

Celso C. Ribeiro
Simone L. Martins (Eds.)

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Experimental and Efficient Algorithms

Third International Workshop, WEA 2004
Angra dos Reis, Brazil, May 2004
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Preface

The Third International Workshop on Experimental and Efficient Algorithms (WEA 2004) was held in Angra dos Reis (Brazil), May 25–28, 2004.

The WEA workshops are sponsored by the European Association for Theoretical Computer Science (EATCS). They are intended to provide an international forum for researchers in the areas of design, analysis, and experimental evaluation of algorithms. The two preceding workshops in this series were held in Riga (Latvia, 2001) and Ascona (Switzerland, 2003).

This proceedings volume comprises 40 contributed papers selected by the Program Committee along with the extended abstracts of the invited lectures presented by Richard Karp (University of California at Berkeley, USA), Giuseppe Italiano (University of Rome “Tor Vergata”, Italy), and Christos Kaklamanis (University of Patras, Greece).

As the organizer and chair of this workshop, I would like to thank all the authors who generously supported this project by submitting their papers for publication in this volume. I am also grateful to the invited lecturers, who kindly accepted our invitation.

For their dedication and collaboration in the refereeing procedure, I would like also to express my gratitude to the members of the Program Committee: E. Amaldi (Italy), J. Blazewicz (Poland), V.-D. Cung (France), U. Derigs (Germany), J. Diaz (Spain), M. Gendreau (Canada), A. Goldberg (USA), P. Hansen (Canada), T. Ibaraki (Japan), K. Jansen (Germany), S. Martello (Italy), C.C. McGeoch (USA), L.S. Ochi (Brazil), M.G.C. Resende (USA), J. Rolim (Switzerland), S. Skiena (USA), M. Sniedovich (Australia), C.C. Souza (Brazil), P. Spirakis (Greece), D. Trystram (France), and S. Voss (Germany). I am also grateful to the anonymous referees who assisted the Program Committee in the selection of the papers to be included in this publication.

The idea of organizing WEA 2004 in Brazil grew out of a few meetings with José Rolim (University of Geneva, Switzerland). His encouragement and close collaboration at different stages of this project were fundamental for the success of the workshop. The support of EATCS and Alfred Hofmann (Springer-Verlag) were also appreciated.

I am thankful to the Department of Computer Science of *Universidade Federal Fluminense* (Niterói, Brazil) for fostering the environment in which this workshop was organized. I am particularly indebted to Simone Martins for her invaluable support and collaboration in the editorial work involved in the preparation of the final camera-ready copy of this volume.

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A Hybrid Bin-Packing Heuristic to Multiprocessor Scheduling

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Abstract. The multiprocessor scheduling problem consists in scheduling a set of tasks with known processing times into a set of identical processors so as to minimize their makespan, i.e., the maximum processing time over all processors. We propose a new heuristic for solving the multiprocessor scheduling problem, based on a hybrid heuristic to the bin packing problem. Computational results illustrating the effectiveness of this approach are reported and compared with those obtained by other heuristics.

1 Introduction

Let $T = \{T_1, \dots, T_n\}$ be a set of n tasks with processing times t_i , $i = 1, \dots, n$, to be processed by a set $P = \{P_1, \dots, P_m\}$ of $m \geq 2$ identical processors. We assume the processing times are nonnegative integers satisfying $t_1 \geq t_2 \geq \dots \geq t_n$. Each processor can handle at most one task at any given time and preemption is not possible. We denote by A_j the set formed by the indices of the tasks assigned to processor P_j and by $t(P_j) = \sum_{i \in A_j} t_i$ its overall processing time, $j = 1, \dots, m$. A solution is represented by the lists of tasks assigned to each processor. The makespan of a solution $S = (A_1, \dots, A_m)$ is given by $C_{\max}(S) = \max_{j=1, \dots, m} t(P_j)$.

The multiprocessor scheduling problem $P||C_{\max}$ consists in finding an optimal assignment of tasks to processors, so as to minimize their makespan, see e.g. [5,16,20]. $P||C_{\max}$ is NP-hard [4,14]. We denote the optimal makespan by C_{\max}^* . Minimizing the schedule length is important since it leads to the maximization of the processor utilization factor [3].

There is a duality relation [5,17,18,24] between $P||C_{\max}$ and the bin packing problem (BP), which consists in finding the minimum number of bins of a given capacity C which are necessary to accommodate n items with weights t_1, \dots, t_n .

The worst case performance ratio $r(H)$ of a given heuristic H for $P||C_{\max}$ is defined as the maximum value of the ratio $H(I)/C_{\max}^*(I)$ over all instances I , where $C_{\max}^*(I)$ is the optimal makespan of instance I and $H(I)$ is the makespan of the solution computed by heuristic H . The longest processing time (LPT)

heuristic of Graham [15] finds an approximate solution to $P||C_{\max}$ in time $O(n \log n + n \log m)$, with $r(\text{LPT}) = 4/3 - 1/3m$. The MULTIFIT heuristic proposed by Coffman et al. [6] explores the duality relation with the bin packing problem, searching by binary search the minimum processing time (or bin capacity) such that the solution obtained by the FFD heuristic [19,21] to pack the n tasks (or items) makes use of at most m processors (or bins). It can be shown that if MULTIFIT is applied k times, then it runs in time $O(n \log n + kn \log m)$ and $r(\text{MULTIFIT}) = 1.22 + 2^{-k}$. Friesen [13] subsequently improved this ratio to $1.20 + 2^{-k}$. Yue [25] further improved it to $13/11$, which is tight. Finn and Horowitz [9] proposed the 0/1-INTERCHANGE heuristic running in time $O(n \log m)$, with worst case performance ratio equal to 2. Variants and extensions of the above heuristics can be found in the literature.

The duality relation between the bin packing problem and $P||C_{\max}$ was also used by Alvim and Ribeiro [1] to derive a hybrid improvement heuristic to the former. This heuristic is explored in this paper in the context of $P||C_{\max}$. Lower and upper bounds used by the heuristic are described in Section 2. The main steps of the hybrid improvement heuristic to multiprocessor scheduling are presented in Section 3. Numerical results illustrating the effectiveness of the proposed algorithm are reported in Section 4. Concluding remarks are made in the last section.

2 Lower and Upper Bounds

The lower bound $L_1 = \max \{ \lceil \frac{1}{m} \sum_{i=1}^n p_i \rceil, \max_{i=1, \dots, n} \{p_i\} \}$ proposed by McNaughton [22] establishes that the optimal makespan cannot be smaller than the maximum between the average processing time over all processors and the longest duration over all tasks. This bound can be further improved to $L_2 = \max \{L_1, p_m + p_{m+1}\}$.

Dell'Amico and Martello [7] proposed the lower bound L_3 . They also showed that the combination of lower and upper bounds to the makespan makes it possible to derive lower and upper bounds to the number of tasks assigned to each processor, leading to a new lower bound L_{ϑ} . Bounds L_2, L_3 , and L_{ϑ} are used in the heuristic described in the next section.

We used three construction procedures for building feasible solutions and computing upper bounds to $P||C_{\max}$:

- Construction heuristic H1: Originally proposed in [1,2], it is similar to the Multi-Subset heuristic in [7]. It considers one processor at a time. The longest yet unassigned task is assigned to the current processor. Next, assign to this same processor a subset of the yet unassigned tasks such that the sum of their processing times is as close as possible to a given limit to the makespan. The polynomial-time approximation scheme MTSS(3) of Martello and Toth [21] is used in this step. The remaining unassigned tasks are considered one by one in non-increasing order of their processing times. Each of them is assigned to the processor with the smallest load.

- Construction heuristic H2: Hochbaum and Shmoys [17] proposed a new approach to constructing approximation algorithms, called dual approximation algorithms. The goal is to find superoptimal, but infeasible, solutions. They showed that finding an ϵ -approximation to $P\|C_{\max}$ is equivalent to finding an ϵ -dual-approximation to BP. For the latter, an ϵ -dual-approximation algorithm constructs a solution in which the number of bins is at most the optimal number of bins and each bin is filled with at most $1 + \epsilon$ (bin capacity $C = 1$ and item weights t_i scaled by t_i/C). In particular, they proposed a scheme for $\epsilon = 1/5$. Given a lower bound L and an upper bound U to C_{\max}^* , we obtain by binary search the smallest value C such that $L \leq C \leq U$ and the $1/5$ -dual-approximation solution to BP uses no more than m bins. This approach characterizes a $1/5 + 2^{-k}$ -approximation algorithm to $P\|C_{\max}$, where k is the number of iterations of the search. At the end of the search, the value of C gives the L_{HS} lower bound to the makespan.
- Construction heuristic H3: This is the longest processing time heuristic LPT [15]. Tasks are ordered in non-increasing order of their processing times. Each task is assigned to the processor with the smallest total processing time.

França et al. [10] proposed algorithm 3-PHASE based on the idea of balancing the load between pair of processors. Hübscher and Glover [18] also explored the relation between $P\|C_{\max}$ and BP, proposing a tabu search algorithm using 2-exchanges and influential diversification. Dell’Amico and Martello [7] developed a branch-and-bound algorithm to exactly solve $P\|C_{\max}$. They also obtained new lower bounds. Scholl and Voss [24] considered two versions of the simple assembly line balancing problem. If the precedence constraints are not taken into account, these two versions correspond to BP and $P\|C_{\max}$. Fatemi-Ghomi and Jolai-Ghazvini [8] proposed a local search algorithm using a neighborhood defined by exchanges of pairs of tasks in different processors. Frangioni et al. [12] proposed new local search algorithms for the minimum makespan processor scheduling problem, which perform multiple exchanges of jobs among machines. The latter are modelled as special disjoint cycles and paths in a suitably defined improvement graph. Several algorithms for searching the neighborhood are suggested and computational experiments are performed for the case of identical processors.

3 Hybrid Improvement Heuristic to $P\|C_{\max}$

The hybrid improvement heuristic to $P\|C_{\max}$ is described in this section. The core of this procedure is formed by the construction, redistribution, and improvement phases, as illustrated by the pseudo-code of procedure C+R+I in Figure 1. It depends on two parameters: the target makespan **Target** and the maximum number of iterations **MaxIterations** performed by the tabu search procedure used in the improvement phase. The loop in lines 1–8 makes three attempts to build a feasible solution S to the bin packing problem defined by the processing times $t_i, i = 1, \dots, n$, with bin capacity **Target**, using exactly m bins. Each of the heuristics H1, H2, and H3 is used at each attempt in line 2. If S is feasible to the associated bin packing problem, then it is returned in line 3. Otherwise, load


```

procedure C+R+I(Target,MaxIterations);
1  for  $k = 1, 2, 3$  do
2    Build a solution  $S = \{A_1, \dots, A_m\}$  to  $P||C_{\max}$  using heuristic Hk;
3    if  $C_{\max}(S) \leq \text{Target}$  then return  $S$ ;
4     $S \leftarrow \text{Redistribution}(S)$ ;
5    if  $C_{\max}(S) \leq \text{Target}$  then return  $S$ ;
6     $S \leftarrow \text{TabuSearch}(S, \text{MaxIterations})$ ;
7    if  $C_{\max}(S) \leq \text{Target}$  then return  $S$ ;
8  end
9  return  $S$ ;
end C+R+I

```

Fig. 1. Pseudo-code of the core C+R+I procedure.

redistribution is performed in line 4 to improve processor usability and the modified solution S is returned in line 5 if it is feasible to the bin packing problem. Finally, a tabu search procedure is applied in line 6 as an attempt to knock down the makespan of the current solution and the modified solution S is returned in line 7 if it is feasible to the bin packing problem. Detailed descriptions of the redistribution and improvement phases are reported in [1].

The pseudo-code of the complete hybrid improvement heuristic HIPC_{max} to $P||C_{\max}$ is given in Figure 2. An initial solution S is built in line 1 using heuristic H3. The lower bound L_2 is computed in line 2. If the current lower and upper bounds coincide, then solution S is returned in line 3. The lower bound L_3 is computed in line 4 and the current lower bound is updated. If the current lower and upper bounds coincide, then solution S is returned in line 5. The lower bound L_4 is computed in line 6 and the current lower bound is updated. If the current lower and upper bounds coincide, then solution S is returned in line 7. A new solution S' is built in line 8 using heuristic H2. The currently best solution and the current upper bound are updated in line 9, while the current lower bound is updated in line 10. If the current lower and upper bounds coincide, then the currently best solution S is returned in line 11. A new solution S' is built in line 12 using heuristic H1. The currently best solution and the current upper bound are updated in line 13. If the current lower and upper bounds coincide, then the currently best solution S is returned in line 14. At this point, UB is the upper bound associated with the currently best known solution S to $P||C_{\max}$ and LB is an unattained makespan. The core procedure C+R+I makes an attempt to build a solution with makespan equal to the current lower bound in line 15. The currently best solution and the current upper bound are updated in line 16. If the current lower and upper bounds coincide, then the currently best solution S is returned in line 17. The loop in lines 18–23 implements a binary search strategy seeking for progressively better solutions. The target makespan $C_{\max} = \lfloor (LB + UB)/2 \rfloor$ is set in line 19. Let S' be the solution obtained by the core procedure C+R+I applied in line 20 using C_{\max} as the target makespan. If its makespan is at least as good as the target makespan

C_{\max} , then the current upper bound UB and the currently best solution S are updated in line 21. Otherwise, the unattained makespan LB is updated in line 22, since the core procedure C+R+I was not able to find a feasible solution with the target makespan. The best solution found S is returned in line 24.

The core procedure C+R+I is applied at two different points: once in line 15 using the lower bound LB as the target makespan and in line 20 at each iteration of the binary search strategy using C_{\max} as the target makespan. This implementation follows the same EBS (binary search with prespecified entry point) scheme suggested in [24]. Computational experiments have shown that it is able to find better solutions in smaller computation times than other variants which do not explore the binary search strategy or do not make a preliminary attempt to build a solution using LB as the target makespan.

4 Computational Experiments

All computational experiments were performed on a 2.4 GHz AMD XP machine with 512 MB of RAM memory.

```

procedure HI_PCmax(MaxIterations);
1  Compute a solution  $S$  using heuristic H3 and set  $UB \leftarrow C_{\max}(S)$ ;
2  Compute the lower bound  $L_2$  and set  $LB \leftarrow L_2$ ;
3  if  $LB = UB$  then return  $S$ ;
4  Compute  $L_3$  using binary search in the interval  $[LB, UB]$  and set  $LB \leftarrow L_3$ ;
5  if  $LB = UB$  then return  $S$ ;
6  Compute  $L_\varnothing$  using  $LB$  and  $UB$  and update  $LB \leftarrow \max\{LB, L_\varnothing\}$ ;
7  if  $LB = UB$  then return  $S$ ;
8  Compute a solution  $S'$  and the lower bound  $L_{HS}$  using heuristic H2;
9  if  $C_{\max}(S') < UB$  then set  $UB \leftarrow C_{\max}(S')$  and  $S \leftarrow S'$ ;
10 Update  $LB \leftarrow \max\{LB, L_{HS}\}$ ;
11 if  $LB = UB$  then return  $S$ ;
12 Compute a solution  $S'$  using heuristic H1;
13 if  $C_{\max}(S') < UB$  then set  $UB \leftarrow C_{\max}(S')$  and  $S \leftarrow S'$ ;
14 if  $LB = UB$  then return  $S$ ;
15  $S' \leftarrow \text{C+R+I}(LB, \text{MaxIterations})$ ;
16 if  $C_{\max}(S') < UB$  then set  $UB \leftarrow C_{\max}(S')$  and  $S \leftarrow S'$ ;
17 if  $LB = UB$  then return  $S$ ;
18 while  $LB < UB - 1$  do
19    $C_{\max} \leftarrow \lfloor (LB + UB)/2 \rfloor$ ;
20    $S' \leftarrow \text{C+R+I}(C_{\max}, \text{MaxIterations})$ ;
21   if  $C_{\max}(S') \leq C_{\max}$  then set  $UB \leftarrow C_{\max}(S')$  and  $S \leftarrow S'$ ;
22   else  $LB \leftarrow C_{\max}$ ;
23 end
24 return  $S$ ;
end HI_PCmax

```

Fig. 2. Pseudo-code of the hybrid improvement procedure to $P||C_{\max}$.