IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.311 ⁘ Peer-reviewed & Refereed journal ⁘ Vol. 13, Issue 3, March 2026

DOI: 10.17148/IARJSET.2026.133106

INTELLIGENT WEB-BASED METAL SHEET OPTIMIZATION SYSTEM

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Abstract: Efficient material utilization is a critical challenge in sheet metal manufacturing industries, particularly in CNC-based cutting environments. Traditional manual nesting approaches often result in suboptimal placement of irregular parts, leading to excessive material wastage, higher production costs, and increased operational time. This project presents an intelligent web-based sheet metal optimization system that automates geometric extraction and implements AI-driven heuristic nesting algorithms to improve sheet utilization efficiency. The proposed system accepts DXF (Drawing Exchange Format) files as input, extracts geometric entities, computes bounding boxes, and performs collision-free placement using optimized space partitioning logic. The AI-based nesting engine arranges irregular shapes within predefined sheet dimensions while dynamically allocating additional sheets when necessary. The system provides real-time visualization of part placement, material efficiency computation, and detailed wastage reports. Experimental validation demonstrates significant improvement in sheet utilization and reduction in material waste compared to conventional manual nesting practices. The framework is particularly beneficial for small and medium scale industries.

Keywords: Web-Based Manufacturing Optimisation, Sheet Metal Nesting, DXF Geometry Extraction, Heuristic Optimisation, Irregular Shape Packing, Material Utilisation, and Collision Detection.

I. INTRODUCTION

The need for intelligent systems that can improve operational efficiency has grown dramatically as a result of the quick development of digital manufacturing and industrial automation. The arrangement of components on raw material sheets directly affects the total amount of material used in cutting operations, which are typically carried out by CNC machines in sheet metal industries. Ineffective part placement frequently results in higher procurement costs, longer production cycles, and excessive scrap generation.

Nesting is typically done by hand or with semi-automated equipment that greatly depends on the knowledge and experience of the operator. In addition to being time-consuming, these traditional methods are very vulnerable to human error, particularly when handling irregular geometries and high production volumes that call for constant accuracy and efficient material use. Two-dimensional irregular shape packing, a computationally challenging and NP-hard optimization problem, is closely related to the nesting problem.

This inherent complexity makes it computationally impractical to determine the exact optimal solution when dealing with large datasets or a large number of irregular components. In order to obtain near-optimal solutions in a reasonable amount of computational time, heuristic and approximation-based techniques are frequently used in industrial applications. Intelligent, web-enabled optimization systems that combine computational geometry, artificial intelligence methods, and interactive visualization capabilities to efficiently automate and streamline manufacturing processes have become increasingly popular with the advent of Industry 4.0 technologies.

The project described in this paper suggests a web-based intelligent sheet metal nesting system that automates every step of the process, from uploading DXF files to creating efficiency reports. Within a single framework, the system combines dynamic multi-sheet allocation, AI-based heuristic placement strategies, automated geometry extraction, and collision detection mechanisms. The suggested system is lightweight and accessible via a standard web interface, in contrast to traditional CAD/CAM-based nesting solutions. It is especially made to be financially feasible for small and medium-sized manufacturing businesses.

II. LITERATURE REVIEW

In the manufacturing sector, sheet metal nesting is crucial because it maximizes material utilization and lowers production waste. In order to minimize the amount of unused space, several irregular shapes are arranged within a fixed sheet area during the nesting process. This issue is frequently represented as a two-dimensional irregular packing problem, which

DOI: 10.17148/IARJSET.2026.133106

falls under the category of NP-hard optimization problems and is computationally challenging. As the number of parts increases, it becomes more challenging to find an exact optimal solution due to this complexity.

Numerous optimization strategies have been developed to increase nesting efficiency in order to address this problem. Because heuristic and metaheuristic methods can yield near-optimal solutions in a reasonable amount of time, they are frequently employed. These techniques maximize material utilization by analyzing the geometry of the parts, identifying collisions between shapes, and strategically positioning them within the sheet. To further enhance nesting system performance, contemporary research also uses geometric algorithms, computational intelligence, and dynamic nesting strategies.

III. RELATED WORKS

The sheet metal nesting problem has been thoroughly examined in the fields of computational geometry and operations research due to its practical significance in manufacturing industries. Early research focused on deterministic geometric approaches that prioritized geometric accuracy and structured placement logic, such as Bottom-Left placement strategies and No-Fit Polygon techniques. When applied to large-scale industrial scenarios with numerous irregular components, these methods frequently encountered computational scalability issues.

Researchers started incorporating metaheuristic optimization methods, such as Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, and Ant Colony Optimization, as computing power increased. Since 2018, studies have concentrated more on hybrid optimization frameworks, which combine heuristic and evolutionary algorithms with geometric preprocessing to increase accuracy and efficiency. These hybrid models are appropriate for industrial applications because they aim to strike a balance between high-quality placement results and computational speed.

Additionally, by learning from past datasets, machine learning and reinforcement learning-based techniques have become viable substitutes for forecasting near-optimal nesting patterns. Adaptive decision-making and better optimization over time are made possible by such methods. But even with their theoretical benefits, a lot of sophisticated AI-driven techniques still need a lot of processing power and are computationally demanding.

Automated nesting solutions for industrial applications are currently available through commercial CAD/CAM systems; however, these platforms usually require specialized hardware infrastructure and high licensing fees. The creation of lightweight optimization platforms that can function in browser-based environments has been made easier by recent developments in web technologies and open-source computational libraries. Accurately handling irregular geometries, putting strong collision detection mechanisms in place, controlling computational complexity, and processing large DXF files quickly are still difficult tasks. These issues are addressed by the suggested system, which places a strong emphasis on usability, computational effectiveness, and real-world application.

IV. PROPOSED METHODOLOGY

The suggested system's modular and structured architecture is intended to automate the sheet metal nesting procedure effectively and methodically. The first step in the process is uploading a DXF file with the geometric definitions of the components that will be manufactured. Lines, arcs, circles, and polylines are among the geometric entities that are extracted by the DXF parsing module and transformed into computational representations appropriate for algorithmic processing.

The dimensional characteristics, surface area, and bounding box parameters of every extracted component are examined. An important preprocessing step is bounding box computation, which permits initial spatial filtering and greatly minimizes the quantity of intricate geometric comparisons needed for placement. The dataset is ready for optimal nesting operations thanks to this preprocessing step, which also increases computational efficiency.

The system uses an AI-based heuristic nesting engine instead of exact optimization techniques because irregular shape packing problems are NP-hard. The goal of the heuristic approach is to maintain high levels of sheet utilization while giving priority to computational efficiency. To improve placement order and minimize fragmentation, components are first sorted according to geometric features like area, width, or height. After each successful placement, the algorithm uses a space partitioning strategy that dynamically updates available areas to find feasible empty regions within the sheet.

A two-stage verification mechanism is used to implement collision detection, which guarantees precise placement without overlapping components. In order to remove obviously conflicting placement positions with the least amount of

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DOI: 10.17148/IARJSET.2026.133106

computational expense, the first stage uses fast bounding-box overlap detection. In order to determine whether there is a real collision between shapes, a second stage conducts exact geometric intersection testing if bounding boxes intersect.

The system automatically creates extra sheets and repeats the nesting process for the remaining parts when all the components cannot fit on a single sheet. The system is developed using Python as the main programming language, ensuring flexibility and compatibility with computational libraries. Flask is used as the web framework to facilitate deployment and interaction with the system through the browser. Numerical computations and geometric calculations are performed using NumPy, while Pandas facilitates data processing and management of results.

V. SYSTEM ARCHITECTURE

The proposed Intelligent Web-Based Metal Sheet Optimization System has a modular and sequential architecture that is intended to automate the entire nesting process, from data entry to system performance reporting. The proposed system is well designed to provide a clear separation of duties between functional modules, which will enhance the efficiency of the processing system. Each module is designed to handle a particular task while systematically passing data to the next stage of the processing system.

The proposed system design approach will enable the independent optimization of individual system components without interfering with the overall system functionality. The process starts with user input in the form of a DXF file, which holds geometric descriptions of sheet metal parts to be manufactured. The uploaded file is then processed by a DXF parsing module, which parses geometric entities and translates them into computational entities amenable to algorithmic processing.

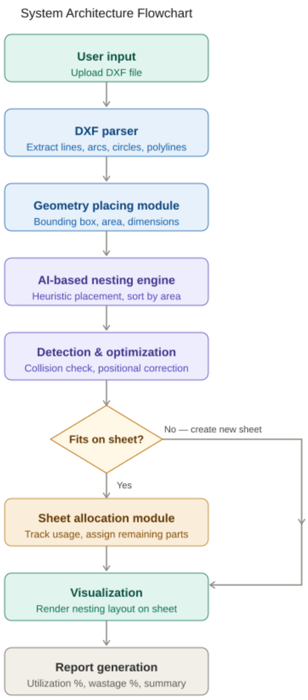

Fig 1.0 System Architecture Flowchart

A. User Input

The User Input module is the entry point of the system. In this phase, the user is required to upload a DXF file that holds the geometric models of the sheet metal parts to be cut. The system checks the format of the uploaded file and its compatibility with the parsing engine. The User Input module is the interface between the user and the backend optimization engine, which allows smooth interaction between the two in a web-based environment.

B. DXF Parser

The DXF Parser module is tasked with the responsibility of extracting geometric entities from the uploaded file. This is because the DXF file usually contains definitions of shapes in a structured manner, including lines, arcs, circles, and

DOI: 10.17148/IARJSET.2026.133106

polylines. The parser module is responsible for the extraction of these entities and their representation as computational geometry objects that can be manipulated programmatically. This is a critical process because optimization algorithms require mathematical representations as opposed to CAD data.

C. Geometry Placing Module

The Geometry Placing module carries out the preprocessing tasks on the shapes that have been extracted. The area, width, height, and bounding box of each part are calculated. The calculation of the bounding box is significant since it makes spatial analysis easier by enclosing irregular shapes in the smallest possible rectangles. This module is responsible for preparing the data for optimization by arranging the shapes based on their geometric properties.

D. AI-Based Nesting Engine

The AI-Based Nesting Engine is the most important part of the system. Because the problem of packing irregular shapes is NP-hard, a heuristic optimization method is used in place of exact methods. The engine finds the best placement order based on the part size and the free space on the sheet. The engine searches dynamically for possible positions on the sheet and positions the parts in such a way that the free space is minimized. The heuristic method strikes a balance between efficiency and maximizing the use of the sheet.

E. Detection and Optimization Module

The Detection and Optimization module is responsible for ensuring that the placed components do not overlap and satisfy spatial constraints. A two-stage collision detection method is used to improve performance. In the first stage, overlap detection between bounding boxes is performed to rule out impossible placements. If there is an overlap between the bounding boxes, a detailed geometric collision check is performed to determine if there is a collision between the shapes. This multi-level verification approach helps to avoid high computational costs while ensuring high placement accuracy.

F. Sheet Allocation Module

The Sheet Allocation module deals with situations where it is not possible to fit all components into a single sheet. As soon as the current sheet is full, the system automatically starts the initialization of a new sheet and then proceeds with the allocation of the remaining components. The dynamic allocation system ensures that there are no interruptions in the optimization process for large production orders. The module calculates the usage of sheets and the efficiency of each sheet.

G. Visualization

The Visualization module creates a visual representation of the optimized nesting arrangement (Fig 2.1). The module shows the boundaries of the sheets and the positioned components. This helps the user to examine the arrangement. Visualization enhances transparency by allowing the user to check the accuracy of the placement and the usage of the space. It also helps in finding the unused areas and interpreting the results of the optimization process. The graphical representation is produced by using computational plotting tools.

H. Report Generation

The Report Generation module generates a performance summary based on the optimization process. The module determines the total sheet area, total occupied area, material wastage percentage, and overall sheet utilization efficiency. The results are organized into a report that can be downloaded or viewed on the web interface. The module promotes transparency and provides tangible proof of the optimization process. The report generated by the module helps in industrial decision-making by estimating the cost savings and material efficiency. (Fig 2.0)

VI. PSEUDO CODE

Input: DXF_File, Sheet Width, Sheet Height
Output: Optimized Layout, Utilization Report

```
Parts ← Parse DXF (DXF_File)
FOR each part in Parts
    Compute Bounding Box(part)
END FOR
Sort Parts by descending area
Initialize Sheet List
Create First Sheet
FOR each part in Parts
    placed ← FALSE
```

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```
        FOR each free Space in Current Sheet
            IF Fits (part, free Space) AND No Collision(part)
                Place(part)
                Update Free Space ()
                placed ← TRUE
                BREAK
            ENDIF
        END FOR
        IF placed = FALSE
            Create New Sheet
            Place(part)
        ENDIF
    END FOR
    Compute Utilization
    Generate Visualization
    Generate Report
```

VII. MATHEMATICAL FORMULATION

The proposed sheet metal optimization system uses geometric and efficiency-based formulas to evaluate part placement and material utilization. The bounding box dimensions of each component are computed as:

$$W = X_{ma}{}^{x} - X_{m}{}^{I}{}_{n}, \quad H = Y_{ma}{}^{x} - Y_{m}{}^{I}{}_{n}$$

where $X_{ma}{}^{x}$, $X_{m}{}^{I}{}_{n}$, $Y_{ma}{}^{x}$, $Y_{m}{}^{I}{}_{n}$ represent the extreme coordinates of the component. The area of irregular polygonal parts is calculated using the shoelace formula:

$$A = \tfrac{1}{2} \mid \Sigma(x_i\, y_{i+1} - x_{i+1}\, y_i) \mid$$

The total sheet area is determined by:

$$A_{s}h_{eet} = W_{s}h_{eet} \times H_{s}h_{eet}$$

The total occupied area is:

$$A_{o} \qquad = \Sigma\, A_i \;\; (i = 1 \text{ to } n)$$

Sheet utilization efficiency and material wastage are calculated as:

$$Utilization\ (\%) = (A_{o} \,/\, A_{s}h_{eet}) \times 100$$

$$Wastage\ (\%) = ((A_{s}h_{eet} - A_{o}) \,/\, A_{s}h_{eet}) \times 100$$

These formulas enable accurate evaluation of nesting performance and material efficiency.

VIII. ALGORITHM

The suggested system effectively arranges irregular sheet metal components within predetermined sheet dimensions using a heuristic nesting algorithm. In order to calculate parameters like bounding boxes and component areas, the algorithm first extracts geometric information from the DXF file. In order to maximise space utilisation, the components are then arranged in descending order according to size. The algorithm uses bounding box filtering and geometric intersection checks to ensure collision-free component placement while dynamically searching for available free regions on the sheet during the nesting process.

The system automatically assigns extra sheets and proceeds with the placement process if there is not enough room on the current sheet. By optimising part arrangement, this algorithm greatly increases sheet utilisation and decreases material waste. Additionally, the automated placement procedure boosts operational efficiency and minimises manual labour.

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Because of this, the suggested method offers a workable and scalable solution for sheet metal nesting, which makes it appropriate for industrial manufacturing settings where cost-effectiveness and efficient material use are crucial.

Input: DXF file containing geometric parts, sheet dimensions (Width, Height)
Output: Optimized layout of parts on sheet, sheet utilization efficiency, wastage report

IX. RESULT AND DISCUSSION

The Intelligent Web-Based Metal Sheet Optimization System developed was successfully tested and validated using various DXF files with irregular components of different levels of complexity. The DXF file parser successfully picked up geometric entities like lines, arcs, circles, and polylines without losing data, and the geometry placement module calculated the bounding box size to prepare the components for nesting. The AI heuristic engine placed the components in the predefined sheet size, reducing wastage to a minimum. The two-step collision detection system ensured that the components did not overlap, with high precision. The system also facilitated the automatic allocation of components to multiple sheets if needed. The visualization module provided a clear representation of the layout, and the report module calculated the sheet utilization and wastage.

The results from the experiments have proved that the system works well in overcoming the limitations that come with manual sheet metal nesting. The system is also able to ensure proper placement and optimization. The bounding box filtering technique is able to reduce the computational cost, while the geometric collision detection is able to ensure that the placement is accurate even for irregular geometries. The system is also able to improve scalability and maintainability through its modular design. The system is also able to improve accessibility through web-based implementation. Future improvements can be done through the use of parallel processing or machine learning techniques.

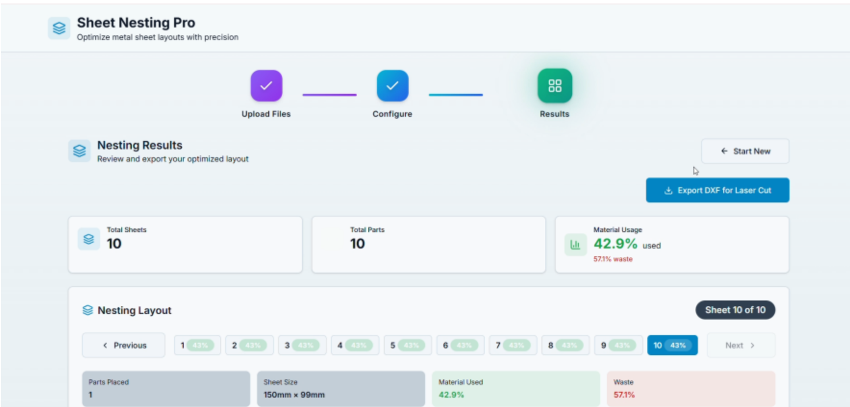

Fig 2.0 Report Generation Output

Fig 2.1 Visualization of Nesting Layout

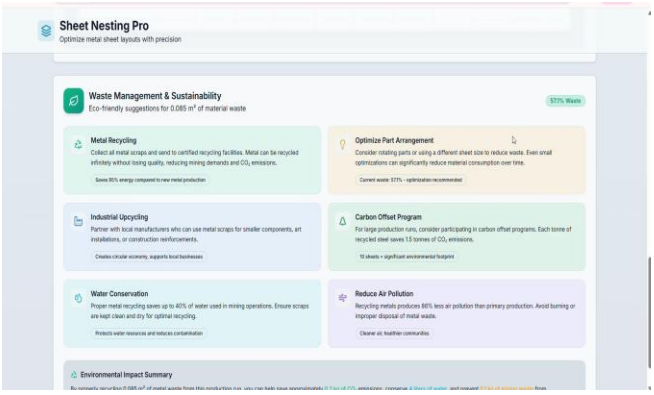

Fig 2.2 Sheet Utilization Result

X. CONCLUSION

This paper has demonstrated an intelligent web-based sheet metal optimization system that aims to reduce material wastage and improve the efficiency of the cutting process in industries. The system combines the use of DXF geometry extraction, heuristic nesting algorithms, collision detection algorithms, and dynamic sheet allocation techniques to address the shortcomings associated with the manual nesting technique. The experimental results have shown improved sheet metal utilization, reduced scrap material, and improved processing speed compared to the conventional method.

The web-based system has improved accessibility and eliminated the need for expensive proprietary CAD/CAM software, making it ideal for small and medium-scale industries. In addition to the economic benefits, the system promotes environmental sustainability due to the efficient use of materials. Future enhancements could involve the use of machine learning predictive optimization techniques, GPU support for handling large datasets, and direct CNC integration.

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