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Optimization of one-dimensional Bin Packing Problem with island parallel grouping genetic algorithms ☆

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ABSTRACT

The well-known one-dimensional Bin Packing Problem (BPP) of whose variants arise in many real life situations is a challenging NP-Hard combinatorial optimization problem. Metaheuristics are widely used optimization tools to find (near-) optimal solutions for solving large problem instances of BPP in reasonable running times. With this study, we propose a set of robust and scalable hybrid parallel algorithms that take advantage of parallel computation techniques, evolutionary grouping genetic metaheuristics, and bin-oriented heuristics to obtain solutions for large scale one-dimensional BPP instances. A total number of 1318 benchmark problems are examined with the proposed algorithms and it is shown that optimal solutions for 88.5% of these instances can be obtained with practical optimization times while solving the rest of the problems with no more than one extra bin. When the results are compared with the existing state-of-the-art heuristics, the developed parallel hybrid grouping genetic algorithms can be considered as one of the best one-dimensional BPP algorithms in terms of computation time and solution quality.

1. Introduction

Many practical optimization problems require efficient grouping (clustering) of a set of items into a collection of disjoint subsets according to some specific constraints. The well-known one-dimensional Bin Packing Problem (BPP) is such a NP-hard combinatorial grouping problem that often occurs in real life including engineering, logistics, and manufacturing (Garey & Johnson, 1979; Johnson, Demers, Ullman, Garey, & Graham, 1974). The BPP appears as the main problem or a significant subproblem in a large number of industrial applications (Camacho, Terashima-Marin, Ochoa, & Conant-Pablos, 2013; Fleszar & Charalambous, 2011; Fleszar, 2012). Two/three dimensional versions of BPP are frequently faced during manufacturing processes. For instance, in clothing, construction, glass, plastic, or metal industries, components need to be cut from the fewest sheets of material (Dahmani, Clautiaux, Krichen, & Talbi, 2013). Similarly, when designing the layout of the pages of a newspaper, the editor needs to arrange the articles on pages of fixed dimensions. In the shipping and transportation industries, packages of identical heights have to be loaded in the minimum number of rectangular bins.

Informally, the BPP is the process of packing n items into a number of same size and shape (for ease of planning and transportation) bins with a capacity of c where the objective is to minimize the number of bins required to contain n items (Gupta & Ho, 1999; Martello & Toth, 1989). The number of bins is assumed to be unlimited, each with capacity $c > 0$. A set of n items is to be packed into bins and the size of item $i \in \{1,\ldots,n\}$ is $s_i > 0$, as shown in Eq. (1):

$$\forall k : \sum_{i \in bin(k)} s_i \leqslant c \tag{1}$$

The goal of one-dimensional BPP is to find the minimum number of bins, M, required for packing all n items (Eq. (2)):

$$M \geqslant \left\lceil \left(\sum_{i=1}^{n} s_i \right) \Big/ c \right\rceil \tag{2}$$

Modern parallel computation environments such as grid and high performance computing have received intensive attention from industry and academia in recent years because of their ability to solve hard problems more efficiently and accurately. In order to overcome the processing power limits, multi-core processors integrate many cores into one chip and deliver higher total computing power. By developing parallel algorithms that can efficiently use all

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of the available processors, the processing power supplied by multi-core processors can increase the solution quality of one-dimensional BPP (Fernandez, Gil, Banos, & Montoya, 2013).

In addition to these benefits of multi-core processors, genetic algorithms (GAs) continue to be promising tools for numerous NP-Hard optimization problems where exact solution methods tend to fail because of the exponential search spaces (Cantu-Paz, 2000; Holland, 1975; Luque & Alba, 2011; Mitchell, 1996; Zitzler & Thiele, 1999). The study of Rohlfshagen and Bullinaria (2007) that we have parallelized is such a recent technique for solving the one-dimensional BPP that views individuals as (eukaryotic) genes instead of (prokaryotic) genomes in order to improve the traditional design of GAs.

In this study, our main motivation was to solve the one dimensional BPP with island parallel grouping genetic algorithms (GGAs) that take advantage of state-of-the-art computation tools. Island parallel GAs are very efficient tools for the solution of many NP-Hard problems (Cantu-Paz, 2000; Gordon & Whitley, 1993; Lim, Yuan, & Omatu, 2000; Luque & Alba, 2011). They bring many of the state-of-the-art computational tools together for better results.

With the proposed novel algorithms, we have combined state-of-the-art computation tools; parallel processing, GGAs, and bin oriented heuristics to efficiently solve the intractable one-dimensional BPP. The majority (88.5%) of the 1318 benchmark problem instances are solved optimally while the rest of the solutions produce only one extra bin. Novel hybrid bin-oriented heuristics with polynomial running times are proposed for GGAs and used to reinsert the remaining items into bins after the process of crossover and mutation. The solution quality of sequential GGAs is improved by the use of subpopulations on multi-core processors and it is shown that there is a potential to solve the BPP even more accurately if additional processors can be supplied.

In Section 2, we briefly review the relevant and the best performing sequential and parallel recent methods in chronological order. Section 3 explains the GGAs, canonical GA crossovers, Falkenauer's crossover, molecular genetics exon shuffling crossover, mutation, and inversion operator. Section 4 gives brief information about the use of BPP heuristics in the developed algorithms. Section 5 defines the proposed parallel hybrid GGAs and the parameter settings. Experimental comparisons of the developed algorithms are given in Section 6. Finally, conclusions and further research directions are discussed in Section 7.

2. Related work

One-dimensional BPP has been solved by numerous heuristics and exact techniques. A classical reference for the BPP is the book by Martello and Toth (1990), in which they describe a number of simple heuristics and lower bounds, introduce a reduction procedure (MTRP), and an exact algorithm (MTP). Best-Fit-Decreasing (BFD) and the First-Fit-Decreasing (FFD) algorithms are the two best known heuristics. Both heuristics sort items in decreasing order and place the largest item in either the first bin it fits (FFD) or the bin with the smallest but sufficient remaining capacity (BFD). A new bin is added whenever no suitable bin can be found.

Studies of Falkenauer (1994) were the early experiments in evolutionary algorithms to describe a Grouping Genetic Algorithms (GGA). Coffman, Garey, and Johnson (1997, 1999) studied approximation algorithms. Scholl, Klein, and Jurgens (1997) developed BISON, an efficient exact algorithm. Schwerin and Wascher (1997) introduced an improved version of the MTP. Valério de Carvalho (1999) developed an exact algorithm with branch-and-bound and studied linear programming models. Vanderbeck (1999) developed an exact algorithm based on column generation. Gupta and Ho (1999) developed the Minimum-Bin-Slack (MBS) heuristic. Fleszar and Hindi (2002) introduced a new heuristic MBS′, which fixes the largest remaining item in a bin before proceeding with the enumeration. Ross, Marin-Blázquez, Schulenburg, and Hart (2003) described a GA-based approach that learns a heuristic combination for solving the BPP. The worst-case performance of heuristics was investigated by Caprara and Pferschy (2004, 2005). Bhatia and Basu (2004) described a multi-chromosomal GGA. A highly effective hybrid improvement heuristic is described by Alvim, Ribeiro, Glover, and Aloise (2004). Singh and Gupta (2007) introduced a compound heuristic, combining a hybrid steady-state GGA. Stawowy (2008) proposed a non-specialized and non-hybridized algorithm that uses a modified permutation with separators encoding scheme, unique concept of separators movements during mutation, and separators removal as a technique of problem size reduction.

Rohlfshagen and Bullinaria (2007) developed an algorithm modeled on the theory of exon shuffling. Poli, Woodward, and Burke (2007) described an algorithm with discrete item sizes by matching the item-size histogram with the bin-gap histogram. Crainic, Perboli, Pezzuto, and Tadei (2007) studied fast lower bounds and their worst-case performance. Loh, Golden, and Wasil (2008) presented a weight annealing heuristic.

Khanafer, Clautiaux, and Talbi (2010) proposed a framework for deriving new data-dependent dual feasible functions. Fleszar and Charalambous (2011) proposed a method of controlling the average weight of items packed by bin-oriented heuristics in which constructive heuristics and an improvement heuristic are introduced. Memetic algorithms are successfully used for the one dimensional BPP and one of these approaches used separate individual learning or local improvement procedures (Le, Ong, Jin, & Sendhoff, 2009; Ong, Lim, Zhu, & Wong, 2006). Segura, Segredo, and Leon (2011) described a multi-objectivized memetic algorithm for the two-dimensional BPP which performs faster than traditional genetic algorithms.

Parallelization studies date back to 1990s. In a theoretical study, Anderson, Mayr, and Warmuth (1989) studied the parallel complexity of polynomial heuristics for the BPP and showed that some well-known simple heuristics are P-complete and they are not likely to be parallelized efficiently. Bestavros, Cheatham, and Stefanescu (1990) studied the asymptotic behavior of the different heuristics and proposed a set of simple data parallel algorithms to provide linear speedup for the packing of hundreds of thousands of bins. Coleman and Wang (1992) introduced a bin packing heuristic that is well-suited for implementation on massively parallel SIMD or MIMD computing systems. The average-case behavior of the technique was predictable when the input data has a symmetric distribution. The method is asymptotically optimal, yields perfect packing and achieves the best possible average case behavior with high probability. A systolic based parallel approximation algorithm that obtains solutions to the one dimensional BPP is presented by Berkey and Wang (1994). The algorithm has an asymptotic error bound of 1.5 and time complexity of $O(n)$. Fernandez et al. (2013) have analyzed how to solve two-dimensional BPPs with rotations and load balancing using parallel and multi-objective memetic algorithms that apply a set of search operators specifically designed to solve this problem. Results obtained using a set of test problems show the good performance of parallel and multi-objective memetic algorithms in comparison with other methods found in the literature.

Although there are existing parallel algorithms for the solution of two/three dimensional BPP (Bozejko, Uchronski, & Wodecki, 2010; Fernandez et al., 2013; Kroger, Schwenderling, & Vornberger, 1991; Pargas & Jain, 1993), to the best of our knowledge, there is no proposed island parallel hybrid GGAs like ours in the literature for the solution of one dimensional BPP. Parallel GAs are efficient tools for the solution of many different NP-Hard