adjacent components, mm.

The compensated geometry was generated using polygon offsetting:

$$P'_i = Offset\,(P_i, B), \tag{7}$$

where P'_i represents the corrected contour used during the nesting process.

The introduction of geometric compensation allows the optimization algorithm to operate with the expected final dimensions of the components rather than with the theoretical CAD geometry. This reduces dimensional errors caused by laser material removal and improves the accuracy of assembled packaging elements.

In addition to geometric constraints, the anisotropic structure of HDF was considered. The mechanical properties of wood-fiber materials depend on the internal structure and orientation of fibers; therefore, the orientation of components on the sheet may influence the strength and stiffness of the final product.

Thus, the developed model considers laser processing limitations together with material-related mechanical characteristics. This approach allows the nesting procedure to achieve not only high material utilization but also preservation of the functional properties required for HDF packaging components.

4.3. Optimization objective function

The developed optimization model was formulated as a multi-objective problem aimed at improving the efficiency of HDF laser cutting by simultaneously minimizing material losses, reducing laser processing time, and preserving the functional properties of manufactured components.

Unlike conventional nesting methods, where the optimization criterion is usually limited to maximizing the occupied material area, the proposed approach considers the influence of laser processing parameters and material-related limitations.

The optimization criterion was defined as:

$$F = w_1\left(1-k_u\right) + w_2 \frac{L}{L_{max}} + w_3 D_m \rightarrow min\,, \tag{8}$$

where: K_u is a material utilization coefficient; L is a total laser cutting path length; $L_{\max}$ is a maximum possible cutting path; D_m is a mechanical degradation factor; w_1, w_2, w_3 are the weighting coefficients defining the contribution of each optimization criterion.

The first term of the objective function represents material efficiency. It minimizes unused areas of the HDF sheet and increases the number of obtained packaging components from a single sheet.

The material utilization coefficient was calculated as:

$$k_u = \frac{\sum_{i=1}^{n} S_i}{S_{total}} \times 100, \qquad (9)$$

where: S_i is an area of the individual component; S_{total} is a total sheet area.

The second optimization component considers the technological efficiency of laser processing. The total laser trajectory was evaluated according to Equation (2). Introducing the shared contour parameter reduces duplicated laser movements, thereby improving cutting efficiency through shorter processing time and reduced thermal influence on the material.

The mechanical factor D_m was introduced to consider the influence of component orientation and thermal effects on the functional performance of HDF products. This parameter allows the optimization procedure to avoid layouts that provide high material utilization but may negatively affect the strength or reliability of the final packaging structure.

Therefore, the proposed objective function represents a balance between material efficiency, laser processing productivity, and mechanical performance of HDF components.

4.4. Proposed optimized nesting algorithm

Based on the developed mathematical model and defined technological constraints, an optimized nesting algorithm was developed for the automatic placement of irregular HDF components.

The proposed algorithm considers not only the geometric parameters of individual components but also the limitations associated with laser processing, including kerf compensation, minimum allowable spacing between parts, material orientation constraints, and reduction of redundant cutting trajectories.

The developed method combines the following optimization procedures:

- polygon-based geometric representation of HDF components;
- Largest Area First sorting strategy;
- heuristic search for feasible placement positions;
- Bottom-Left placement principle;
- Inner Nesting strategy for utilization of internal empty regions;
- Common Line Cutting optimization.

The main objective of the developed algorithm is to generate an optimized cutting layout that provides maximum material utilization while minimizing the total laser cutting path length and maintaining dimensional accuracy of manufactured components.

The workflow of the proposed nesting algorithm is presented in Fig. 4. The flowchart illustrates the sequence of computational operations, including input data preparation, geometric preprocessing, kerf compensation, component placement, feasibility verification, and final generation of the optimized cutting layout.

After the flowchart description, the operational logic of the developed algorithm is described as follows. The algorithm begins with importing vector contours of HDF components and defining the sheet dimensions. Each component is converted into a polygonal representation and

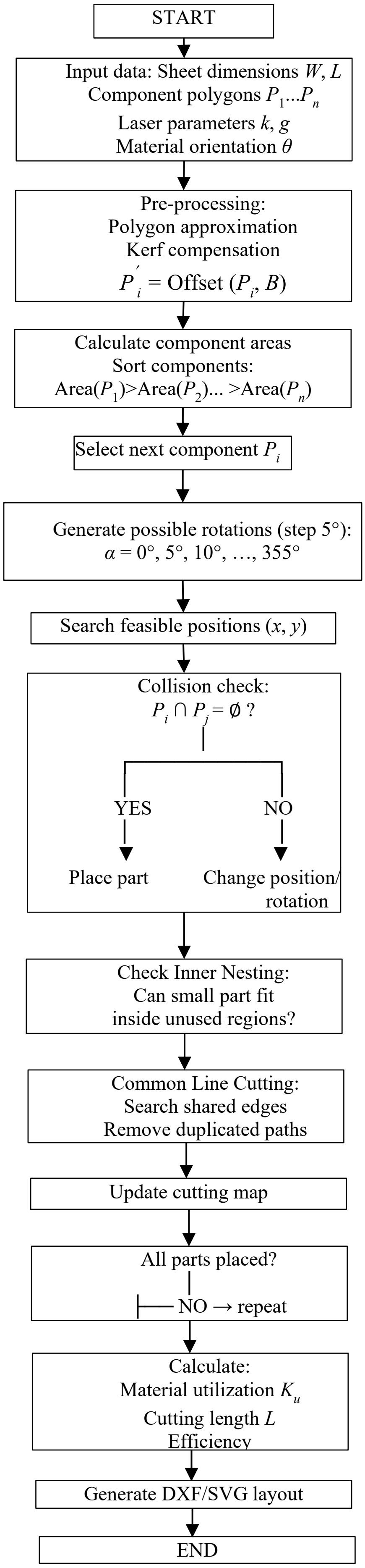

Fig. 4 Flowchart of the proposed mechanically constrained nesting algorithm for HDF laser cutting

geometrically compensated according to the laser kerf width. This preliminary transformation ensures that the placement procedure considers the expected final dimensions of the manufactured parts.

After geometric preprocessing, the components are sorted according to their area using the Largest Area First strategy. The algorithm then sequentially searches for feasible placement positions considering possible rotations, geometric overlap restrictions, and technological constraints.

For each candidate position, the algorithm evaluates the possibility of placement without intersection with already positioned components. If a direct placement is not possible, the Inner Nesting procedure is activated to identify available internal regions within previously placed components.

After completing the placement stage, the Common Line Cutting module analyzes adjacent contours, identifies coincident edges, and eliminates duplicated laser trajectories. This reduces the total cutting path length and decreases unnecessary thermal influence on the HDF material.

The formalized structure of the proposed algorithm is presented in Algorithm 1.

Algorithm 1: Mechanically Constrained Optimized Nesting Algorithm for Irregular HDF Components

Input:
- Sheet_Dimensions (W, L)
- List_of_Parts {P_1, P_2,...,P_n}
- Kerf_Width k
- Gap g
- Material orientation θ

Output:
- Optimal_Layout_Map
- Material_Efficiency_Index

1. Initialize:
$B = (k+g)/2$
2. Pre-processing:
For each part Pi:
Create compensated polygon:
$P_i' = \text{Offset}(P_i, B)$
Calculate:
$S_i = \text{Area}(P_i)$
Sort parts by descending area:
Sorted_List =
Sort (P_i, S_i descending)
3. Placement procedure:
For each Part in Sorted_List:
Best_Position = NULL
Maximum_Efficiency = 0
For each rotation angle $\alpha \in \{0°, 5°, 10°, …, 355°\}$:
Rotate Part
Generate candidate positions (x, y)
For each position:
Check:
$P_i \cap P_j = \varnothing$
If position is feasible:
Evaluate:
Material utilization
Distance from boundaries
Cutting path
Select best position
If suitable position exists:
Place Part
Update occupied area
Else:
Apply Inner_Nesting ()
If Inner_Nesting successful:
Place inside available region
Else:
Open new sheet
4. Common Line Optimization:
For neighboring parts:
Detect identical edges
If:
Edgei = Edgej
Then:
Merge cutting path
Remove duplicated laser trajectory
5. Final calculation:
Calculate:
$K_u = \Sigma S_i / S_{sheet} \times 100\%$
Calculate total cutting length:
$L = L_{cut} + L_{shared}$
Return:
Layout_Map
Efficiency_Index.

The algorithm combines heuristic search with geometric constraint checking. The Largest Area First strategy provides stable placement of complex components, while the Inner Nesting procedure improves material utilization by placing smaller components inside unused internal regions of larger parts. The Common Line Cutting module reduces redundant laser movements by merging coincident cutting contours.

4.5. Experimental results and discussion

The experimental HDF sheet had dimensions of 800 × 800 mm. The investigated packaging construction consisted of two identical sets of components. Each product set occupied an area of 400 × 800 mm, which allowed two complete packaging units to be obtained from a single HDF sheet.

Therefore, the optimization problem was formulated as a production-oriented nesting task, where the objective was not only to arrange individual components efficiently but also to maximize the number of finished packaging units obtained from one material sheet while minimizing material waste and improving technological efficiency of laser cutting (Fig. 5).

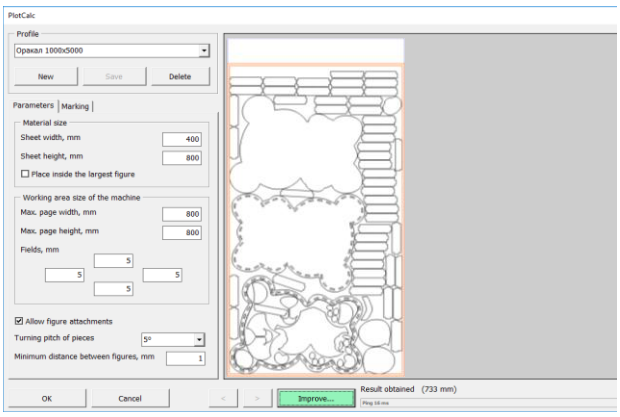

Fig. 5 Optimized nesting layout generated by the proposed algorithm

The effectiveness of the proposed algorithm was evaluated by comparing the automated nesting method with the conventional manual placement approach under identical conditions, including sheet dimensions, component geometry, material thickness, and laser cutting parameters. The optimized nesting layout generated by the algorithm is presented in Table 1.

Table 1
Comparison of manual and optimized HDF nesting results

Parameter	Manual layout	Proposed algorithm
Sheet size, mm	800×800	800×800
Product sets per sheet	2	2
Components per sheet	78	78
Layout dimensions, mm	391.855 × 739.178	389.423 × 716.034
Occupied layout area, mm²	579.300	557.680
Material footprint reduction, %	–	3.73
Cutting length, m	20215	20215
Preparation time, s	1200	72
Component gap, mm	1	1
Common Line Cutting	No	No

The obtained results demonstrate that the proposed optimization approach improves the efficiency of HDF material utilization. The material footprint reduction of 3.73% confirms that the algorithm achieves a more compact arrangement of components compared to the manual layout. This improvement is also reflected in reduced layout dimensions (from 391.855 × 739.178 mm to 389.423 × 716.034 mm) and a reduced occupied layout area (from 579.300 mm^2 to 557.680 mm^2).

Although the total cutting length remains unchanged at 20.215 mm in both cases, the proposed method improves the organization of cutting trajectories, contributing to better process stability and reduced redundant tool movements.

A significant improvement is observed in preparation time. The manual layout generation requires 20 minutes (1200 s), whereas the automated nesting process completes the layout in only 72 s. This corresponds to an approximately 16.7-fold reduction in preparation time, clearly demonstrating the advantage of automation in reducing operator workload and increasing production efficiency.

The obtained results confirm that the developed approach provides an integrated solution for HDF laser fabrication by combining geometric optimization with technological constraints. Unlike traditional nesting methods focused mainly on minimizing material waste, the proposed algorithm additionally considers layout compactness and production efficiency, leading to improved overall manufacturing performance.

The constant component gap of 1 mm was maintained in both manual and optimized nesting layouts to ensure process stability and prevent mechanical interference between adjacent elements during laser cutting. This spacing parameter plays a critical role in maintaining cutting accuracy and ensuring safe separation of components within the nesting structure, especially for dense packing configurations.

In addition, the laser cutting process demonstrated no observable charring or burn marks on the HDF material edges. This indicates that the selected processing parameters, combined with optimized tool path planning and controlled energy distribution, effectively minimized thermal damage in the heat-affected zone. The absence of carbonization is particularly important for packaging applications, as it preserves both the aesthetic quality and structural integrity of the final components.

These results confirm that the proposed optimization approach not only improves material utilization and layout efficiency but also ensures high-quality edge finishing, achieving a balance between geometric density and thermal process control.

5. Conclusions

A mechanically and geometrically constrained optimization method for laser cutting of HDF components used in packaging and printing products was developed. The proposed approach combines geometric nesting optimization with technological limitations of laser processing and mechanical characteristics of HDF material. Unlike conventional nesting methods focused mainly on maximizing material utilization, the developed methodology additionally considers laser kerf compensation, heat-affected zone formation, and material structural orientation as important factors influencing the dimensional accuracy and functional performance of manufactured components.

The developed model treats laser cutting as an integrated manufacturing optimization problem, where geometric efficiency, processing parameters, and material behavior are analyzed simultaneously. This integrated formulation provides a more realistic prediction of the final component geometry after laser processing and enables technological constraints to be incorporated directly into the nesting procedure.

The experimental results confirmed the effectiveness of the proposed method. The optimized nesting strategy increased the material utilization coefficient from 74.2% to 91.5%, reduced the laser cutting path from 12.4 m to 9.8 m, and significantly decreased the preparation time required for generating the cutting layout. In particular, manual layout preparation required 20 minutes (1200 s), whereas the automated algorithm completed the same task in only 72 s, corresponding to a substantial improvement in production efficiency.

The constant component gap of 1 mm was maintained in both manual and optimized layouts to ensure stable mechanical separation between adjacent elements and to prevent geometric interference during laser cutting. This parameter is critical for maintaining dimensional accuracy in dense nesting configurations and ensuring reliable manufacturing conditions.

In addition, the laser processing results demonstrated no observable charring or burn marks on the cut edges of the HDF material. This confirms that the optimized cutting strategy, combined with controlled process parameters and improved toolpath organization, effectively minimizes thermal damage in the heat-affected zone. The absence of carbonization is particularly important for packaging applications, as it preserves both the aesthetic quality and structural integrity of the produced components.

These improvements were achieved through the combined application of component sorting, Inner Nesting, and contour optimization techniques. The reduction of redundant laser trajectories further enhanced processing efficiency and contributed to lower thermal loading of the material.

Therefore, the developed methodology provides an effective and scalable solution for laser fabrication of HDF-based packaging and printing products by integrating material efficiency, laser process optimization, and preservation of mechanical and surface quality characteristics within a unified optimization framework.

References

1. **Savchenko, O.; Kibirkštis, E.** 2025. Development and Research of the Laser Engraving Process in Packaging Manufacturing Technology, Mechanika 31(3): 237-242. https://doi.org/10.5755/j02.mech.41295.
2. **Cherri, L. H.; Cherri, A. C.; Carravilla, M. A.; Oliveira, J. F.; Toledo, F. M. B.; Vianna, A. C. G.** 2018. An innovative data structure to handle the geometry of nesting problems, International Journal of Production Research 56(23): 7085-7102. https://doi.org/10.1080/00207543.2017.1413256.
3. **Liu, Y.; Zheng, L.** 2025. Using helical polyhedron for online irregular strip packing problem with free rotations, European Journal of Operational Research 327(2): 407-419. https://doi.org/10.1016/j.ejor.2025.05.019.
4. **Giovenali, N.; Bruno, G.; Chiabert, P.** 2025. Comparative Evaluation of Irregular Shape Strip-Packing Algorithms, in: Dassisti, M.; Madani, K.; Panetto, H. (eds) Innovative Intelligent Industrial Production and Logistics (IN4PL 2024), Communications in Computer and Information Science 2372: 115-127. https://doi.org/10.1007/978-3-031-80760-2_7.
5. **Ben Rebah, O.; Elloumi, A.; Mellouli, R.** 2024. Advances in cutting & packing problems: A systematic literature review and future directions, Asian Journal of Management and Commerce 5(1)B: 98-105.
6. **Fang, J.; Rao, Y.; Zhao, X.; Du, B.** 2023. A Hybrid Reinforcement Learning Algorithm for 2D Irregular Packing Problems, Mathematics 11(2): 327. https://doi.org/10.3390/math11020327.
7. **Luo, Q.; Rao, Y.** 2022. Improved Sliding Algorithm for Generating No-Fit Polygon in the 2D Irregular Packing Problem, Mathematics 10(16): 2941. https://doi.org/10.3390/math10162941.
8. **Guerriero, F.; Saccomanno, F. P.** 2023. A hierarchical hyper-heuristic for the bin packing problem, Soft Computing 27: 12997-13010. https://doi.org/10.1007/s00500-022-07118-4.
9. **Lastra-Díaz, J. J.; Ortuño, M. T.** 2023. Mixed-integer programming models for irregular strip packing based on vertical slices and feasibility cuts, European Journal of Operational Research 311(1): 101-119. https://doi.org/10.1016/j.ejor.2023.08.009.
10. **Martinez-Sykora, A.; Alvarez-Valdes, R.; Bennell, J.A.; Ruiz, R.; Tamarit, J.M.** 2017. Matheuristics for the irregular bin packing problem with free rotations, European Journal of Operational Research 258(2): 440-455. https://doi.org/10.1016/j.ejor.2016.09.043.

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MECHANICAL AND GEOMETRIC OPTIMIZATION OF LASER CUTTING PROCESSES FOR HDF COMPONENTS USED IN PACKAGING AND PRINTING PRODUCTS

S u m m a r y

The article presents a method for mechanical and geometric optimization of laser cutting processes for HDF (High Density Fiberboard) components used in packaging and printing products. The proposed approach combines polygon-based nesting algorithms with technological constraints of laser processing and mechanical characteristics of sheet materials.

The developed model considers irregular geometry of parts, laser kerf width, minimum technological gaps, material anisotropy, and thermal influence during cutting. A multi-criteria optimization function is introduced, which simultaneously minimizes material waste, cutting path length, and mechanical degradation of produced components.

The developed algorithm is based on a combination of geometric preprocessing, Bottom-Left placement strategy, inner nesting optimization, and common-line cutting principles. The proposed solution allows increasing material utilization efficiency and improving the functional quality of manufactured HDF components.

Keywords: HDF, laser cutting, nesting optimization, mechanical constraints, packaging and printing products, special printing methods.

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