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Three-stage heuristic algorithm for three-dimensional irregular packing problem

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ABSTRACT

This paper studies a new practical problem which can be decomposed into three three-dimensional packing problems: three-dimensional irregular packing with variable-size cartons problem, three-dimensional variable-size bin packing problem, and the single container loading problem. Since the three sub-problems are NP-hard, searching a good solution becomes more difficult. In this paper, mathematical models of each sub-problem are developed and three-stage heuristic algorithms are proposed to solve this new problem. Experiments are conducted with random instances generated by real-life case. Computational results indicate that the proposed algorithm is efficient and can yield satisfactory results.

1. Introduction

Packing is one of the important resource allocation problems across different industrial sectors, it is especially true in the logistics and manufacturing industries. As computer technology to improve the utilization of resources, the packing algorithm, especially for the three-dimensional (3D) packing problem, plays a pivotal role in combinatorial optimization problems. Optimal loading space utilization saves not only space but also transportation cost and resources.

This paper investigates a new problem from the industrial field. In this problem, customers order irregular-shaped fasteners. There are three types of fasteners: hexagon nuts, double end stud, and hexagon head bolts. The same type of fasteners ordered by one customer is packed into a carton. The first problem is how to pack these irregular fasteners into cartons with variable size such that the utilization of cartons is highest. At the same time, cartons belonged to the same customer are packed into a crate, the second problem is regarded as a three-dimensional (3D) variable-bin packing problem. Finally, different crates are loaded into a container for delivery by a truck. Therefore, it involves a single container loading problem. The 3D bin packing problem is a NP-hard problem in a strong sense (Martello et al. [1]). Therefore, this new problem described here is NP-hard and more challenging. In this paper, we propose a novel algorithm for 3D irregular fasteners packing problem and 3D bin packing problem.

Although the logistics and manufacturing industries in Asia-Pacific region have been expanding gradually in recent years, the research topics so far are focused on theory such as algorithm design, the practical applications of 3D-packing algorithms receive less attention from stakeholders.

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This paper presents a three-stage heuristic algorithm for a new practical problem. The first stage uses an efficient heuristic algorithm to pack the fasteners into cartons. The second stage solves the problem of packing cartons into crates. The final stage addresses a single container loading problem. The algorithms for the last two stages are based on a heuristic block loading algorithm proposed by Zhang et al. [2].

This new practical problem is far too important for a fastener factory which manufactures fasteners of many types. Usually, the fasteners are in small size but in large quantity, and are transported to different destinations. These features (large amount, different types, transported to different destinations, etc.) result in the difficulty of transportation. To dispatch the fasteners easily, they are loaded in three stages, and in each stage, fasteners are packed into different kinds of containers. In practice, the efficient packing strategy is hard to generate artificially. This paper aims to propose an algorithm to help improve the competitiveness and logistics efficiency of the fastener industry.

This paper is organized as follows. In Section 2 we introduce the related work. Section 3 presents the model of the new problem. The detailed algorithm is introduced in Section 4 . Section 5 reports the computational results of the practical test instances. Finally, the last section summarizes the work.

2. Literature review

The new problem addressed in this paper includes a single container loading problem, three-dimensional variable-size bin packing problem (3DVSBPP) and 3D irregular packing problem with variable-size cartons.

The container loading problem is an NP-hard problem and exact algorithms are often used to solve problems of small scale. In reality, heuristic algorithms are preferentially used to solve problems of large scale. The first algorithm for this problem is proposed by George and Robinson [3]. It uses a wall-building approach, but it does not take constraints like orientation restriction into consideration.

To solve this problem more efficient, a number of approaches have been proposed to arrange the boxes into layers and towers. Pisinger [4] developed an algorithm which fills the container with layers. Gehring and Bortfeldt [5] proposed an algorithm based on the conception tower, and the algorithm is proved to attain good stability. Lim et al. [6] also developed a basic heuristic and two augmenting heuristics for 3-D container packing problem. Huang and He [7,8] proposed two effective heuristic algorithms by using the idea of caving degree for a class of container loading problems. Bischoff and Marriott [9] compared 14 kinds of layer-based approaches.

Eley [10] and Bortfeldt et al. [11] developed an algorithm based on the concept of block, which tries to compose one or two types of boxes into blocks. Zhang et al. [12] proposed a combined heuristic algorithm using a simulated annealing and a bin-loading algorithm to solve this problem. Fanslau and Bortfeldt [13] developed an algorithm which constructs the basic blocks into a compound block. Zhang et al. [2] proposed a block-loading algorithm based on multi-layer search. The algorithm chooses a block to make the result closer to the best solution. Liu et al. [14] developed a tree search algorithm for the container loading problem. Several meta-heuristic algorithms are also developed for the single container loading problem with practical constraints (Wang et. al. [15]; Lim et al. [16]). For classification and survey of container loading problems, the readers can refer to Dyckhoff and Finke [17], Bortfeldt and Wäscher [18].

For the three-dimensional bin packing problem (3DBPP), Chen et al. [19] developed a mixed integer programming formulation without orientation restriction. Martello et al. [1] proposed an exact algorithm for filling a single bin and discussed the lower bounds for this problem. Martello et al. [20] developed an algorithm to solve moderately large instances better for the general 3DBPP.

Due to the strong NP-hardness of this problem, heuristic algorithms are often used in reality. Bischoff et al. [21] presented a pallet loading heuristic algorithm for 3DBPP with non-identical cartons. George [22] gave a case study of pipe packing for multiple container packing. Lodi et al. [23] introduced a tabu search framework by using a constructive heuristic to evaluate the neighborhood. Pisinger [4] developed a heuristic algorithm based on the wall-building approach. Faroe et al. [24] presented a heuristic algorithm based on a guided local search to pack cartons into a minimum number of identical containers. Baltacioglu et al. [25] developed a new heuristic algorithm based on mimicking human intelligence to solve the 3DBPP. Correia et al. [26] presented a two-level tabu search for 3DBPP with fixed orientations. More recently, Parreño et al. [27] developed a hybrid GRASP/VND algorithm for two- and three-dimensional bin packing problem. Wu et al. [28] proposed a genetic algorithm based on packing index to utilize the special problem feature for the 3DBPP. Zhu et al. [29] developed a prototype column generation strategy for the multiple container loading problem. He et al. [30] proposed a global search framework for the practical three-dimensional packing with variable carton orientations. Gonçalves et al. [31] presented a biased random key genetic algorithm for 2DBPP and 3DBPP. In the steel industry, Viegas et al. [32] proposed a tabu search algorithm for the 3DBPP to address a real-world steel cutting problem from a retail steel distributor, which reduce the stock variation by up to 179%.

Although the algorithms for the BPP with identical bins can be extended to solve the 3DVSBPP, research on the 3DVSBPP is relatively scarce. Alvarez-Valdes et al. [33] proposed a GRASP/Path relinking algorithm to solve the three-dimensional multiple bin-size bin packing problem. The GRASP algorithm includes a constructive procedure, a post-processing phase and some improvement moves. The best solutions obtained from the algorithm are then combined into a Path Relinking procedure. A new lower bound for 3DVSBPP was found by Alvarez-Valdes et al. [34]. The proposed bounds improve the results of previous bounds by more than 10%. For the practical problem, Paquay et al. [35] solved a 3DVSBPP with additional constraint in the field of air transportation by mixed integer linear program. Recently, Wei et al. [36] developed