Available online at www.sciencedirect.com
ScienceDirect
Computers & Operations Research 36 (2009) 358–378
computers & operations research
www.elsevier.com/locate/cor

A comparison of scheduling algorithms for flexible flow shop problems with unrelated parallel machines, setup times, and dual criteria

Jitti Jungwattanakit[a], Manop Reodecha[a], Paveena Chaovalitwongse[a], Frank Werner[b,*]

[a]*Department of Industrial Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand*
[b]*Faculty of Mathematics, Otto-von-Guericke-University, P.O. Box 4120, D-39016 Magdeburg, Germany*

Available online 10 October 2007

Abstract

This paper considers a flexible flow shop scheduling problem, where at least one production stage is made up of unrelated parallel machines. Moreover, sequence- and machine-dependent setup times are given. The objective is to find a schedule that minimizes a convex sum of makespan and the number of tardy jobs in a static flexible flow shop environment. For this problem, a 0–1 mixed integer program is formulated. The problem is, however, a combinatorial optimization problem which is too difficult to be solved optimally for large problem sizes, and hence heuristics are used to obtain good solutions in a reasonable time. The proposed constructive heuristics for sequencing the jobs start with the generation of the representatives of the operating time for each operation. Then some dispatching rules and flow shop makespan heuristics are developed. To improve the solutions obtained by the constructive algorithms, fast polynomial heuristic improvement algorithms based on shift moves and pairwise interchanges of jobs are applied. In addition, metaheuristics are suggested, namely simulated annealing (SA), tabu search (TS) and genetic algorithms. The basic parameters of each metaheuristic are briefly discussed in this paper. The performance of the heuristics is compared relative to each other on a set of test problems with up to 50 jobs and 20 stages and with an optimal solution for small-size problems. We have found that among the constructive algorithms the insertion-based approach is superior to the others, whereas the proposed SA algorithms are better than TS and genetic algorithms among the iterative metaheuristic algorithms.

Keywords: Flexible flow shop; Constructive algorithms; Simulated annealing; Tabu search; Genetic algorithms

1. Introduction

Production scheduling is a decision-making process in the operation level. It can be defined as the allocation of available production resources to carry out certain tasks in an efficient manner. Such a frequently occurring scheduling problem is difficult to solve due its complex nature.

This paper is primarily concerned with industrial scheduling problems, where one first has to assign jobs to limited resources and then sequence the assigned jobs on each resource over time. It is mainly concerned with processing industries that are established as multi-stage production facilities with multiple production units per stage (i.e. parallel machines), e.g. a textile industry (Karacapilidis and Pappis [1]), an automobile assembly plant (Agnetis et al. [2]), a

* Corresponding author. Tel.: +49 391 6712025; fax.: +49 391 6711171.
E-mail address: frank.werner@mathematik.uni-magdeburg.de (F. Werner).

0305-0548/$ - see front matter
doi:10.1016/j.cor.2007.10.004

printed circuit board manufacture (Alisantoso et al. [3], and Hsieh et al. [4]), and so on. In such industries, at some stages the facilities are duplicated in parallel to increase the overall capacities or to balance the capacities of the stages, or either to eliminate or to reduce the impact of bottleneck stages on the shop floor capacities. Due to the mixed character of such a production system, which lies between flow shop and parallel machines, it is known as a flexible or hybrid flow shop environment.

An ordinary flow shop model is a multi-stage production process, where the jobs have to visit all stages in the same order, whereas a flexible flow shop model, a generalization of the classical flow shop model, is more realistic, and it assumes that at least one stage must have multiple machines. Moreover, a machine can process at most one job at a time and a job can be processed by at most one machine at a time. Preemption of processing is not allowed. The problem consists of assigning the jobs to machines at each stage and sequencing the jobs assigned to the same machine so that some optimality criteria are minimized.

Although the flexible flow shop problem has been widely studied in the literature, most of the studies related to flexible flow shop problems are concentrated on problems with identical processors, see for instance, Gupta et al. [5], Alisantoso et al. [3], Lin and Liao [6], and Wang and Hunsucker [7]. In a real world situation, it is common to find newer or more modern machines running side by side with older and less efficient machines. Even though the older machines are less efficient, they may be kept in the production lines because of their high replacement costs. The older machines may perform the same operations as the newer ones, but would generally require a longer operating time for the same operation. In this paper, the flexible flow shop problem with unrelated parallel machines is considered, i.e. there are different parallel machines at every stage and speeds of the machines are dependent on the jobs. Moreover, several industries encounter setup times which result in even more difficult scheduling problems. In this paper, both sequence- and machine-dependent setup time restrictions are taken into account as well.

A detailed survey for the flexible flow shop problem has been given by Linn and Zhang [8] and Wang [9]. Most of the earlier literature has considered the simple case of only two stages. Arthanari and Ramamurthy [10] and Salvador [11] are among the first who define the flexible flow shop problem. They propose a branch-and-bound method to tackle the problem. Such a method is an exact solution technique which guarantees optimal solutions. However, the exact algorithm presented can only be applied to very small instances. Other exact approaches for the multi-stage flexible flow shop problem are proposed by many authors, e.g. branch-and-bound algorithms are given by Brah and Hunsucker [12] and Moursli and Pochet [13].

Whenever an exact algorithm is applied to large flexible flow shop problems, such an approach can take hours or days to derive a solution. On the other hand, a heuristic approach is much faster but does not guarantee an optimum solution. Gupta [14] proposes heuristic techniques for a simplified flexible flow shop makespan problem with two stages and only one machine at stage two. Sriskandarajah and Sethi [15] develop simple heuristic algorithms for the two-stage flexible flow shop problem. They discuss the worst and average case performance of algorithms for finding minimum makespan schedules. Their solutions are based on Johnson's rule. Guinet et al. [16] also propose a heuristic for the makespan problem in a two-stage flexible flow shop based on Johnson's rule. They compare this heuristic with the shortest processing time (SPT) and the longest processing time (LPT) dispatching rules. They conclude that the LPT rule gives good results for the two-stage makespan problem. Gupta and Tunc [17] consider the two-stage flow shop scheduling problem when there is one machine at stage one and the number of identical machines in parallel at stage two is less than the total number of jobs. The setup and removal times of each job at each stage are separated from the processing times. They propose heuristic algorithms that are empirically tested to determine the effectiveness in finding an optimal solution. Santos et al. [18] investigate scheduling procedures which seek to minimize the makespan in a static flow shop with multiple processors. Their method is to generate an initial permutation schedule based on the Palmer, CDS, Gupta and Dannenbring flow shop heuristics, and then it is followed by the application of the first-in first-out (FIFO) rule.

To obtain a near-optimal solution, metaheuristic algorithms have also been proposed. Gourgand et al. [19] present several simulated annealing (SA)-based algorithms for the flexible flow shop problem. A specific neighborhood is used and the authors apply the methods to a realistic industrial problem. Jin et al. [20] consider the flexible flow shop with identical parallel machines. They propose two approaches to generate the initial job sequence and use an SA algorithm to improve it. It can be seen that an SA algorithm has been successfully applied to various combinatorial optimization problems. For an extensive survey of the theory and applications of the SA algorithm, see Koulamas et al. [21]. Furthermore, Nowicki and Smutnicki [22] propose a tabu search (TS) algorithm for the flexible flow shop makespan problem. A genetic algorithm (GA) has been widely used in many previous works for the flow shop makespan