

Cut Smarter, Move Less: A Hybrid Strategy for Laser Cutting Path Optimization

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ABSTRACT

Efficient extraction of small two-dimensional components from larger material sheets remains a recurrent and critical challenge in various manufacturing contexts. This task is categorized within the broader class of Cutting and Packing (C&P) problems. The present study focuses on a specific subproblem of cut path determination (CPD), namely the Laser Cutting Path Planning Problem (LCPP). The objective of the LCPP is to define an optimal sequence of cutting and non-cutting (gliding) head movements that minimizes the total time required to separate all parts. This article presents a hybrid approach for optimizing cutting paths in industrial layouts comprising multiple parts of varying shapes. The proposed method integrates spatial data structures (QuadTree), efficient search algorithms (KD-Tree), and minimum connection heuristics (MST) to reduce the total operation time. Assuming that tool displacements are significantly faster than actual cutting time, the strategy aims to minimize both the number of displacements and the total distance traveled. Experimental results on synthetic layouts and real-world applications validate the method's effectiveness in large-scale scenarios, demonstrating its practical applicability and computational efficiency gains.

KEYWORDS. Laser Cutting Path Planning (LCPP). Cutting Path Optimization. Manufacturing Optimization. Paper topics: MH – Metaheurísticas, POI – PO na Indústria

1. Introduction

Reducing production costs through efficient material cutting strategies is a common objective in manufacturing research. Following the optimization of the parts' layout (nesting), the next critical step is computing an efficient cutting sequence, a task known as the Cutting Path Determination Problem (CPDP) [Silva et al., 2019]. This work addresses the Laser Cutting Path Planning (LCPP) problem, a specialized form of CPDP that seeks to minimize the total operation time required to cut all parts in a layout.

The LCPP is closely related to the well-known Traveling Salesman Problem (TSP), a classical NP-hard problem [Dewil et al., 2016]. Consequently, heuristic and metaheuristic approaches are often essential in practice [Junior et al., 2023]. To address the complexity of layouts with hundreds or thousands of parts, we propose a hybrid strategy based on spatial data structures and routing algorithms. Our method uses QuadTrees for spatial decomposition [Samet, 2006], KD-Trees for local refinement, and a Minimum Spanning Tree (MST) for efficient inter-cluster connections [Cormen et al., 2009].

2. Problem Definition

In the Laser Cutting Path Planning (LCPP), the input consists of a layout and a cutting machine. The objective is to determine a sequence of movements for the machine head that cuts all parts in the shortest possible time. The head operates in two modes: cutting, with speed μ , and moving (gliding), with speed π . A solution must specify both the path and the mode for each segment.

Formally, the input is a set of m polygons P_i , not necessarily convex and placed in the plane without overlap. The focus is on the polygonal edges to be cut. Let $\mathcal{P}$ be the set of all edges of the polygons P_i . The traversal time of each path segment depends on the operational mode. Since the total length of the edges in $\mathcal{P}$ is fixed, the total time in cutting mode is a constant. The optimization challenge thus reduces to minimizing the total time in non-cutting mode by finding the shortest possible path for the machine head to travel between the cutting segments.

3. Proposed Hybrid Strategy

To address the complexity of the LCPP, we propose a modular hybrid strategy that re-frames the task from a monolithic optimization problem into a structured pipeline. The approach begins by organizing the spatial data to handle large and irregular layouts efficiently. For large-scale instances, a recursive QuadTree partitioning is employed to cluster spatially proximal parts, dividing the layout into manageable quadrants [Samet, 2006]. This hierarchical decomposition preserves local coherence and reduces the problem's overall complexity.

Following the spatial organization, a proximity graph is constructed where each polygon is a node and the edges represent the shortest possible gliding moves between them. To achieve this efficiently, a KD-Tree containing all vertices from all polygons is built, enabling nearest-neighbor searches in sublinear time. This process yields a complete, weighted graph where edge weights correspond to the optimal gliding costs. Subsequently, a Minimum Spanning Tree (MST) is computed on this graph to establish a globally optimal "skeleton" for the gliding path, dictating the high-level traversal order across the entire layout [Cormen et al., 2009].

The final, detailed traversal path is generated from this MST, treated as a "cutting tree," as shown in Figure 1. A recursive, depth-first traversal ensures full coverage while avoiding redundant passes, as shared edges are cut only once.

4. Results and Discussion

The algorithm was implemented in Python 3.12.7 and tested on a MacBook Pro with an Apple M4 processor. To ensure a fair validation, we used the benchmark instances from Amaro Junior et al. [2021], which are divided into two types: connected (C), where polygons may share

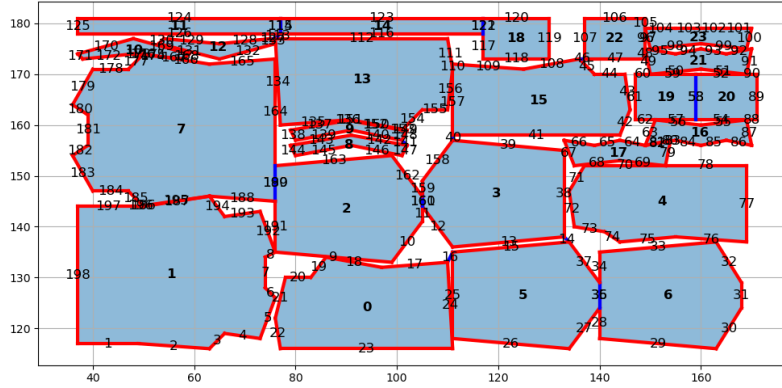


Figure 1: Final path generated by the hybrid strategy, showing cutting segments (red) and gliding moves (blue).

common edges, and separated (S), where they do not. The complete implementation and all experimental results are publicly available at Amaro Junior et al. [2025].

The proposed algorithm consistently achieved high-quality solutions. As shown in Table 1, our heuristic produced significantly improved solutions for several complex instances, with objective function (FO) gains of up to 27%. The most significant contribution is its exceptional computational efficiency. While the state-of-the-art method [Amaro Junior et al., 2021] reports execution times up to 300 seconds, our approach solved the most complex instance in approximately 2.61 seconds.

Table 1: Selected results comparing with Amaro Junior et al. [2021]

INSTANCE	TYPE	TIME (s)	FO	FO Amaro Junior et al. [2021]	GAP
trousers	C	2.607	231.91	307.56	0.25
trousers	S	1.441	257.89	354.94	0.27
inst_art_26pol.h	C	1.284	128.41	157.02	0.18
inst_art_26pol.h	S	1.203	180.56	218.27	0.17
blaz1	C	0.027	153.98	154.29	0.00
dighe2	C	0.038	57.42	53.88	-0.07

5. Conclusion

This paper presented a novel, hybrid methodology for solving the LCPP, combining spatial data structures with principles from graph theory to yield a scalable and high-performing cutting path planner. Unlike monolithic global optimization techniques, which often become intractable as layout complexity increases, our modular strategy enables hierarchical problem handling, preserving geometric locality and reducing unnecessary traversal.

The empirical results underscore the method's practical effectiveness, consistently producing high-quality cutting sequences. Performance gains of up to 27% in the objective function value were observed, accompanied by a drastic, orders-of-magnitude reduction in computation time. These findings highlight not only the algorithm's efficiency but also its potential to generate substantial operational benefits in industrial contexts, such as tangible savings in energy consumption,

machine wear, and production cycle time. The robustness and speed of the method make it well-suited for integration into high-throughput manufacturing pipelines.

Future research will explore dynamic instance decomposition techniques and the incorporation of adaptive metaheuristics to enhance solution quality. Additional investigations will also focus on extending the model to handle multi-head cutting machines, thermal constraints, and dynamic part sequencing based on evolving production priorities.

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