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Research of Ship Nesting Based on Maximum Residual Rectangle Strategy Integrated Improved Genetic Algorithm

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Abstract. In this paper, a maximum residual rectangle genetic (MRRG) algorithm based on multi-heuristic strategies is proposed, which combines the advantages of heuristic algorithm and intelligent optimization algorithm to improve the material utilization and stability of the solution. In this method, the optimal local solution is obtained by constructing the maximum residual rectangle (MRR) algorithm based on the heuristic algorithm firstly, and the free rectangle area table update method of MRR algorithm is put forward. Secondly, in order to further improve the diversity of solutions, five heuristic strategies which are bottom-left strategy, minimum area difference strategy, minimum short side strategy, minimum long side strategy and maximum contact perimeter strategy are proposed for the MRR algorithm. Lastly, the global solution is calculated by the improved genetic algorithm, in which the five solutions obtained by heuristic MRR algorithm are used as initial solutions. The test results show that the material utilization can be increased from 91.5% to 95.9%, and further to 97.5%, which verifies the feasibility and effectiveness of the proposed algorithm.

Keywords. Maximum residual rectangle genetic (MRRG) algorithm; Multi-heuristic strategies; Material utilization; Intelligent optimization algorithm; Genetic algorithm

1. Introduction

With the development of the world economy, the competition of the shipbuilding industry is becoming fiercer, how to reduce the cost and improve the competitiveness is an important problem facing the shipyard at present. Nesting skill is generally regarded as the fundamental technology because of its large impact on cost and productivity. It is to layout ship parts of various sizes and shapes in steel boards under certain requirements or constraints for achieving maximum material utilization with the help of advanced computer technology. Different ships have different categories of parts, how to improve the universality of the algorithm and improve the material utilization has been a hot topic in the field of shipbuilding.

Nesting problems, usually known as cutting problems or packing problem, are common in industries ranging from clothing and furniture to shipbuilding and aerospace.

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It is a NP-hard problem with tiptop calculation complexity, and an optimal solution is difficult to calculate in a timely manner[1]. From 1940s, many researchers have attempted to develop methods or algorithms for nesting different shaped parts on different shaped sheets[2].

Gilmore & Gomory[3] proposed the delayed pattern generation technique using linear and dynamic programming to solve 1D and 2D cutting stock problems. Gomes & Oliveira[4] developed a heuristic method to guide search through the solution space. These methodologies required significant time to obtain an efficient solution. Adamowicz & Albano[5] described a two stages approach. The first stage was to cluster shapes into rectangles and the second stage was to layout the rectangles. Once the shapes had been clustered into a rectangle, relative position of the shapes had been fixed and this can eliminate potentially good solutions. Pal & Charkhgard[6] proposed a mixed algorithm based on several heuristic algorithms to solve single objective and bi-objective optimization problem. Grange et al.[7] studied the 2D nesting problem with repetitive parts and the proposed comprehensive optimization algorithm for facility layout problems. Liu et al.[8] proposed three heuristics that include the modified classical best-fit heuristic to solve a practical problem of variable-size bin packing with time windows. A. Cemil *et al.*[9-10] made a series of research on the problem of ship parts nesting problem. The combination algorithm of analytic method and heuristic strategy was studied, resulting in a successive elimination method for ship stock-cutting problems. A heuristic algorithm adapted to different stock material sizes was developed. These research results are crucial for achieving automated nesting of ship parts and demonstrate the effectiveness of combining irregular parts into regular ones prior to nesting.

Based on current research and industrial application, clustering ship parts into rectangles and optimizing their layout is an effective method. Improving material utilization in rectangular part layout is crucial for ship nesting. This paper introduces the Maximum Residual Rectangle Genetic (MRRG) algorithm with multi-heuristic strategies, combining heuristic and intelligent optimization algorithms. It enhances material utilization, algorithm adaptability, and solution stability in ship nesting of rectangular parts.

2. MRR Algorithm

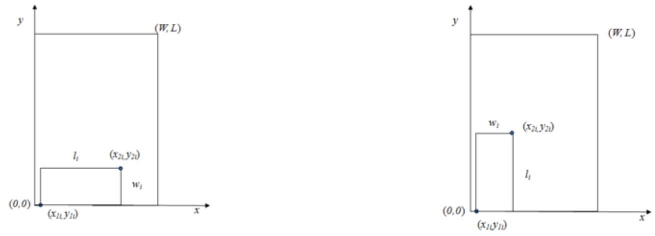
2.1. Basic Principle of MRR Algorithm

The rectangle nesting optimization problem is to layout rectangular parts of various shapes and sizes in boards which have given length and width. These parts can't overlap with each other or be placed over the boundary. The goal is to achieve the maximum utilization of material. Because the ship parts thickness is same on the board, the rectangle nesting problem can be simplified as a 2D problem.

Based on the residual rectangle algorithm, this paper presented MRR algorithm in order to avoid the loss of good solution due to the unbefitting free rectangle region division. The existing residual rectangular algorithm is a local search algorithm that places the rectangular part in the bottom-left corner of the board and then the remaining blank region is divided into two new free rectangle regions vertically or horizontally.

Rectangular part can be placed horizontally or vertically in the board, the nesting form of part is shown in figure 1: (a) is in the horizontal direction and (b) is in vertical direction. Their coordinate relations are shown as follows:

$$\begin{cases} x_{2i} = x_{1i} + l_i \\ y_{2i} = y_{1i} + w_i \end{cases} or \begin{cases} x_{2i} = x_{1i} + w_i \\ y_{2i} = y_{1i} + l_i \end{cases} \quad (1 \le i \le N) \tag{1}$$



(a) (b)

Figure 1. The nesting form of part

The target function can be described in the following function 2. To sum up, the nesting model is as follows function 3.

$$f(i) = \max \frac{\sum_{i=1}^{n} (x_{2i} - x_{1i})(y_{2i} - y_{1i})}{S_b} \tag{2}$$

$$f(i) = \max \frac{\sum_{i=1}^{n} \left((1-e_i)l_i + e_i w_i\right)\left((1-e_i)w_i + e_i l_i\right)}{S_b} \tag{3}$$

$$s.t \begin{cases} u\left(x_{1i} - x_{1j} - (1-e_j)l_j - e_j w_j\right) + u\left(x_{1j} - x_{1i} - (1-e_i)l_i - e_i w_i\right) + \\ u\left(y_{1i} - y_{1j} - (1-e_j)w_j - e_j l_j\right) + u\left(y_{1j} - y_{1i} - (1-e_i)w_i - e_i l_i\right) \ge 1 \\ 0 \le x_{1i} \le W - (1-e_i)l_i - e_i w_i \\ 0 \le y_{1i} \le L - (1-e_i)w_i - e_i l_i \\ i \ne j \\ e_i = 0 \, or 1 \\ i, \; j = 1, \; 2, \; \ldots, \; n \end{cases}$$

where: logic parameter e_i to distinguish the nesting form of each part, e_i =0 means the horizontal placement, and e_i =1 means the vertical placement, $\mathrm{u}(x)$ is a leaping order function, shown as follows

$$\mathrm{u}(x) = \begin{cases} 1 & x \ge 0 \\ 0 & x < 0 \end{cases} \tag{4}$$

2.2. Free Rectangle Region Table Update Method

In MRRP, the maximum free rectangle region is recorded in the free rectangle region table, but each maximum free rectangle region is not independent of each other, and they have a common overlapping domain (shown in figure 2). Therefore, when a new rectangular part is packed into one of the maximum free rectangle regions in the table and the new maximum free rectangle regions are obtained by using the MRRP, the free rectangle region table needs to be updated:

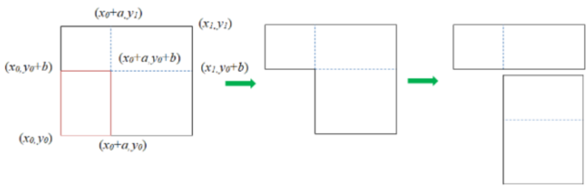


Figure 2. Maximum free rectangle region division diagram of MRR algorithm

The following examples illustrate the steps for updating the free rectangle region table. It is assumed that the bottom-left and top-right coordinates of the steel board are (0,0) and (8,12). Three rectangular parts are packed already. Their coordinates are R_1{(0,0), (3,8)}, R_2{(3,0), (5,6)} and R_3{(5,0), (6,4)}. So far the free rectangle region table H records four maximum free rectangle regions, which are red H_1, yellow H_2, green H_3 and blue H_4, shown in figure 3(a).

When the new rectangular part R_4 is packed, the free rectangle region H_2 is selected, shown in figure 3(b). Perform MRRP on R_4 and H_2. Two new maximum free rectangle regions are obtained, and they are H_5 and H_6. Then delete H_2 and add H_5 and H_6 into the free rectangle table. Now the table contains H_1, H_3, H_4, H_5 and H_6.

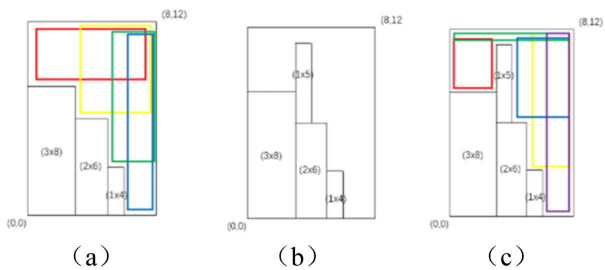


Figure 3. Nesting diagrams of MRR algorithm

Then begin the first step of table update. Check whether R_4 overlaps with other free rectangle regions in the table. It is clear that only R_4 and H_1 overlap. Perform MRRP on R_4 and H_1, then refresh the free rectangle region table H.

Follows the second step, the redundancy among the free rectangle region table needs to be deleted, then refresh the free rectangle region table H. H now contains yellow H_3, purple H_4, blue H_6, red H_7 and green H_8, marked in figure 3(c).

From the above description of the MRR algorithm, it can be found that the matched between the nested rectangular part R_i and the free rectangle H_i in the free rectangle table needs to follow a certain heuristic strategy. A single nested heuristic strategy is difficult to meet the needs of various nesting problems, which also leads to the lack of universality of existing methods. Five heuristic strategies are establish based on MRRP in the MRR algorithm. Different heuristic strategy will lead to different nesting solution with different material utilization.

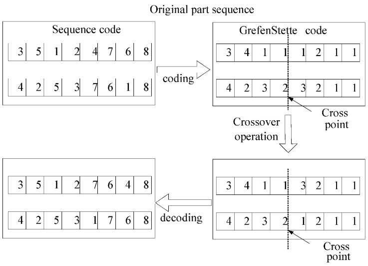
(1) Bottom-left strategy
(2) Minimum area difference strategy
(3) Minimum short side strategy
(4) Minimum long side strategy
(5) Maximum contact perimeter strategy

3. MRRG Algorithm

3.1. Coding Method

In order to apply GA to rectangular parts nesting problem, the appropriate coding method should be selected firstly. In this paper, decimal coding is used to represent the nesting sequence of rectangular parts, and each rectangular part is given a different decimal number. When a rectangular part is inputted, the part is assigned a decimal identification (ID) number, and the ID sequence composing of all parts ID numbers is a genetic individual and a solution to the nesting problem.

The Grefenstette[11] coding and decoding processes of crossover operation and mutation operation are shown in figure 4 and figure 5.



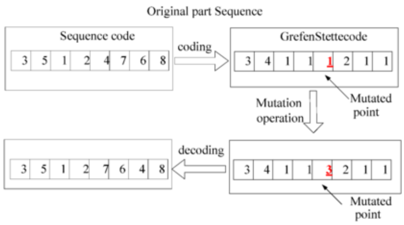


Figure 4. Grefenstette code of crossover operation **Figure 5.** Grefenstette code of mutation operation

3.2. Selection Operator

The selection operator in GA chooses individuals from the current population based on fitness and transfers them to the next generation using specific rules. The improved GA in this paper adopts the roulette selection strategy.

3.3. Crossover Operator

The proposed algorithm in this paper utilizes a self-adaptive crossover strategy for its crossover operator. This strategy aims to simultaneously retain superior individuals and discard inferior individuals. The formula for the self-adaptive crossover is presented below:

$$P_c = \begin{cases} p_{c1} - \dfrac{(P_{c1} - P_{c2})(f - f_{avg})}{(f_{max} - f_{avg})}, f \geq f_{avg} \\ P_{c1}, f < f_{avg} \end{cases} \tag{5}$$

where: f_{avg} is the average fitness value in present generation, $f_{\max}$ is the maximum fitness value, f is the larger value in the selected individual. P_{c1} and P_{c2} is relatively high and low crossover probability.

3.4. Mutation Operator

The optimization ability of the genetic algorithm (GA) is significantly affected by the mutation probability (P_m). In this paper, the mutation operator for the nesting problem employs an adaptive mutation strategy, as described by function 6.

$$P_m = \begin{cases} p_{m1} - \dfrac{(P_{m1} - P_{m2})(f - f_{avg})}{(f_{max} - f_{avg})}, f \geq f_{avg} \\ P_{m1}, f < f_{avg} \end{cases} \tag{6}$$

where: f_{avg} and $f_{\max}$ is respectively the average fitness value and maximum fitness in present generation, f is the fitness value of mutation individual. P_{m1} and P_{m2} is respectively higher and lower mutation probability.

In MRRG algorithm, the maximum generation number is used as the stopping criterion. The flow chart of MRRG algorithm is shown in figure 6.

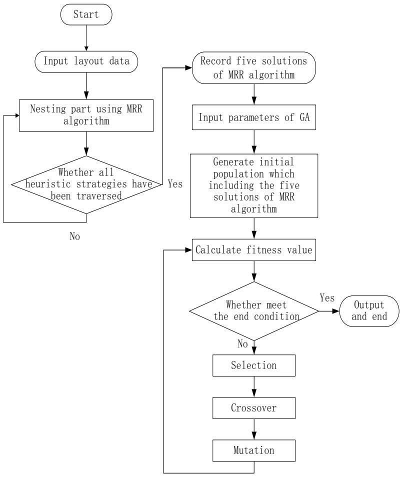


Figure 6. MRRG algorithm flow chart

4. Test Results and Discussion

We select the nesting samples from reference[12] to test the proposed MRRG algorithm. In reference[12], several versions of algorithm are calculated, the nested result of GA combined with optimal search strategy is the best, its material utilization rate is 91.5%. The detailed nesting diagram is shown in figure 7.

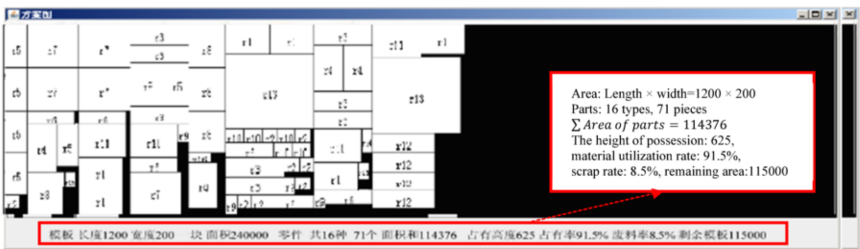


Figure 7. Nested result of reference[12]

As for the MRR algorithm with five heuristic strategies, the results of the same nested resource under five heuristic strategies are shown in table 1. It is clear that the MRR algorithm can produce five individual solutions for one nested resource due to five concurrent heuristic strategies. The five nested solutions can be used as a reference for designers. Each nested solution is the optimal solution under the given heuristic strategy. For the nested resource tested above, the nested solution under MSSS is the best and its board utilization is 95.9%. The nested diagram is automatically generated in AutoCAD software, shown in figure 8.

Table 1. Nested result of MRR algorithm

Heuristic strategy	Board use ratio	Board number	Last board length(cm)
MSSS	95.9%	1	596
MLSS	47.7%	1	1200
MADS	84.1%	1	680
BLS	88.7%	1	645
MCPS	47.7%	1	1200

Table 2. Nesting result of MRRG algorithm

Algorithm	Board use ratio	Board number	Last board length(cm)
MRRG	97.5%	1	586

As for the MRRG algorithm proposed in this paper, the result of the same nested resource is 97.5%. Detail information is displayed in table 2, and the nested diagram is shown in figure 9.

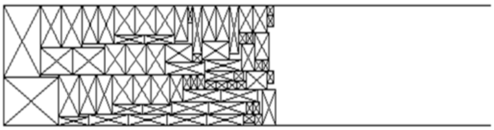


Figure 8. Nested result of MRR algorithm based on MSSS

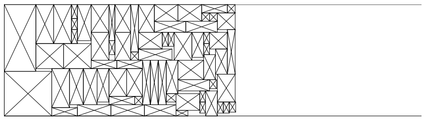


Figure 9. Nested result of MRRG algorithm

Through comparison, we can find that the MRR algorithm presented in this paper has better performance than the algorithm in reference[12]. The material utilization is improved from 91.5% to 95.9%. And the MRRG algorithm which combined the advantages of heuristic algorithm and intelligent optimization algorithm gets better optimization results, the material utilization ratio reaches 97.5%, it demonstrates the feasibility and efficiency of MRRG algorithm. In order to compare the two series of test data of MRR and MRRG algorithm more intuitively, the material utilization comparison diagram is made, as shown in figure 10.

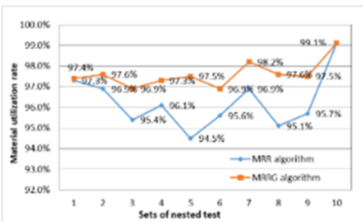


Figure 10. Material utilization comparison diagram

5. Conclusion

It is an effective way to solve the problem of ship parts nesting problem by combining the parts of various shapes into regular rectangles and then layout the rectangles. Therefore, how to further improve the material utilization of rectangular parts layout is one of the key technologies to the ship nesting problem. Combining the advantages of heuristic algorithm and intelligent optimization algorithm, this paper presents a maximum residual rectangle genetic (MRRG) algorithm with five concurrent heuristic strategies for ship nesting problem to improve the material utilization rate. In this method, the optimal local solution is obtained by the maximum residual rectangle (MRR) algorithm based on multi-heuristic algorithm, and the free rectangle region table update method of MRR algorithm is put forward. At the same time, five concurrent heuristic strategies of BLS, MADS, MSSS, MLSS and MCPS are introduced to improve universality of the MRR method. And then the global solution is calculated by improved GA, in which the five solutions obtained by MRR algorithm will be used as initial solutions. Finally, the suitable test samples are selected, and MRRG algorithm is tested. The results are proved that the MRRG algorithm proposed in this paper is feasible and effective. As a further study, the effective method of converting the irregular shapes into rectangles or right triangles will be researched.

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References

[1] Lee Wen-Chen, Mab Heng, Cheng Bor-Wen. A heuristic for nesting problems of irregular shapes[J]. Computer-Aided Design, 2008, 40, 625–633.
[2] Jia Z X. State-of-the-art and Future Trends of Cutting and Packing Studies[J]. Journal of Computer-aided Design & Computer Graphics,2004,7:890-897
[3] Gilmore P.C., Gomory R.E. A linear programming approach to the cutting stock program[J]. Operations Research, 1961, 9: 849-859.
[4] Gomes AM, Oliveira JF. A 2-exchange heuristic for nesting problems[J]. European Journal of Operational Research, 2002, 141: 359–70.
[5] Adamowicz M., Albano A. A solution of the rectangular cutting stock problem[J]. IEEE Transactions on Systems, Man, and Cybernetics, 1976, 6 (4), 302-310.
[6] Pal A, Charkhgard H. A Feasibility Pump and Local Search Based Heuristic for Bi-objective Pure Integer Linear Programming[J]. Informs Journal on Computing, 2019, 31(1), 115-133.
[7] Grange A, Kacem I, Martin S. Algorithms for the Bin Packing Problem with Overlapping Items[J]. Computers & Industrial Engineering, 2018, 115, 331-341.
[8] Liu Q, Cheng H B, Tian T, et al. Algorithms for the Variable-Sized Bin Packing Problem with Time Windows[J]. Computers & Industrial Engineering, 2021, 155: 107-175.
[9] Cemil Dikili A., Ebru SarıÖz, Nazan Akman Pek. A successive elimination method for one-dimensional stock cutting problems in ship production[J]. Ocean Engineering, 2007, 34:1841-1849.
[10] Cemil Dikili A., Ali Can Takinacı, Nazan Akman Pek. A new heuristic approach to one-dimensional stock-cutting problems with multiple stock lengths in ship production[J]. Ocean Engineering, 2008, 35, 637-645.
[11] Grefenstette J J, Gopal R, Rosmaita B J, et al. Genetic Algorithms for the Traveling Salesman Problem[J]. International Conference on Genetic Algorithms, 1985, pp: 160-168.
[12] Song K S. Research on Two-dimensional Nesting Based on the Genetic Algorithm [D]. Harbin Engineering University, 2010.