Research on Bin Packing Problem Based on Supply Chain Economic Efficiency

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Abstract. The study of the bin packing problem is of great academic significance and plays an extremely important role in the economy and society. By studying the bin packing problem, find the optimal packing layout to achieve resource conservation and economic benefits. This paper summarizes, analyzes and concludes the constraints and algorithms of the packing problem under the background of one-dimensional and two-dimensional, puts forward the shortcomings of the current research on the bin packing problem, and gives corresponding suggestions for the shortcomings of the problem and proposes the future research directions. The experiments show that RLHA significantly outperformed the other four algorithms.

Keywords: bin packing problem · exact algorithm · approximate algorithm · heuristic Algorithm

1 Introduction

The research on the bin packing problem originated in the 1960s. In the bin packing problem, there are generally two types of items, including the goods to be packed and the boxes. Which usually have a quantity limit. The boxes are hollow and the goods need to be filled into the boxes to complete the packing process. Throughout the process, researchers focus on changing the layout of the items to improve the utilization rate of space so as to increase economic benefits. From the perspective of actual production, due to the improvement of packing layout, each packing can reduce the waste of boxes, thereby reducing production costs. Especially in the context of mass production, the improvement of box utilization rate has important economic significance.

In order to effectively solve various types of packing problems, researchers have constantly put forward new ideas and solutions. Nevertheless, the packing problem is still one of the problems in the current academic circle, and there are certain limitations in all kinds of studies. In the existing literature, most studies choose regular rectangular objects as the research objects, and few studies choose non-rectangular or irregular or spherical objects. In addition, one-dimensional packing is relatively mature due to its early presentation and low difficulty, and the focus of research has shifted to two-dimensional and three-dimensional packing with higher difficulty.

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This paper mainly reviews and analyzes the constraints and algorithms of packing problems in recent years according to the spatial dimension of bin packing problems. The second chapter mainly summarizes the common constraints of one-dimensional and two-dimensional packing problems. The third chapter mainly summarizes the commonly used algorithms of one-dimensional and two-dimensional bin packing problems. The fourth chapter summarizes the influence of packing problems on the economic benefits of supply chain and the significance of studying packing problems in economic society. The fifth chapter summarizes the existing research and gives the future research direction.

2 Overview of Packing Problem

The bin packing problem belongs to the classical NP-hard problem, which exists in various application scenarios. It provides solutions for various resource allocation problems in the actual production and manufacturing process, and ultimately achieves the improvement of economic benefits. The NP-hard problem is difficult to be solved in polynomial time, that is, there is no effective algorithm for this kind of problem. Therefore, in the previous research process will choose to sacrifice the optimality of the solution to find a suboptimal solutions within a reasonable range, and the algorithms would be designed. The diagram of NP-hard problem is shown in Fig. 1.

After a long time of research and testing, various excellent algorithms have emerged in the research field of packing problem. The idea of the algorithm has also been referred to the actual production to achieve better resource allocation. According to the packing dimension and the chronological order of the literature, some research results at home and abroad will be expounded in turn.

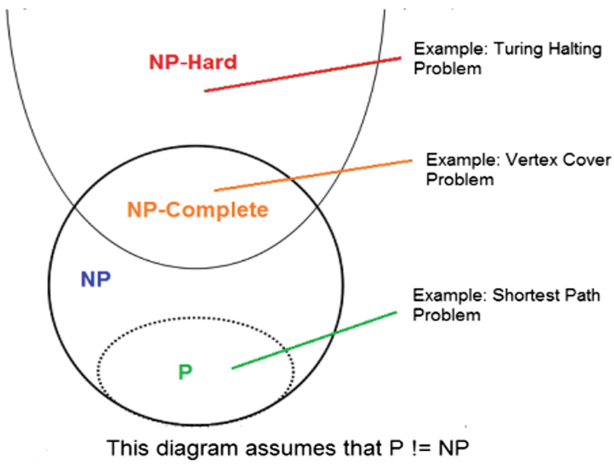

Fig. 1. Diagram of NP-hard problem

2.1 One-Dimensional Packing Problem

One-dimensional packing problem is an optimization problem with practical significance, including the cutting of wooden sticks, wiring of wires and cutting of thin materials, etc., All of these are one-dimensional packing problems with dimensions. However, the size of one-dimensional packing problem is not limited to the size of the physical meaning of length, but also can represent the generalized one-dimensional quantity such as volume and cubage, etc., This problem mainly studies how to rationally allocate the items to be loaded, so that they are arranged in a certain order, and finally all of them enter the box of unit volume and make the number of boxes used minimum or the number of items contained in the unit box maximum.

In their research, Gu Xiaodong, Xu Yinlong, etc. [1] for the one-dimensional packing problem with start-up space constraints, the common algorithms are used to test it. The final results show that most of the classical online packing algorithms do not have a deterministic worst-case asymptotic ratio when solving this problem, and thus FC-NF online packing strategy is proposed. The study effectively proves that the algorithm has a deterministic worst-case approximation ratio for packing problems with start-up space constraints and classical BPP problems.

Dong Yihong and Zhao Jieyu [2] in the study of the non-ferrous packing problem, found that the previous use of the KC-A algorithm on the basis of the original problem increased the pre-classification of this process, and ultimately lead to bad experimental results, thus making improvements on the KC-A algorithm, proposing the SCPF-A algorithm, the same color unified classification, and in place to follow the “first place” principle, the final example proves that SCPF-A algorithm in the case of low color algorithm superiority.

Cao Jing, Zheng Wei, and Xu Minhong [3] proposed to use greedy algorithm to solve the multi-objective constrained one-dimensional packing problem under the actual production background. Compared with the commonly used optimization method of random search, they innovatively proposed the optimization idea of discrete combination, added optimization variables to the rough solution to achieve the optimal solution, and proposed the tree search to make up for the limitations of the greedy algorithm, and combined with the pruning algorithm to find the optimal model. According to the actual data test, this method has significantly improved the accuracy of the algorithm, but the algorithm is only applicable to the one-dimensional packing problem.

In studying of the one-dimensional boxing problem with time dimension, Wang Junling [4] proved that the greedy algorithm is the optimal algorithm for the ordered baking problem under this domain, and proposed four improved algorithms based on the BASIC algorithm for the unordered baking problem, including the SIZE algorithm, TIME algorithm, SIZETIME algorithm, and QUASIHUMAN algorithm. The examples show that the four algorithms have different effects under different conditions, and the best way is to use four algorithms at the same time.

When Zhang Minghui and Han Xin [5] studied the one-dimensional packing problem based on item size division, they set the constraint that the upper limit of the size of all loaded items is 1 / 2. Under this constraint, they proposed a new one-dimensional online packing algorithm, and added size division and set new packing rules in the algorithm design. In addition, they also reduced the competition ratio by expanding the buffer. Finally, the worst-case ACR analysis of the algorithm is carried out, and the asymptotic competition ratio is 1.4236. Under the background of the new example, the lower bound value is reduced to 1.4231.

When Cheng Huibing [6] studied the packing problem with time window constraints (1DBPP-TW), for 1DBPP-TW and variable-size packing problem with time window constraints (VSBPPTW), he proposed greedy algorithm based on time range and optimal adaptation algorithm to generate the initial solution of the problem, and developed iterative local search algorithm (ILS) for the generated initial solution to improve the quality of the solution. After case testing, the designed ILS has high performance in solving 1DBPP-TW and VSBPPTW, and can be applied to VSBPP problems.

2.2 Two-Dimensional Packing Problem

The two-dimensional packing problem refers to the rational arrangement of the items to be packed under the two orthogonal directions, and the packing is loaded into the space with constraints. Its goal is to pursue the minimum space for the use of packing or to achieve the highest economic benefit of packing in a fixed space. The constraints include: 1) There should be no overlap in dimensions between the packing items; 2) The packing items should not exceed the boundary of the given space in each dimension. The problem widely exists in the logistics of goods loading, container loading and cloth production scenarios, with high practical and economic significance.

Yao Yi and Lai Chaoan [7] proposed to use a two-dimensional packing heuristic algorithm based on sequential value correction strategy to solve the two-dimensional packing problem with shear constraints. This method can set a higher value for the items that are difficult to be packed to prioritize packing, effectively avoiding the formation of poor schemes, and ultimately improving the packing rate. However, it takes more time to call the algorithm multiple times.

In Wang Yongsheng's [8] research, He proposed to use the first-fit heuristic algorithm based on open space to solve the two-dimensional packing problem with unloading constraints. In this study, the line segment tree structure is used to realize the unloading constraint, and the open space method is used to efficiently describe the position of the filled rectangular block. Finally, the algorithm is optimized by the local search method and the iterative algorithm. This method is superior to the GRASP algorithm in most case tests, and has obvious advantages over the B & C algorithm in large-scale samples.

Sun Baofeng, Wang Shuai, etc. [9], when studying the two-dimensional packing problem with conflict relationship, proposed constructing conflict matrix, packing conflict goods separately and considering load safety, and finally established two-dimensional packing optimization model with cargo conflict. According to the characteristics of the algorithm, the greedy algorithm is preferentially used to preprocess the solution set to quickly obtain the initial feasible solution that meets the requirements, and then the combined optimization algorithm of simulated annealing algorithm is adopted as a whole to effectively avoid falling into local optimum, and verifies its superiority through experiments.

In their research, Zhou Yujing, Chen Guowei, etc. [10] proposed a two-dimensional packing with placement constraints in combination with the constraints on the placement of goods in practical cases, including parts loading need to face outward, vertical stacking restrictions. They designed the loading optimization scheme based on the case-based algorithm, applied it to the actual scene, and optimized the parameters according to the production demand. The final results show that the process and algorithm can obtain better solutions than the actual operation, effectively reduce the number of logistics operations and improve the logistics loading rate.

Shang Zhengyang, Huang Qiuyan et al. [11]. In their research, aiming at the two-dimensional packing problem with one-size-fits-all constraint, they put forward the IPH algorithm based on the selective placement and space segmentation strategy of filling effect priority proposed by Zhang et al., and introduced the "bricklaying method" in the algorithm design, and proposed the brick-building space segmentation rule, which improves the solution performance of the algorithm and reduces the possible space waste. The final experimental results show that IPH has better performance in running efficiency and solving accuracy than the existing fast algorithms.

3 Common Algorithms for Packing Problems

3.1 One-Dimensional Algorithm

In the study of one-dimensional packing, the ratio of the solution of the algorithm in the worst case to the optimal solution of the instance problem is defined as the approximate ratio of the algorithm. For any instance I, the solution obtained by the operation of algorithm A, that is, the number of boxes calculated by algorithm A is A(I); OPT(I) represents the minimum number of boxes actually used in instance I, the optimal solution. For any instance I, $A(I) \leq \alpha OPT(I)$, then the maximum approximation ratio of algorithm A is α, also known as the absolute approximation ratio of algorithm A is α. If for any instance I, $A(I) \leq \alpha OPT(I) + o(OPT(I))$, the maximum asymptotic approximation ratio of algorithm A is α, and the lower bound of all α satisfying the formula is the asymptotic approximation ratio of algorithm A, denoted as r_A^∞. The closer the α value is to 1, the closer the number of boxes calculated by the algorithm is to the minimum number of boxes used in the actual situation.

The one-dimensional packing problem was first studied by Ullman JD [12] in 1971 and first proposed the First-fit algorithm, and then proposed the Best-fit algorithm, and proved that the two algorithms satisfy $FF(i) \leq 1.7OPT(I)+3$ and $BF(i) \leq 1.7OPT(i)+3$ for any instance I. Based on the fact that the packing rules in the First-fit algorithm and the Best-fit algorithm will have the same worst-case in some cases, Johnson, D. S. [13] proposed in 1974 that the input list in the one-dimensional packing problem should be arranged in advance in descending order, which can effectively improve the above worst case. Finally, it is proposed that the worst case of the linear time approximation algorithm is as good as that of the First-fit algorithm under the condition of meeting the constraints. In 1985, C. C. Lee and D. T. Lee et al. [14] proposed a space-constrained HARMONIC algorithm which is superior to the First-fit algorithm and proved that the approximation ratio of the algorithm is less than 1.636 in the worst case. Adriana C. F. Alvim [15] proposed a hybrid improved heuristic algorithm for the packing problem in 2004. This method includes the following characteristics: using the lower bound strategy, using the dual minimax problem to generate the initial solution, using the improved process based on dominant, differential and unbalanced load distribution and using emergency search. The empirical test shows that compared with other approximate algorithms, the hybrid improved heuristic algorithm can find the maximum number of optimal solutions. In 2012, Balogh, J. [16] and others improved the optimal lower limit of the online algorithm proposed by van Vliet in 1992 and "the asymptotic approximation ratio without online algorithm can be better than 1.54014", and the value was finally accurate to 1.54037. In addition, they also improved Csirik's proposal in 1983 that "without online algorithm, the asymptotic approximation ratio can be less than 8 / 7 after non-incremental preprocessing," and increased the result to 54 / 47.

3.2 Two-Dimensional Algorithm

In the study of two-dimensional packing problem, since 2D-SPP is proved to be NP-hard, there are three main solutions for this kind of problem: exact algorithm, approximate algorithm and heuristic algorithm.

The objective of the exact algorithm is to find the optimal solution of the problem. The main methods include tree search algorithm, branch and bound method and some derivative algorithms. These methods can obtain the optimal solution when solving small-scale problems, but are not suitable for large-scale scenarios. The approximation algorithm cannot guarantee the optimal solution, but it can give the gap between the obtained solution and the optimal solution. The main algorithm includes the bottom-left algorithm proposed by Baker et al. [17] in 1980, and the absolute approximation ratio of the algorithm is 3. It is proposed that the rectangular goods problem and the goods sequence problem should be considered. By 2014, Nikhil Bansal [18] had adopted an improved approximation algorithm based on R & A architecture, using the NFDH process in the preprocessing, with an absolute approximation accuracy of 1.405.

The heuristic algorithm is the most commonly used method in this field. It relies on the subjective and experience of the constructor to design the algorithm to give a feasible solution in an acceptable range. The quality of the solution has no theoretical guarantee, which usually includes genetic algorithm, simulated annealing algorithm, neural network algorithm and hybrid heuristic algorithm. In 2011, Leund et al. [19] proposed a layer-based heuristic algorithm to solve the large-scale packing problem with orthogonal rotation and without guillotine packing constraint. After the test of each scale data, the algorithm has superior performance and does not involve the selection of parameters to ensure its stability, which has good practical value. In 2019, Gao Dongchen [20] improved the original rule R by adding relaxation constraints on the basis of Leund et al., and proposed simulated annealing algorithm SA2 based on α-R rule and reinforcement learning algorithm SA3 based on scorer scoring function. The experimental results show that the effect of using scorer scoring function and α-R rule at the same time is better, and the improved rule is more suitable for actual data. In addition to some heuristic algorithms mentioned above, Qu Yuan and Wang Xuelian [21] use tabu algorithm to solve large-scale packing problem, which uses natural number coding and introduces penalty function to represent space utilization constraints. The convergence process of the algorithm is stable and can ensure the superiority of the solution obtained in large-scale situations. Jiang Jinshan and Lin Zhengchun [22] proposed adaptive genetic algorithm, adding function to simulate the harsh environment in the algorithm, so that the crossover rate and mutation rate can be adjusted according to the actual situation to achieve adaptive, and improved the fitness function, solved the problem of crossover and overlap, and effectively improved the convergence speed of the algorithm.

The algorithm has important practical significance for solving the packing problem, but the application scenarios of the three algorithms (exact algorithm, approximate algorithm and heuristic algorithm) are different, which need to be selected and adjusted according to the actual needs. The exact algorithm determines the disadvantage of time complexity due to its own nature, which is suitable for solving small-scale and low-dimensional packing problems. Approximate algorithm and heuristic algorithm make a concession on the quality of the solution, in order to obtain a better solution in a shorter time. The heuristic algorithm is designed by subjective experience to obtain feasible solutions with acceptable time, which is more suitable for large-scale scenarios than the approximate algorithm.

4 The Impact of Packing Problem on Economic Efficiency of Supply Chain

4.1 Impact of Container Shortage on Global Supply Chain

As of March 2020, the resumption of work of container transport related enterprises is as follows: the resumption rate of intermodal transport enterprises such as ports, barges and railways has reached 100%, transit and warehousing enterprises' rework rate is 90%, and the remaining enterprises are gradually resuming work. Although reprocessing enterprises can ensure the recovery of their own production capacity, due to the backlog of orders, lack of supply and shortage of road transport capacity, enterprises from all sides cannot respond to demand in a timely manner. In addition, due to the uneven rework outlets of transportation enterprises, the regional shortage problem is particularly obvious, and there are still many regions that cannot be reworked under the influence of local policies. As a result of the above situation, the supply chain stops for a long time, and a large number of containers are backlogged up in the previous ports, transfer stations, logistics parks, etc. which cannot be shipped out due to insufficient policy or transportation capacity and subsequent containers cannot be entered, occupying a large number of limited space and causing economic losses.

After the epidemic situation was stable in December 2020, the heat of overseas orders made the shortage of containers widely concerned. Due to the global epidemic situation, the international logistics capacity decreased, resulting in the soaring freight of container ships and serious shortage of containers. The lack of containers is mainly due to the mismatch between supply and demand cycles. The global trade contraction in the past two years and the sudden outbreak of the epidemic and the implementation of the blockade policy have led to a decline in the capacity of container enterprises. Subsequently, countries such as Europe and the United States have reopened their economies and rebounded in demand, resulting in insufficient container capacity. In addition, the semi-shutdown of ports in some overseas countries is also the main reason for the prolonged turnover of containers.

4.2 Container Shortages Has a Significant Impact on Global Supply Chains

With the gradual deepening of economic globalization, the economies and policies of various countries in the world are integrated, and enterprises are looking for partners on a global scale. In the era of underdeveloped information technology and logistics, the competition of enterprises completely depends on their own development, which requires their own design, production and transportation products. Each link consumes a lot of manpower and material resources to maintain operation. In the modern economic environment, the competition of enterprises has evolved into the competition of the complete supply chain. The upstream enterprises design products, deliver them to the downstream suppliers for production and manufacture, and sell them to the customers by the distributors. Each link is closely linked. It does not require an enterprise to manage each step, and can devote all efforts to optimize product design or process skills.

With the deepening of trade links, the supply chain network has become rapid and efficient. When emergencies occur, such as the outbreak of the new coronavirus at the end of 2019 and due to the different epidemic situations and policies in various countries, some links are in a state of regional closure, and the production activities are suspended, which leads to the stagnation of the whole supply chain. The stagnation of production and transportation affects the supply of commodities, and ultimately leads to a significant reduction in the economic benefits of enterprises. Most enterprises in society need to face the risk of shrinking returns or even bankruptcy due to the cessation of production or some links, which ultimately affects the GDP of the whole region. The suspension of enterprises causes employees to have no wage income and no living security (such as the lack of daily necessities), makes employees panic caused instability in local areas, and ultimately affects the social situation, resulting in social instability. The outbreak of the epidemic caused some links of the supply chain to pause or even destroy, through the transmission of the supply chain to the upstream and downstream enterprises of the link, and finally the domino effect, affecting the whole region and even the global economy.

4.3 Study the Effect of Packing Problem on Improving Economic Benefit of Supply Chain

The packing problem is essentially a combinatorial optimization problem, and the problem itself is to study the packing type problem, with the purpose of saving packing space and improving economic efficiency. Under the influence of the new coronavirus epidemic, in order to prevent the interpersonal spread of the virus, the government announced relevant prevention and control policies, requiring all types of enterprises to stop production and work, and restricting and blocking the various gateways of road transportation. Therefore, containers have become a hot commodity due to the sudden decline in production capacity and the blockade of road transportation. Due to the shortage of containers, international transportation enterprises cannot arrange the export of goods, resulting in the cancellation or default of foreign trade orders, and the slowdown in international commodity circulation, which eventually leads to a decline in the total international trade economy.

The research on the packing problem has reference significance for the improvement of the utilization rate of container space. If more goods can be contained in the limited container space, the economic benefits of single export can be improved, the international trade turnover can be accelerated, and the total international trade economy can be improved. At the same time, the increase in the number of export goods, will help to restore the production capacity of the subsequent commodity supply chain, so as to ensure the timely supply of necessary goods and daily necessities, so as to meet the market demand and restore regional economic benefits. When the necessities of life are met, the tension among the people in the region is eased, which has important practical significance for social stability.

5 Experimental Design and Result Analysis

To verify the effectiveness of RLHA, we compare and analyze the trained model framework with current well-known heuristic algorithms. Part of the experimental data for our comparative analysis comes from standard datasets. We will conduct experiments on six standard datasets: C, N, NT, 2SP, BWMV, Nice and Path. We will compare the experimental results of the five algorithms and mark the data with the best solution in bold. The reason why we did not consider the standard dataset ZDF is that there are large-scale instances in this dataset, and the current reinforcement learning model can take too long to process large-scale instances. Due to limitations in computing power and running time, These two datasets containing large-scale problem instances are not subjected to experimental analysis. From the experimental results in Table 1, the performance of RLHA on the N dataset is the same as that of HHA. The N dataset is a zero-wave rate dataset, and our algorithm has achieved optimal solutions in most instances. Therefore, the performance of the two algorithms on this dataset is not different. The performance of RLHA on the 2SP dataset is the same as that of HHA. The reason for this may be related to the characteristics of the data. The number of data rectangles is small and there are some specific instances that require more elaborate strategies to improve. Our heuristic designed rules may have fallen into a bottleneck in the performance of this dataset, so they did not achieve better results. For the remaining datasets, RLHA outperformed HHA, and in all datasets, RLHA significantly outperformed the other four algorithms.

Table 1. Computational results on benchmark data

Dataset	Average gap rate (%)				
	GRASP	SVC	ISA	HHA	RLHA
C	0.93	1.05	0.85	0.45	0.44
N	1.26	1.12	0.95	0.21	0.21
NT	2.12	2.05	2.31	0.96	0.96
2SP	2.17	1.96	1.98	1.32	1.32
BWMV	1.94	1.63	2.05	1.24	1.02
Nice	1.69	1.01	1.14	0.96	0.75
Path	1.68	0.98	1.33	0.35	0.34
Average	1.68	1.40	1.52	0.84	0.72

6 Conclusion

6.1 The Deficiency of Current Research on Packing Problem

So far, most of the existing studies have set various constraints to the packing problem according to actual needs, including the selection of one or more of the objects such as goods, boxes and packing methods to limit the discreteness of the problem solution. In addition, a more efficient solution can be achieved by preprocessing the goods with a reasonable packing method. Due to the combination of various constraints, the packing problems are different. For different packing problems, we usually have two kinds of thinking logic: static thinking and dynamic thinking. Static thinking is to regard the dynamic packing process as countless static time points, which need to meet the needs of static at each time point, so as to achieve the overall satisfaction of the needs. Dynamic thinking needs to present the time line deduction, and simulate the process to observe the dynamic process in a clearer way. For the presentation of static thinking, researchers usually use the drawing form to describe the packing mode with accurate model diagrams. For the display of dynamic processes, it is difficult to achieve image description only by static graphic or pseudo-code, and it is limited to help readers understand the dynamic model. In high dimensional cases, especially with time dimension, there is also such a situation, that is, the content and ideas that the researcher wants to express cannot be clearly displayed.

In the algorithm research of packing problem, due to the differences in dimensions, constraints and optimization objectives, the methods used by researchers are different. Some of these methods do not have universality, and are only applicable to certain specific situations. For example, due to the high cost of solving the exact algorithm, it is generally only used for small and low-dimensional packing problems, and it is not necessarily possible to obtain the optimal solution. Therefore, most researchers prefer heuristic algorithms and hybrid algorithms, and thus pay insufficient attention to the research of the exact algorithm. The number of literature has decreased significantly since 2010. However, with the progress of science and technology, such as cloud computing, quantum computers and other technologies, the rapid improvement of disposable computing power has been achieved, which is very helpful for solving exact algorithms with high time complexity. Therefore, in the future research of packing problems, researchers can use more exact algorithms in large-scale and high-dimensional packing problems.

6.2 Outlook

The packing problem is still an important part of combinatorial optimization problems. The solution of packing problem has important reference value for practical applications (such as industrial applications, resource scheduling, etc.). Based on the research and analysis in this paper, the following prospects are given:

(1) Nowadays, the research of packing problem has a variety of emphases, such as large-scale, high-dimensional, dynamic and so on. It is difficult to help readers better understand the researchers' ideas only by static graphics and pseudo-code interpretation. It is necessary to devote more energy to the simulation software and dynamic model program related to packing problem.

(2) The algorithm of packing problem is largely affected by the scale of packing, the way of packing and the number of dimensions. Limited by the number of disposable computing power, the research of exact algorithm has progressed very slowly since 2010, and now cloud computing, quantum computers and other technologies have been scaled up, and the number of disposable computing power in the study has increased significantly. Therefore, the research of exact algorithm should get higher attention from researchers to achieve a balance between the solution quality and the complexity of the algorithm time.

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