Computers & Industrial Engineering 59 (2010) 436–447

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

An effective heuristic for flexible job-shop scheduling problem with maintenance activities ☆

Shijin Wang [a,*], Jianbo Yu [b]

[a] Department of Management Science and Engineering, School of Economics & Management, Tongji University, Shanghai 200092, China
[b] College of Mechatronics Engineering and Automation, Shanghai University, Shanghai 200072, China

ARTICLE INFO

Article history:
Received 12 September 2009
Received in revised form 25 February 2010
Accepted 18 May 2010
Available online 24 May 2010

Keywords:
Flexible job-shop scheduling problem
Availability constraints
Filtered beam search
Preventive maintenance

ABSTRACT

Most production scheduling problems, including the standard flexible job-shop scheduling problem (FJSP), assume that machines are continuously available. However, in most realistic situations, machines may become unavailable during certain periods due to preventive maintenance (PM). In this paper, a flexible job-shop scheduling problem with machine availability constraints is considered. Each machine is subject to preventive maintenance during the planning period and the starting times of maintenance activities are either flexible in a time window or fixed beforehand. Moreover, two cases of maintenance resource constraint are considered: sufficient maintenance resource available or only one maintenance resource available. To deal with this variant FJSP problem with maintenance activities, a filtered beam search (FBS) based heuristic algorithm is proposed. With a modified branching scheme, the machine availability constraint and maintenance resource constraint can be easily incorporated into the proposed algorithm. Simulation experiments are conducted on some representative problems. The results demonstrate that the proposed filtered beam search based heuristic algorithm is a viable and effective approach for the FJSP with maintenance activities.

1. Introduction

Due to their importance both in the fields of manufacturing industries and operations research, production scheduling and maintenance planning have been received considerable attention both in academia and in industry. However, in practice, production scheduling and maintenance planning are typically made independently despite the implicit common goal of maximizing equipment productivity between them (Cassady & Kutanoglu, 2003, 2005).

Production scheduling is to allocate a limited set of resources to a number of jobs with optimization of one or multiple system criteria over time, while taking various constraints into account. Most of them assume that machines are always available at constant speed. They either ignore equipment failure or treat it as a random event (Cassady & Kutanoglu, 2003). Although reactive scheduling (or rescheduling) considers response scheduling after machine breakdown, it does not consider the practical requirement of high reliability for some equipment (e.g., furnace in steel plant, thermal generating units in power system (Mohanta, Sadhu, & Chakrabarti, 2007)). Reactive scheduling does not radically improve the reliability of machines either. Moreover, too often rescheduling may make the production system into a kind of chaos, because rescheduling leads to rearrangement of supporting resources (e.g., personnel, spare parts, and material handling devices). Therefore, a more realistic scheduling model should consider the machine availability constraint. This helps reducing the frequency of rescheduling and improving the robustness. Maintenance activities, especially preventive maintenance (PM), can restore the reliability of machines before it goes to breakdown. However, on one hand, maintenance activities take time that could otherwise be used for production scheduling; on the other hand, industrial applications cannot ignore the forecasted maintenance operations on the machines (Mauguiere, Billaut, & Bouquard, 2005). Therefore, the problem of simultaneously scheduling production jobs and maintenance activities obtains great attentions in recent years.

Preventive maintenance planning is usually generated in a maintenance system, like Computerized Maintenance Management Systems (CMMS) and Asset Management System (AMS). Preventive maintenance planning requires some pre-scheduled or reserved unavailability interval of machines. Therefore, production scheduling with maintenance activities is also treated as availability constraint of machines in the literature. Schmidt (2000) has reviewed most results related to deterministic scheduling problems with availability constraints published before 1998. After Schmidt's work, many efforts are devoted to the production scheduling with maintenance activities in different machine environ-

☆ This manuscript was processed by Area Editor Maged M. Dessouky.
* Corresponding author. Tel.: +86 21 65981443; fax: +86 21 65981443.
E-mail address: shijinwang0223@yahoo.com.cn (S. Wang).

0360-8352/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cie.2010.05.016

ments with different job characteristics and different optimality criteria.

In the single machine context, Graves and Lee (1999) considered the scheduling problem with *semiresumable*[1] jobs and two maintenance intervals of a fixed duration on a single machine to minimize either total weighted completion time or the maximum lateness. Cassady and Kutanoglu (2003) proposed an integrated model that simultaneously determines production scheduling and preventive maintenance for a single machine in terms of the total weighted tardiness of jobs. This model is further extended into a similar model in terms of total weighted completion time in Cassady and Kutanoglu (2005). Compared with the total enumeration procedure in Cassady and Kutanoglu (2005), Sortrakul, Nachtmann, and Cassady (2005) presented heuristics based on the genetic algorithm (GA) for the same model. The job characteristics considered in these three papers are *resumable* and non-preemptive for PM. Chen and Liao (2005) studied the deterministic and probabilistic models of a single machine problem with different maintenance situations and *resumable* jobs with respect to the minimization of number of tardy jobs. The research is employed into a textile company. Ji, He, and Cheng (2007) analyzed the worst-case ratio of the LPT (longest processing time) dispatching rule for a single machine scheduling problem with *nonresumable* jobs and several periodic maintenance in terms of makespan minimization. Chen (2008) presented two optimization models and a heuristic for a single machine scheduling problem with nonresumable jobs and with flexible and periodic maintenance to minimize the makespan. Chen (2009) proposed a heuristic based on Moore's algorithm and a branch-and-bound (B&B) algorithm to a single machine problem with periodic maintenance and *nonresumable* jobs with respect to the minimization of number of tardy jobs.

In the parallel machine context, Lee and Chen (2000) extended the work of Graves and Lee (1999) to parallel machines with *nonresumable* jobs to minimize total weighted completion time. Gharbi and Haouari (2005) considered the identical parallel-machine scheduling problem with availability restrictions for both jobs (release time and delivery time constraints) and machines. The objective is to minimize the makespan and they presented an exact branch-and-bound algorithm to solve this problem. With the objective of makespan minimization, Liao, Shyur, and Lin (2005) studied the two-parallel machine problem with only one machine unavailable for a fixed and known period. Both nonresumable and resumable cases are considered and the problem is solved with modified methods based on the Two-Machine Optimization (TMO) algorithm. Then, Lin and Liao (2007) extended the same problem to the case where each machine has a fixed and known unavailable period. Lee and Yu (2008) discussed a parallel-machine scheduling problem with the objectives of minimization of the expected sum of weighted completion times and the expected number of tardiness jobs, respectively. Both resumable and nonresumable cases are studied. Liao and Sheen (2008) analyzed the parallel-machine scheduling problem with machine availability and eligibility constraints while minimizing the makespan. The problem is formulated into a maximum flow problem and a binary search algorithm is proposed. Mellouli, Sadfi, Chu, and Kacem (2009) considered the identical parallel-machine scheduling problem with availability constraints and total completion time criterion. Three exact approaches (mixed integer linear programming based methods, a dynamic programming method and a branch-and-bound method) are proposed as well as some heuristics adapted from the Shortest Processing Time (SPT) rule.

Because of their fundamental characteristic and simplicity, single machine and parallel-machine scheduling problems with availability constraints under different criteria have been extensively studied. Readers are referred to Ma, Chu, and Zuo (2010) for a relative comprehensive overview.

Recently, scheduling problems with availability constraints in more complicated environments, such as flow shop, job-shop and hybrid environments, have being attracted more and more attentions. Allaoui and Artiba (2004) studied the scheduling problem in a hybrid flow shop with both *resumable* and *nonresumable* jobs and maintenance constraints to minimize flow time and due date based criteria. Setup, cleaning and transportation times are also considered. Three dispatching rules, a simulated annealing (SA) heuristic and a flexible simulation model are separately used to solve the problem. Aggoune (2004) addressed a flow shop with machine availability constraints to minimize the makespan. Two variants of the non-preemptive constraints are considered: the starting times of maintenance activities are either fixed or flexible. An algorithm based on GA and tabu search (TS) is applied to solve the problem. Mauguiere et al. (2005) presented a new job-shop scheduling problem with machine availability constraints. The jobs can be either *resumable* or *nonresumable* depending on the unavailability period. Kubzin and Strusevich (2006) studied both a two-machine open shop problem and a two-machine flow shop problem to minimize the makespan. Each machine is subject to preventive maintenance, and the length of each maintenance period depends on its starting time. Breit (2006) investigated a problem of scheduling n preemptive jobs in a two-machine flow shop where the first machine is not available for processing during a given time interval, with the minimization of makespan. Gao, Gen, and Sun (2006) considered a flexible job-shop scheduling problem (FJSP) with machine availability constraints. The periods of unavailability are non-fixed and flexible within an end-time window and have to be determined during the scheduling procedure. A hybrid genetic algorithm is proposed to solve the problem. Ruiz, Garcia-Diaz, and Maroto (2007) considered preventive maintenance and production scheduling in regular flow shops and six meta-heuristics are proposed with comparisons. The multi-purpose machine (MPM) scheduling problem with fixed machine availability constraints in a job-shop is studied in Zribi, Kamel, and Borne (2008). A two-phase heuristic method is proposed to solve the problem. In the first phase, a heuristic based on priority rules to solve the assignment problem is developed, which can be improved with a tabu search algorithm. In the second phase, a GA is presented to solve the sequencing problem. Yang, Hsu, and Kuo (2008) investigated a two-machine flow shop where maintenance activities with a constant time must be done after completing a fixed number of jobs at most. The objective is to find the optimal job combinations and the optimal job schedule to minimize the makespan. Naderi, Zandieh, and Ghomi (2009) investigated a job-shop scheduling problem with sequence-dependent set-up times and maintenance activities to minimize the makespan. Two meta-heuristics, simulated annealing (SA) and GA are used to solve the problem.

Based on the previous works review mentioned above, two gains could be drawn. Firstly, most existing literature focus on the problem of integrating production scheduling with preventive maintenance activities in the context of single machine, parallel machine and flow shop (especially two-machine problems). There is much less literature in the flexible job-shop manufacturing environment. As mentioned above, Gao et al. (2006) studied the general flexible job-shop scheduling problem combined with maintenance and production. Zribi et al. (2008) considered the MPM job-shop scheduling problem with availability constraints,

[1] *Resumable* means that if a job cannot be finished before a maintenance activity, it can continue the processing once the maintenance activity is finished. *Nonresumable* means a job must be reprocessed fully after the maintenance if its processing is interrupted by the maintenance activity on a machine. *Semiresumable* means that if a job is not processed to completion before the machine is stopped for maintenance, an additional set-up time is necessary when the processing is resumed.