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Study of Optimal Cutting Paths for Steel Plates Based on Enumeration and Nonlinear Programming

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Abstract: With the development of society and economy, mould processing enterprises have an increasingly strong need to reduce costs and increase economic efficiency. Improving the efficiency of the cutting process is one of the key links to achieve this goal, and the planning of the cutting path occupies a major position in it. Under the condition that the actual cutting distance is fixed, the shortest air distance becomes the goal pursued by enterprises. In this paper, the optimal cutting path problem for steel plates is studied, and the optimal paths under different cutting tasks are found by enumeration method and nonlinear planning model.

Keywords: Plate cutting path optimisation; Shortest path for air travel; Enumeration; Non-linear Planning Models; Mould Processing Efficiency.

1. Introduction

With the acceleration of industrialization and the increasing demand for product personalization, mold processing enterprises are increasingly urgent in their need to reduce costs, improve efficiency, and increase economic benefits [1]. Steel plate cutting, as a critical process in mold manufacturing, is essential for enhancing the overall efficiency of the enterprise [2]. Steel plate cutting involves using specialized cutting techniques to process steel plates based on given cutting layout drawings, and the planning of the cutting path is a key aspect of this process [3]. Optimizing the cutting path can bring multiple benefits. In actual production, the path planning for steel plate cutting involves complex calculations and optimization problems [4]. How to achieve the shortest empty travel and the shortest processing time while ensuring cutting quality is a problem worthy of in-depth research. The optimization of the steel plate cutting path not only needs to consider production efficiency and cost but also must take into account the utilization rate of raw materials, equipment utilization, and the coordination of production scheduling.

Therefore, the study of steel plate cutting path planning is of great significance for mold processing enterprises to enhance their competitiveness, reduce production costs, and achieve sustainable development. Through the optimization of steel plate cutting path planning, enterprises can realize intelligent and digitalized production processes, providing more competitive advantages. This helps to meet the personalized needs of customers and further promotes the improvement of production efficiency and resource utilization optimization in the entire industry. Thus, in-depth research on the problem of steel plate cutting path planning is of significant practical importance for mold processing enterprises.

2. Model Assumptions

The data used in this paper comes from Question A of the May 1 Mathematical Modelling Competition 2024. To construct a more precise mathematical model, we make the following reasonable assumptions or constraints based on the actual situation:(1) During the steel plate cutting process, we ignore any errors caused by the machine's lack of precision; (2) We ignore the errors caused by the volume of the cutting tool and abstract the tool as an ideal point; (3) During the cutting process, the steel plate does not move, deform, or undergo any other changes.

3. Enumeration Method Based on Finding the Path

Need to cut the line segments B4B1, B1B2, B2B3, A3A4, A4A1, A1A2, A2A3, due to the actual need to cut the route are the same length, then the shortest total route on the shortest air distance, from the border to the inner hole should follow the principle of the shortest air distance, you should go to the nearest point or plumb line. The starting point of its departure cutting bore respectively B1, line B1B2 on any point, B2, B2B3 on any point B3, B4, B4B1 on any point.

3.1. Starting point B1

By B1 to cut the hole, B1 from the rectangle A1A2A3A4 A1 nearest, so the shortest path from B1 for cutting the starting point of the inner hole as follows, recorded as path 1 (black line for the actual cutting path, the red line for the empty range):

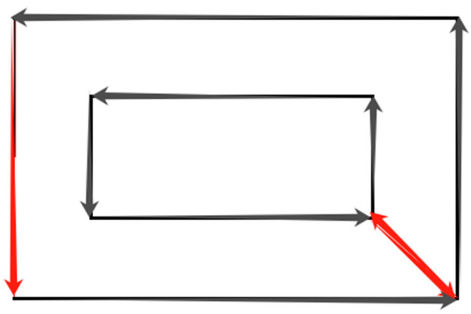

Figure 1. Schematic diagram of path 1

3.2. Any point on the starting point B1B2

From any point on B1B2 to cut holes, B1B2 to the rectangle A1A2A3A4 A1A2 of the shortest perpendicular distance, so from any point on B1B2 to cut holes, for cutting holes in the starting point of the shortest path is as follows, recorded as path 2:

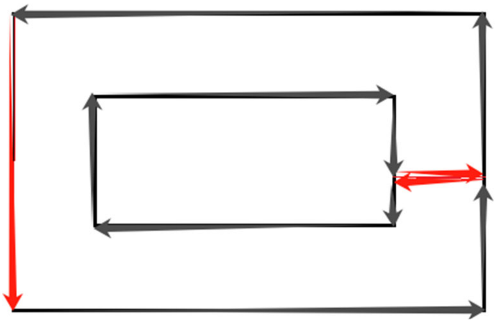

Figure 2. Schematic diagram of path 2

3.3. Starting point B2,B4

The situation is the same as when the starting point is B1, and the paths are as follows, which are recorded as paths 3,4 respectively:

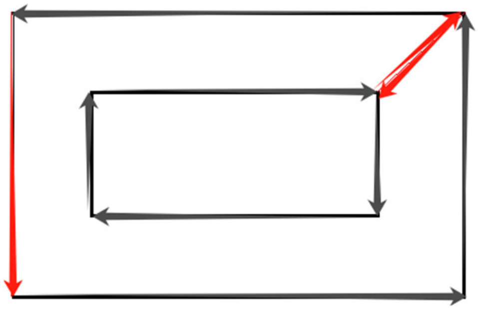

Figure 3. Schematic diagram of path 3

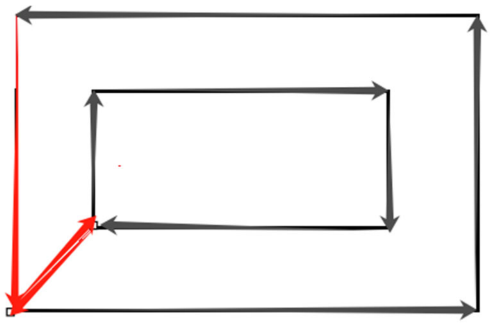

Figure 4. Schematic diagram of path 4

3.4. Starting point B2B3, B4B1 any point on the

The situation is the same as when the starting point is any point on B1B2, the path is as follows, respectively, recorded as path 5,6:

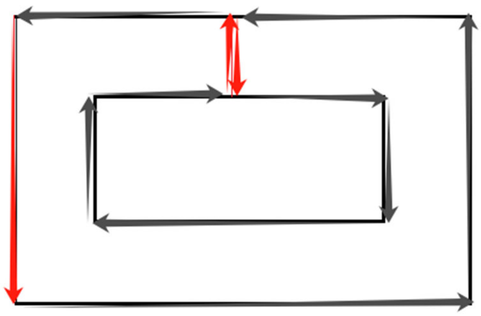

Figure 5. Schematic diagram of path 5

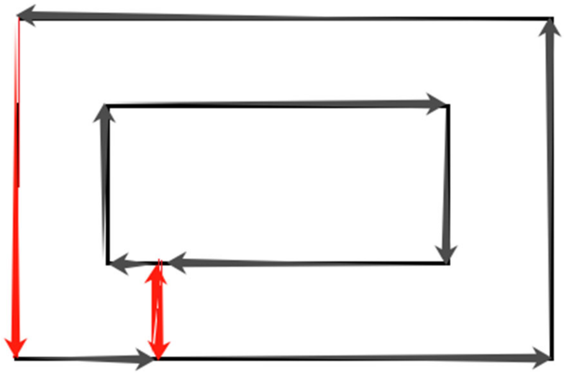

Figure 6. Schematic diagram of path 6

3.5. Point of departure B3

Since B3B4 is the boundary line of the steel plate, without cutting, so you can go from B3 to A3 or A3A4 on any point or A4, and then to B4, respectively, recorded as path 7,8,9:

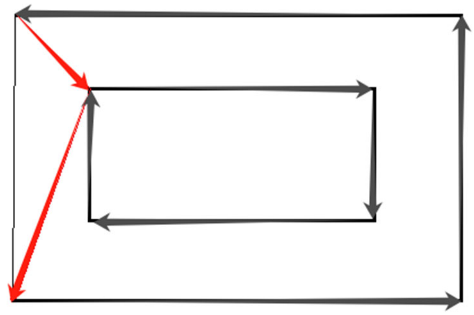

Figure 7. Schematic diagram of path 7

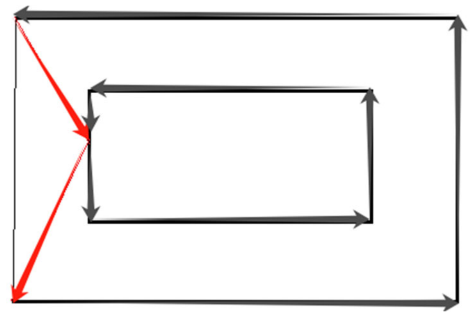

Figure 8. Schematic diagram of path 8

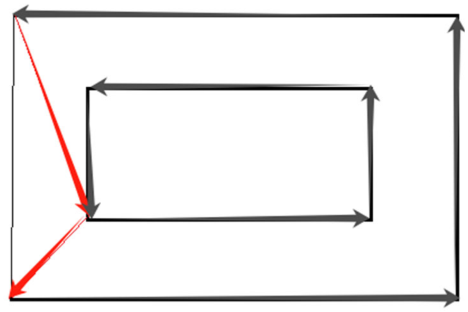

Figure 9. Schematic diagram of path 9

4. Calculate the Length of the Empty Journey of Each Path to Find the Optimal Cutting Route

4.1. Explanation of symbols

Total air travelling length L_i : Indicates the total air travelling distance from the starting point to the end point.

Coordinates of each point (x_{mn}, y_{mn}): Indicates the coordinates of each cutting point on the steel plate. The specific coordinates are as follows:

A1(60,15),A2(60,35),A3(20,35),A4(20,15),B1(80,0),B2(80,50),B3(0,50),B4(0,0).

i=1,2,...,9 denotes the path number; m=A,B denote the different cutting regions; n=1,2,3,4.

4.2. Calculation

In order to solve the problem defined by

$$L_1 = L_3 = L_4 = (y_{B3} - y_{B4}) + \sqrt{(x_{B1} - x_{A1})^2 + (y_{A1} - y_{B1})^2}$$

$$L_1 = L_3 = L_4 = (50 - 0) + \sqrt{(80 - 60)^2 + (15 - 0)^2} = 75$$

$$L_2 = L_5 = L_6 = (y_{B3} - y_{B4}) + (x_{B1} - x_{A1})$$

$$L_2 = L_5 = L_6 = (50 - 0) + (80 - 60) = 70$$

$$L_7 = L_9 = \sqrt{(x_{A3} - x_{B3})^2 + (y_{B3} - y_{A3})^2} + \sqrt{(x_{A3} - x_{B4})^2 + (y_{A3} - y_{B4})^2}$$

$$L_7 = L_9 = \sqrt{(20 - 0)^2 + (50 - 35)^2} + \sqrt{(20 - 0)^2 + (35 - 0)^2} = 65.3113$$

L_8: Find the shortest path by air from B3 to any point on A3A4 and then to B4., we wrote the following MATLAB programme and ran it to get the results:

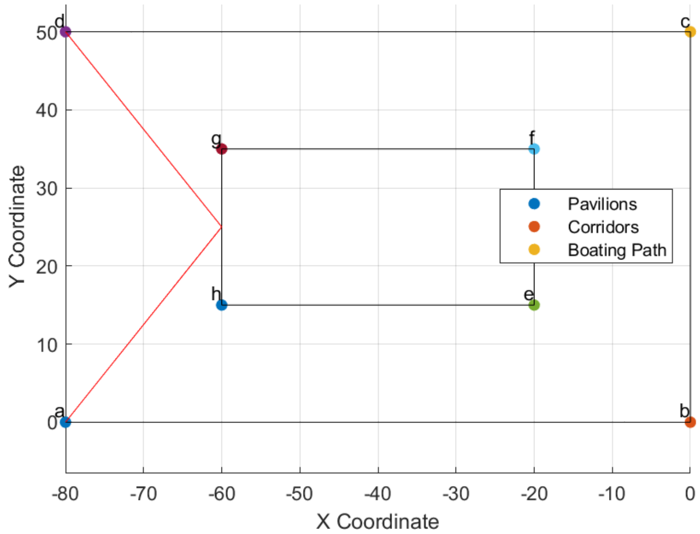

Figure 10. Schematic diagram of the shortest case of path 8

The final result is 64.0312, and a comparison is made to find that L_8 is the shortest, so its the optimal cutting route: B1-B4-A4A3 midpoint-B3-B2-B1, and the total length of the empty journey is 64.0312.

5. Find the Closest Distance of A Circular Hole From The Boundary

Define the endpoint letters:

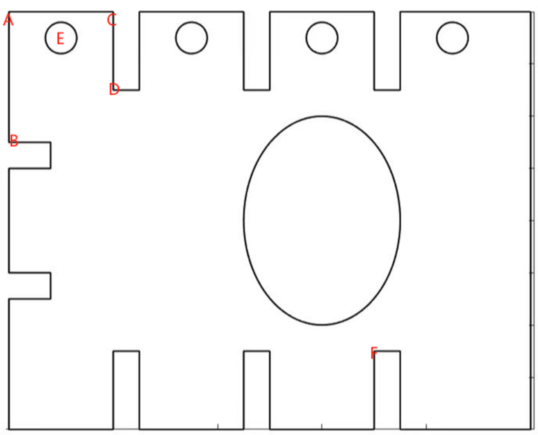

Figure 11. Task N2 Defining Endpoint Letters

Find the closest distance from the boundary using circle E as an example:

$$AB: X = 0$$

$$\text{Circle } E: (X - 10)^2 + (Y - 75)^2 = 3^2$$

The shortest distance between the straight line AB and circle E is solved for using MATLAB to obtain: the shortest distance is 7, corresponding to the point (0, 75).

$$AC: Y = 80$$

The shortest distance between the line AC and the circle E is solved using MATLAB: the shortest distance is 2 and the corresponding point is (10, 80).

$$CD: X = 20$$

The shortest distance between the line CD and the circle E is solved using MATLAB: the shortest distance is 7, which corresponds to the point (20, 75).

It can be concluded that the centre of the circle upward to make a vertical line intersecting the circle and the boundary at two points, the distance between these two points for the shortest distance between the empty range, 2, the other holes in the circle to the boundary of the shortest distance with its same, similar to the method of solving.

6. Find the Closest Distance from The Boundary of The Elliptical Hole

Observe the target graph of task N2, and find that the point

F on the boundary is the closest to the ellipse, now the problem is transformed into finding the shortest distance from the point F to the ellipse, and establish a nonlinear planning model [5]:

$$\text{objective function: } F(X) = \sqrt{(X_1 - X_p)^2 + (X_2 - Y_p)^2}$$

Where (X_p, Y_p) are the coordinates of the point to be sought and (X_1, X_2) are the coordinates of the optimisation variables.

$$\text{constraint:} \quad G(X) = \frac{(X_1 - X_C)^2}{a^2} + \frac{(X_2 - Y_C)^2}{b^2 - 1}$$

Here (X_c, Y_c) are the coordinates of the centre point of the ellipse, and a and b are the lengths of the short and long axes of the ellipse respectively.

The solution is performed and visualised using MATLAB and the results are given below:

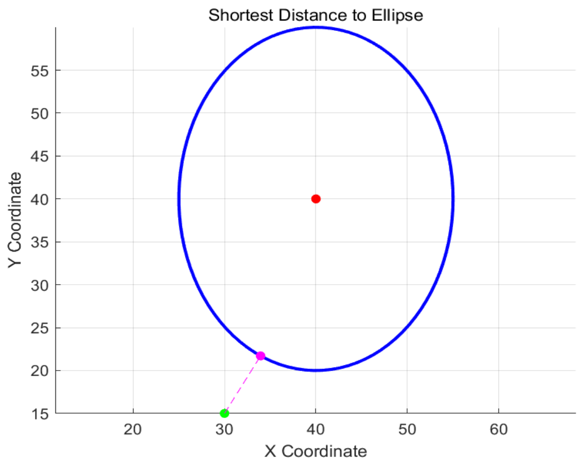

Figure 12. Shortest path from the ellipse to the boundary

The shortest path length is 7.78, so the total length of the null journey is and the optimal route is as follows:

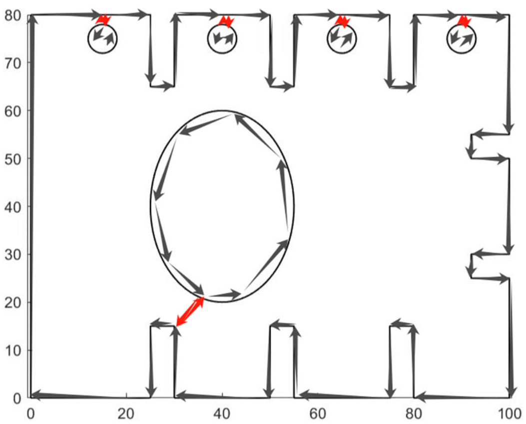

Figure 13. Optimal route for cutting task 2

7. Conclusion

In this paper, a method to find the optimal path under different cutting tasks is proposed by studying the optimisation of steel plate cutting paths. In cutting task N1, nine possible cutting paths are identified by enumeration method, and B1-B4-A4A3 midpoint-B3-B2-B1 is determined as the optimal path with a total length of 64.0312 units of empty travel. This result shows that, under the consideration of the discontinuity between the boundary and the bore, the rational arrangement of the cutting sequence can significantly reduce the air-travel length and improve the cutting efficiency. In cutting task N2, the bore includes four circles and one ellipse. The shortest distance from the boundary to each inner hole is found by solving the nonlinear programming model. For the circular bore, the shortest air distance is 2 units, and two round trips are 4 units, which is 16 units for a total of four circles. For elliptical bores, the shortest distance is 7.78 units for a one-way trip, and the total air distance of the optimal path is 31.56 units. These results further verify that in the cutting task of complex geometries, the air travel length can be effectively reduced by scientific path planning, which improves the productivity and economic efficiency. In summary, this study not only provides a specific optimization method, but also provides theoretical support and technical guidance for the path planning of mould processing enterprises in the actual production, which helps enterprises to achieve cost reduction and benefit enhancement under the premise of ensuring the cutting quality.

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