

Optimisation of Steel Plate Cutting Paths Based on Generalised Traveller Model and Hybrid Greedy Heuristic Algorithm

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Abstract. In this paper, aiming to reduce the empty travelling distance in steel plate cutting process, a hybrid greedy based heuristic algorithm, combined with simulated annealing algorithm and genetic algorithm, is proposed for optimising the process path of steel plate cutting through Python program. Firstly, Dijkstra's algorithm and greedy algorithm are used to optimise the paths for simple cutting layouts and successfully reduce the empty journey length. Subsequently, the simulated annealing algorithm is applied to complex cutting layouts such as internal efficient cutting routes and complex outer boundary shapes, which significantly optimises the cutting efficiency. Further considering the case of cutting multiple rectangular pieces inside an ellipse, a genetic optimisation algorithm is applied to effectively solve the complex constraints of symmetric distribution and cutting order. Finally, a nonlinear objective function and Dijkstra's algorithm are designed to optimise the paths for cutting four small rectangular parts inside the ellipse, and the optimal position and number of "bridges" are determined, which further improves the productivity and cost-effectiveness. Through these methods and experimental results, the significant impact of path optimisation on productivity in industrial applications is verified.

Keywords: Cutting Path Optimisation, Dijkstra, Simulated Annealing Algorithm, Genetic Optimisation Algorithm.

1. Introduction

With the rapid development of science and technology, by improving the efficiency of steel cutting to reduce production costs has become a growing concern for many related enterprises. In the case of effective cutting path to determine the actual cutting path for optimal planning has become a firm tool and related enterprises in the steel cutting process a close attention. Steel plate cutting process, the length of the air distance or not, directly affects the enterprise's selling price and consumer spending tendency, and then related to the economic development of the whole society.

In reality, the criteria for judging the optimality of the path include the length of the overall path of the plan, the distance of the empty journey, the angle of the turn, the number of turning points, etc., and this question only needs to study the shortest distance of the empty journey [3]. In field production, part bridging has always been a difficult problem to deal with, which needs to consider factors such as the size, thickness, and position of the part on the steel plate. A more optimal algorithm should be sought for this problem to be handled, and the software should be set up in a more refined way so that the parts can be cut smoothly and not fall under the platform [4]. This paper investigates the problem of cutting path optimisation for a given layout, covering challenges ranging from simple geometries to complex combinations of multiple shapes.

This article deals with the shortest path optimisation problem in steel plate cutting process, aiming to achieve the optimisation of the cutting path through mathematical modelling and algorithm design, so as to minimise the total length of air travel. The article progressively develops from simple to complex and addresses the following problems in turn:

Firstly, for the basic undercutting layout (N1), starting from the initial point, the mathematical model is established by the greedy algorithm and Dijkstra's algorithm to design the optimal cutting route to ensure the shortest air travel. Secondly, it is extended to the more complex undercutting layout

(N2), which considers the outer boundary of the member and the effective cutting route inside. Using methods such as the simulated annealing algorithm, a mathematical model is developed and the optimal cutting route with the minimum total length of air travel is calculated. Further, in Layout N3, the requirement of cutting 12 rectangular members inside the ellipse is added. The symmetric distribution and cutting sequence of the rectangular pieces are handled by techniques such as genetic optimisation algorithms to ensure that the optimal cutting route is designed and the total length of the air travel is calculated. Finally, in the complex undercutting layout (N4), in addition to dealing with the requirement of cutting four small rectangular parts inside the ellipse, the problem of "crossing the bridge" is also considered. A non-linear programming model is developed to determine the number and location of the "bridges" and to design the optimal cutting routes as well as to minimise the total length of the air travel, taking into account the constraints of the width and distance of the "bridges".

2. Literature review

2.1. Research background of steel plate cutting path problem

In the process of steel cutting and processing, in order to improve processing efficiency, the need to complete the premise of the machining task, the shortest path to cut, and save raw materials as much as possible, and the key to the completion of this task is to optimise the cutting path. Cutting path optimisation is affected by a variety of conditions and parameters, these parameters and conditions need to be included in a unified model, and according to the set target constraints to complete the optimization process [1]. Steel plate cutting path optimisation problem is widely used in the field of ship parts cutting, the number of ship parts, large volume, and different shapes, high cost of steel, so it is particularly important to set the optimal cutting path in the process of cutting parts to improve the quality of cutting [2].

2.2. Research significance of steel plate cutting path problem

With the continuous improvement of the world's industrial level, the demand for steel parts is rising, and the problem of cutting efficiency of steel plate has been a very important engineering problem. In the steel plate cutting process, the process in which the tool does not produce the actual cutting effect during the cutting process is called the empty path [3]. In recent years, some companies in the steel cutting stay in the "can cut" stage, only can complete the cutting, but ignored how to "cut well", "cut fast", "cut the province" of the problem, resulting in a two-way waste of time and materials. In response to this problem, some mainstream enterprises in the industry continue to innovate cutting technology, significantly improve the cutting efficiency at the same time, shorten the manufacturing cycle, improve the utilisation rate of the steel plate, so that the manufacturing cost has decreased significantly, for the development of steel plate cutting related industries is significant [4].

2.3. Meaning of the traveller problem in a broad sense

The traveller problem [5], or TSP problem, is the shortest [6] path among all paths given any number of cities and the corresponding distance between each two cities, and then the shortest [6] path among all paths on the premise that the traveller passes through all of them and returns to the place of departure.

2.4. Meaning of hybrid greedy heuristic algorithm

Hybrid greedy algorithm is an optimisation algorithm which combines the features of greedy algorithm [7] and heuristic algorithm [8], the algorithm introduces heuristic information on the basis of greedy algorithm, which improves the search efficiency and the quality of the solution, the algorithm is widely used in a variety of optimisation problems, such as the TSP, VRP problems, etc., the process of solution needs to be balanced between the local optimum and the global optimum considerations.

2.5. Literature Summary

In the actual production process, setting the optimal steel plate cutting path and improving the cutting quality are the key steps to reduce the production cost of steel plate and improve the profitability of the industry.

The world's industrial level advances with the times, steel cutting from "can cut" stage to "cut well", "cut fast", "cut save" stage gradually over, so the steel cutting path is the key step to reduce the cost of steel plate production and improve industrial profitability. "Stage gradually over, so the setting of the optimal cutting path of the steel plate is of great significance for the sustainable development of the steel plate industry [9].

The generalised traveller problem can be simply summarised as the problem of finding the shortest path under the premise of passing through all the required points.

Hybrid greedy algorithm is one of the optimisation algorithms [10] that combines greedy algorithms with heuristic algorithms.

3. Modelling and solving

3.1. Modelling and solving of the basic undercutting layout

3.1.1. Modelling process

The optimal air travelling path in the cutting process is required. For the optimisation problem, we build an optimal function model: first, abstract the layout graph as a graph $\text{graph} = (P, S)$, where P is the set of nodes and S is the set of edges, and take B1 as the starting point in the graph, and B3 and B4 as the end points in the graph. Then, the weight of each edge is set to the corresponding geometric length. Finally, using Dijkstra's algorithm with the aid of the greedy algorithm, the optimal solution for the total length of the null journey is found through python programming, and the corresponding optimal roadmap is derived.

3.1.2. Modelling

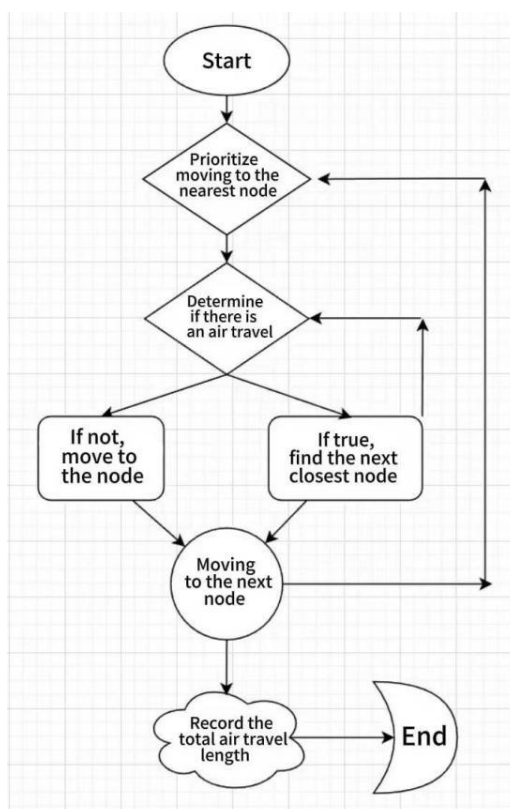


Fig. 1 Flowchart of the algorithm

With the idea of greedy algorithm to improve Dijkstra's algorithm: each iteration, search for the optimal solution and the answer according to the update. The flow of ideas for finding the shortest empty journey is shown in the above figure 1.

3.1.3 Solving the model

(1) Algorithm

[Step1]: According to the greedy algorithm, derive the local optimal solution, and introduce the overall optimal length of the empty journey as 64.03;

[Step2]: According to Dijkstra's algorithm, combined with the greedy algorithm, verify that 64.03 is the correct answer;

(2) Result

The total length of the empty journey of the optimal cutting path is about 64.03, and the optimal cutting roadmap is shown in Figure 2 below:

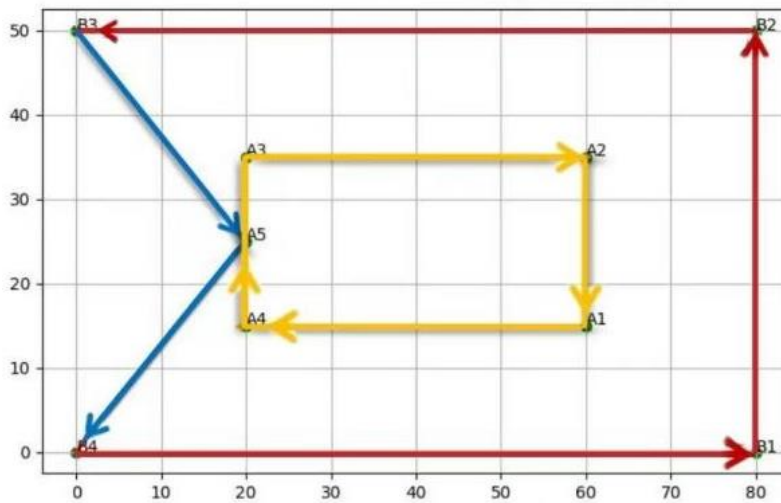


Fig. 2 Presentation of results

3.2. Consideration of effective cut routes to the outer boundary and interior of the member

3.2.1 Modelling process

Firstly, take B4 as the coordinate origin, the direction where B4-B1 is located as the X-axis positive semi-axis, and the direction where B4-B3 is located as the Y-axis positive semi-axis to establish the coordinate system. Then the cutting start point is fixed at the lower right corner of the graph at the designated place of the title, and the cutting order, the inner hole cutting rule, and the outer contour cutting rule are used as the constraints. Finally, the objective function is defined as the sum of the distances between the end point and the start point of all the cutting lines, and then according to the definition of the length of the empty range, the optimal planning path is obtained by programming based on the simulated annealing algorithm in python software, and the optimal solution is found.

3.2.2 Modelling

Firstly, establish the objective function, i.e., to find the minimum value of the sum of distances between all neighbouring cutting points, which is embodied by the cumulative sum of Euclidean distances.

Second, determine the constraints. Condition one requires that the arrangement constituted by each point in sequential order is a full arrangement and conforms to a specific cutting order. Condition two and three require that the five inner holes and the outer contour conform to a specific cutting rule. 10 special nodes (transition points between the outer contour and the inner holes) are now taken for judgement: whether they are included in the whole actual cutting line.

$$\min \sum_{i=1}^n \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} - S_2 \quad (1)$$

$$\left\{ \begin{array}{l} (x_1, y_1) = (100, 0) \\ \bigcup_{i=1}^5 w_i \subseteq \bigcup_{i=1}^m l_i \\ \bigcup_{i=1}^5 a_i \subseteq \bigcup_{i=1}^m b_i \\ s: \{1, 2, \dots, m\} \rightarrow \{1, 2, \dots, m\} \end{array} \right. \quad (2)$$

3.2.3 Solving the model

(1) Algorithm.

[STEP1] Generate a more reasonable initial path using heuristics;

[step2] According to the simulated annealing algorithm, set the initial temperature to = 150 °C (i.e., the initial path), and the cooling coefficient is α . Under the premise of ensuring that the constraints of the model of the problem are satisfied, iterate the inner loop on the relatively suitable temperature (i.e., the relatively suitable path), and the number of iterations is $L = 100$, until the optimal temperature (i.e., the optimal route) is found;

[STEP3] At the current optimal temperature, the corresponding optimal cutting path is perturbed and a neighbouring solution domain is generated, and finally the objective function value of the neighbouring solution domain, i.e., the optimal air distance length, is calculated.

(2) Results

The total length of the empty journey of the optimal cutting path is about 31.55, and the optimal cutting roadmap is shown in Fig. 3:

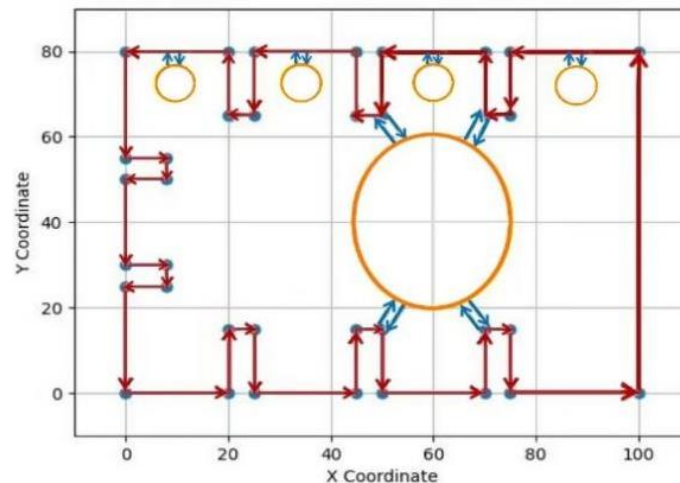


Fig. 3 Presentation of results

3.3. Handling the inside of an ellipse to cut four small rectangular parts

3.3.1. Modelling process

This is still a generalised travelling quotient problem.² With 12 more rectangular paths to be cut inside the ellipse and one more constraint (all rectangular pieces inside the ellipse to be cut before the ellipse), the problem can be reduced to the problem of finding the optimal paths to be cut for the ellipse and the 12 rectangular parts inside it. A genetic optimisation algorithm in a heuristic algorithm can be used.

Firstly, population initialisation is performed and each individual in the population is considered as a cutting path;

Then, the fitness of each individual is calculated, i.e., the total length of the empty journey of the path represented by the corresponding individual;

At the end of the calculation, new individuals are generated by crossover, selection and mutation, and the population is updated at the same time;

Repeat steps two and three until a satisfactory solution is found;

Finally, output the optimal cutting path and the corresponding shortest empty journey length.

3.3.2. Modelling

Firstly, the objective function and constraints are established, and then a new conditional constraint is added based on the isolated ellipse and the rectangles inside it. The conditional constraint is to ensure that each rectangle is completely cut by taking the four vertices of each rectangle (taken as, $i=1,2,\dots,48$) as well as the special point of transitioning from the rectangle to the ellipse (taken as) to ensure that the paths denoted by the ellipse and the rectangles are included in the total cutting path. Finally, with the constraints in mind, the objective function is output according to the genetic optimisation algorithm, i.e., the most cut paths and their corresponding null-range optimal solutions are outputted.

$$\min (\sum_1^n \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} - S_3) \quad (3)$$

$$\text{s.t.} \begin{cases} (x_1, y_1) = (100, 0) \\ \bigcup_{i=1}^5 w_i \subseteq \bigcup_{i=1}^m l_i \\ \bigcup_{i=1}^5 a_i \subseteq \bigcup_{i=1}^m b_i \\ s: \{1, 2, \dots, m\} \rightarrow \{1, 2, \dots, m\} \\ \bigcup_{i=1}^{49} p_i \subseteq \bigcup_{i=1}^m q_i \end{cases} \quad (4)$$

3.3.3. Solving the model

(1) Algorithm.

[STEP1] Perform population initialisation, and consider each individual in the population as a cutting path;

[step2] Set the appropriate fitness function Fitness Function, and carry out population updating through constant mutation, selection and crossover of the population, and cycle the above steps until the most satisfactory solution is output;

[STEP3] Finally, output the optimal cutting path and the corresponding shortest empty journey length.

(2) Result

The total length of the empty journey of the optimal cutting path is about 81.7, and the outer contour, i.e., the cutting paths of the four circles, is the same as that of Problem 2, in which the optimal cutting roadmap of the elliptical part is shown in Fig. 4

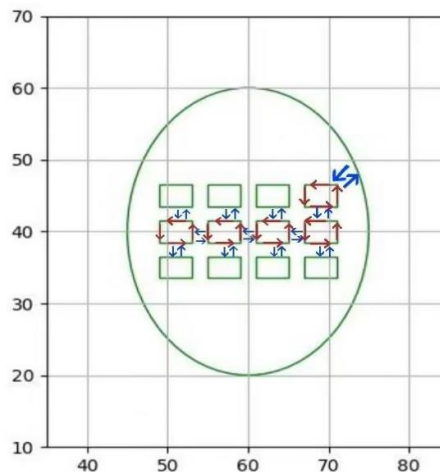


Fig. 4 Demonstration of optimal path planning for the elliptical part

3.4. "Bridging" problems

3.4.1. Modelling process

With the addition of four rectangular cutting paths and the constraint of "crossing the bridge", the problem can be simplified to the optimal cutting paths of the ellipse and four rectangles under the premise of setting "crossing the bridge".

Firstly, the Dijkstra algorithm is used to determine the exact position of each small part and bridge by setting the nonlinear objective function;

Then, the whole cutting process is simulated by genetic algorithm, including the process of cutting each small part, setting the crossing bridge and finally cutting the ellipse.

Finally, find the optimal path from all the paths through population updating and evolution, and output the optimal length of the empty journey.

3.4.2. Model building

Firstly, the system building operation is carried out, taking the lower left corner point as the origin to build the system and solve the functional analytical equation of the ellipse:

$$\frac{(y - 40)^2}{400} + \frac{(x - 60)^2}{225} = 1 \quad (5)$$

Considering the endpoints of the four rectangles, it is found that the coordinates of the upper left corner of the upper left rectangle (48,52) satisfy the equation of the ellipse, so the transition cut from the ellipse to the internal parts is considered to be performed from this point, and the distance of the empty rows in the process of the transition cut is 0, which is optimal.

Then, a nonlinear objective function is established and constraints are combined to determine the exact location of each small part and "bridge". There are additional constraints: each small rectangular part is connected to at least one "bridge" and each "bridge" is connected to at most two small rectangular parts. The minimum distance between a "bridge" and the boundary of a small rectangular part is 1.

$$\min (\sum_1^n \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} - S_4) \quad (6)$$

$$\text{s.t.} \left\{ \begin{array}{l} (x_1, y_1) = (100, 0) \\ U_{i=1}^5 w_i \subseteq U_{i=1}^m l_i \\ U_{i=1}^5 a_i \subseteq U_{i=1}^m b_i \\ s: \{1, 2, \dots, m\} \rightarrow \{1, 2, \dots, m\} \\ U_{i=1}^{49} p_i \subseteq U_{i=1}^m q_i \\ 2 \leq \sum_1^4 \sum_1^4 d_{ij} \leq 3 \\ \forall i, \sum_1^4 d_{ij} \geq 1 \\ \forall i, d(e_i - f_i) \leq 1 \end{array} \right. \quad (7)$$

Finally, the whole cutting process is simulated by genetic algorithm to find out the optimal cutting path and its corresponding shortest air travel length.

3.4.3. Solving the model

(1) Algorithm

[step1] Set the nonlinear objective function, combined with the constraints of the "bridge", to determine the exact position of each small part and the "bridge";

[step2] Simulate the whole cutting process by genetic algorithm, and output the optimal cutting path map through population update and evolution;

[step3] Finally, according to the optimal cutting path diagram, calculate the optimal total length of the air distance.

(2) Result

The number of "bridges" is 2, and the position is shown as the red line in the following figure. [The centre of the bridge connecting the upper part of the small rectangle: (58.5, 47.5), the centre of the bridge connecting the lower part of the small rectangle: (58.5, 37).]

The total length of the empty journey of the optimal cutting path is about 49.55, and the optimal cutting roadmap is shown in Figure 5 below:

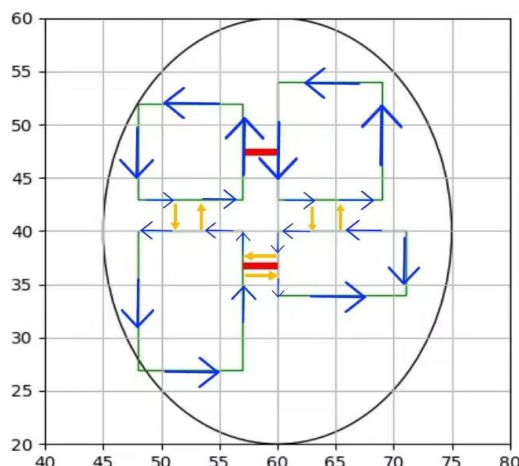


Fig. 5 Selection of the position of the "bridge" and the optimal cutting route

4. Conclusions

In this paper, we take path optimisation in steel plate cutting process as the research object, and explore and optimise it by establishing mathematical models and applying advanced algorithms. From simple to complex different cutting layouts (N1 to N4), we applied Dijkstra's algorithm, simulated annealing algorithm and genetic optimisation algorithm, etc., respectively, to design the optimal cutting paths, which effectively reduces the total length of the air travel. Through the application of these algorithms, we successfully solved the path planning problem under different conditions, and provided a feasible optimisation scheme for steel plate cutting in real production.

In the course of the study, we found that path optimisation is not only about the reduction of the length of the air travel, but also about the improvement of the production efficiency and the reduction of the production cost. Each layout poses challenges to the selection and parameter tuning of the algorithms, and we further demonstrate the potential of the algorithms to be applied in real-world engineering by continuously optimising the use of the algorithms, especially in complex layouts (e.g., N3 and N4) that take into account the additional geometrical constraints and bridging problems.

Overall, the research in this paper has not only deepened the understanding of the path optimisation problem theoretically, but also accumulated valuable experience in engineering practice. Future research can continue to explore the optimisation algorithms in more complex scenarios and to design more refined algorithms in conjunction with the needs in the actual production environment, in order to further improve the efficiency and quality of the steel plate cutting process.

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