Engineering Applications of Artificial Intelligence 72 (2018) 294–309

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Heuristic algorithm for RPAMP with central rectangle and its application to solve oil–gas treatment facility layout problem

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ARTICLE INFO

Keywords:
Two-dimensional rectangle packing problem
Heuristic algorithm
Central rectangle
Aspect ratio
Computational complexity
Facility layout problem

ABSTRACT

In this study, we address a specific 2D rectangle packing area minimization problem with central rectangle (CR-RPAMP). The most distinguishing feature of CR-RPAMP is that there exists at least one central rectangle among the candidate rectangles. The proposed MHACR (modified heuristic algorithm for CR-RPAMP) includes three new strategies which are strategy of monitoring the aspect ratio, strategy of decreasing computational complexity and strategy of filling the marginal inner space. The computational complexity analyses show that MHACR has a lower computational complexity than the existing algorithms IHACR (improved heuristic algorithm for CR-RPAMP) and HACR (heuristic algorithm for CR-RPAMP). Then, a series of experiments based on 34 benchmark instances are carried out, and the experimental results show that MHACR can produce better solutions as compared with IHACR and HACR, especially under a narrow limited scope of aspect ratio. Finally, MHACR is used to solve the facility layout problem of oil–gas treatment factory, and the final layout generated by MHACR is more suitable than that obtained by IHACR. Therefore, we can conclude that MHACR is a remarkable heuristic algorithm to solve CR-RPAMP.

1. Introduction

The two-dimensional rectangle packing area minimization problem (RPAMP) is one of the most difficult problems in combinational optimization (Fleszar, 2016; Alvarez-Valdes et al., 2009), and has been applied in many industries such as metal, wood, glass, paper, automobile, aerospace, and textiles (Wei et al., 2011; He and Wu, 2013). As shown in the current literatures, there are many classification methods for RPAMP: (1) it can be divided into the strip packing problem (SPP) and the rectangle packing problem (RPP) based on the feature of the packing zone; (2) according to whether the candidate rectangles are in the oriented case, it can be classed as “O” (the items are oriented rectangles) and “R” (the items can be rotated by 90°); (3) in terms of guillotine cutting, RPAMP can be categorized into “G” and “F”, “G” means that guillotine cutting is required, “F” means that guillotine cutting is not required (Zhao et al., 2016; Alvarez-Valdes et al., 2008).

Since RPAMP is a kind of NP-hard problem, it is very difficult to solve it by using exact approaches (Horta et al., 2016). Therefore, lots of heuristic and meta-heuristic methods were presented in order to obtain a good solution in an efficient way (Beasley, 2004; Yu et al., 2016; Jansen and Prädel, 2016). The bottom-left (BL) fill method proposed by Brenda et al. (1980) and Bernard (1983) is one of the earliest and most famous heuristic algorithm. In BL, rectangles are placed into the container one by one, and every item is placed at the bottom-most and left-most location in the current layout (Liu and Teng, 1999). Besides, in order to find a satisfactory solution for RPAMP, Lodi et al. (2002) presented floor-ceiling (FC) method and touching perimeter (TP) method. Valenzuela and Wang employed genetic algorithm when solving the rectangle packing problem (Valenzuela and Wang, 2001). Moreover, the simulated annealing approach was used to iteratively improve the solutions, and to achieve good results on small size problem (Lai and Chan, 1997; Faina, 1999). For the purpose of finding a minimum height for two-dimensional SPP, a heuristic algorithm with a recursive structure was proposed by Zhang et al. (2006). To improve the performance of heuristic algorithm when solving big scale RPAMP, a heuristic algorithm was recommended based on the corner-occupying action and caving degree (Huang and Chen, 2007). In order to find a satisfactory solution for RPAMP, Wei et al. (2009) introduced the least wasted first (LWF) strategy. Edmund et al. (2001) proposed a packing method based on squeaky wheel optimization.

In last several years, many approaches have been presented to solve RPAMP. Ji et al. (2017) proposed an iterative merging packing algorithm. However, this algorithm just can address the soft rectangle

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https://doi.org/10.1016/j.engappai.2018.04.008
Received 27 September 2017; Received in revised form 6 April 2018; Accepted 8 April 2018
Available online 8 May 2018

packing problem, which is a variant of RPAMP. Wei et al. introduced an improved best-fit heuristic (ISH) to solve the 2D strip packing problem (Wei et al., 2017). Funke et al. (2016) introduced a new algorithm designed to solve floorplanning problem optimally. To address the strip packing problem, a hybrid metaheuristic that combines an improved heuristic algorithm with a variable neighborhood search was proposed by Zhang et al. (2016). Besides, the integer linear programming (ILP) model was provided by Martello and Monaci (2015). Dynamic reduction algorithm is another method presented by He and Ji (2015), this algorithm can transform the original problem to many RPP instances by dynamically determining the dimensions of the enveloping rectangles. Wang and Chen (2015) introduced a heuristic algorithm with a policy: maximize the residual space during packing. Bortfeldt (2013) presented a generic approach based on two algorithms, one for the 2D Knapsack Problem (KP), and the other for the 2D SPP. Based on the action space, He et al. (2013) proposed a deterministic heuristic algorithm to solve rotatable 2D strip packing problem. Bennell et al. (2013) utilized genetic algorithm for searching the solution space. Verstichel et al. (2013) proposed an improved BF heuristic named three-way best-fit heuristic. Leung et al. (2011) introduced a novel scoring rule to enhance the BF (Wei et al., 2017).

With different application requirements from industrial processes, the constraints and objectives are different when solving RPAMP (Wannakrairot and Phumchusri, 2016; Zhao and Shen, 2016). Recently, a specific two-dimensional rectangle packing area minimization problem with central rectangle named CR-RPAMP, was introduced. In CR-RPAMP, there exists at least one specific item (central rectangles) which must be placed near the center of the final layout, and the length–width ratio of the final layout is variable rather than fixed, but should be within a reasonable scope (Wu et al., 2017). Actually, CR-RPAMP widely occurs in industry, it is very significant to do deeply research on how to solve CR-RPAMP. Due to the particularity of CR-RPAMP, a specific heuristic algorithm named HACR was proposed (Wu et al., 2016). In HACR, a series of definitions and rules were introduced to form a basic framework on solving CR-RPAMP. Firstly, in order to make sure that the central rectangle is near the center of the final layout, it is advisable to constrain the betweenness centrality of central rectangle. Secondly, it is feasible to constrain the aspect ratio of the final enveloping rectangle to ensure the length–width ratio of the final layout within the limited scope. Besides, based on the priorities of candidate rectangles and strategy of padding inner space, the filling rate of the final layout can be in a high level. However, the main disadvantage of HACR is time-consuming. Thus, an improved HACR (IHACR) was presented to overcome the shortcomings of HACR (Wu et al., 2017). The experimental results show that the filling rate obtained by IHACR is higher than HACR, and the computing time of IHACR is much shorter. Although the new strategies included in IHACR can decrease the computational complexity, the computing time of IHACR is too long to solve large scale instance. Therefore, further improvements should be designed to solve CR-RPAMP.

The main focus of this study is to propose a preferable heuristic algorithm for CR-RPAMP. Based on the analyses of IHACR and HACR, some issues are illuminated based on specific instances. Actually, IHACR and HACR are powerless if the limited scope of aspect ratio of final layout is quite narrow. Therefore, novel strategy of monitoring the aspect ratio is presented so that it is noticed once the length–width ratio is not within the limited scope and then necessary operations will be carried out. In addition, another mechanism named strategy of decreasing computational complexity is introduced to effectively reduce the computational complexity of algorithm. Besides, for the purpose of increasing the filling rate of final layout, strategy of filling the marginal inner space is introduced. After integrating all the three strategies, a modified heuristic algorithm for CR-RPAMP called MHACR is presented. Then, the comparisons between MHACR and IHACR are performed based on a specific instance, and computational complexity analyses of MHACR are given to take an insight into the proposed algorithm. Then, we evaluate the proposed algorithm MHACR on a set of 34 benchmark instances, the experimental results show that MHACR has better performance compared with IHACR and HACR, especially under a narrow limited scope of aspect ratio. Finally, MHACR is employed to solve a real-word layout problem, the facility layout problem of oil–gas treatment factory.

The following sections are organized as shown below. Section 2 introduces the descriptions of CR-RPAMP. In Section 3, three strategies are described in detail and MHACR is stated, and then schematic descriptions showing the differences between MHACR and IHACR are introduced. The computational complexity analyses of MHACR are also shown in Section 3. The experimental results and comparisons are shown in Section 4. In Section 5, MHACR is employed to solve facility layout problem of oil–gas treatment factory. At last, the final section ends with a conclusion.

2. Descriptions of CR-RPAMP

Based on features of CR-RPAMP, it can be described as follows:

Given n rectangles with each item $\pi_i (1 \ll i \ll n)$ having width w_i and height h_i, the rectangle's area is calculated as $area_{\pi_i} = w_i \cdot h_i$. Then, based on the layout plane, a two-dimensional Cartesian Reference Frame is established. For every rectangle π_i, (x_{i1}, y_{i1}) and (x_{i2}, y_{i2}) are the bottom-left vertex coordinate and upper-right vertex coordinate (Wu et al., 2016).

$$min\ Area_n = H_n \cdot W_n \tag{1}$$

$s.t.$

$$(x_{i2} - x_{i1}, y_{i2} - y_{i1}) \in \{(w_i, h_i), (h_i, w_i)\} \tag{2}$$

$$max(x_{i1} - x_{j2}, x_{j1} - x_{i2}, y_{i1} - y_{j2}, y_{j1} - y_{i2}) \geq 0 \tag{3}$$

$$0 \leq x_{ik} \leq W_n, 0 \leq y_{ik} \leq H_n, k \in \{1, 2\} \tag{4}$$

$$Nar_n \in [Nar_{min}, Nar_{max}] \tag{5}$$

$$Z_{H,m} \in [Z_{H,min}, Z_{H,max}] \tag{6}$$

$$Z_{W,m} \in [Z_{W,min}, Z_{W,max}] \tag{7}$$

Formula (1) means to find a minimum area of the final layout; formula (2) means that each rectangle must be packed orthogonally; formula (3) means that the rectangles are packed with no overlap occurs; formula (4) means that all rectangles are included in the final layout; formula (5) means that the aspect ratio of the final layout must meet the requirements; formula (6) and formula (7) mean that the betweenness centrality of central rectangle must fall in the scope.

In this paper, the definitions and rules mentioned in IHACR and HACR will still be used, and the detailed descriptions are referred as shown in the corresponding literature. Here, we just list the names and related symbols in Table 1. Moreover, in order to facilitate the comparisons with existing algorithms, the flowchart of IHACR is shown in Fig. 1 according to literature (Wu et al., 2017).

3. MHACR: A modified heuristic algorithm for CR-RPAMP

In this section, a modified heuristic algorithm named MHACR including three new strategies (strategy of monitoring the aspect ratio, strategy of decreasing computational complexity and strategy of filling the marginal inner space) is illuminated. Actually, one of the main advantages of MHACR is that it can monitor the aspect ratio of transitional layout, the strategy of monitoring the aspect ratio can effectively improve the length–width ratio of the final layout especially there exists a rigorous constraint for the value of aspect ratio. In detail, before selecting the next rectangle, MHACR will check the aspect ratio of the current layout. It is noticed once the length–width ratio of the current layout is not within the limited scope of aspect ratio. Then, MHACR will give a suggestion for the packing position of the next rectangle to produce a satisfactory transitional layout. Besides, if there are live inner spaces in the current layout, MHACR will calculate and record the information of these inner spaces, and then implement strategy of