Computers & Industrial Engineering 97 (2016) 26–40

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Minimizing tardiness and maintenance costs in flow shop scheduling by a lower-bound-based GA

Andrew Junfang Yu *, Javad Seif

Department of Industrial and Systems Engineering, The University of Tennessee, Knoxville, TN 37996, United States

ARTICLE INFO

Article history:
Received 11 June 2015
Accepted 29 March 2016
Available online 7 April 2016

Keywords:
Maintenance optimization
Flow shop scheduling
Mixed integer linear programming
Lower bound
Genetic algorithm
Construction machinery management

ABSTRACT

A permutation flow shop scheduling problem is reformulated as a mixed-integer linear program after incorporating flexible and diverse maintenance activities for minimizing total tardiness and maintenance costs. The terms "flexible" and "diverse" mean that the maintenance activities are not required to perform following fixed and predetermined time intervals, and there can be different types of maintenance activities for each machine. The problem is proved to be NP-hard and a lower bound for the problem is proposed. A lower-bound-based genetic algorithm (LBGA) is presented, in which the algorithm parameters are first tested through a factorial experiment to identify the statistically significant parameters. The LBGA algorithm self-tunes these parameters for its performance improvement based on the solution gap from the lower bound. While it is experienced that only the population size is statistically significant in improving the quality of solutions, through a computational experiment it is also shown that an optimal population size for one problem size yields the same quality of solutions for larger sizes of problems and increasing the population size beyond the optimal size for larger sizes of problems will only negatively affects the efficiency of the algorithm. Computational results that show efficiency and effectiveness of the algorithm are also provided.

1. Introduction

In conventional machine scheduling problems, it is assumed that the machines are continuously operating and available over the planning horizon (Pinedo, 2012) which cannot be the case in real world problems where equipment could be unavailable due to breakdown and/or maintenance activities. Although maintenance planning and production scheduling are often studied separately such as in semiconductor manufacturing (Xiaodong, Fernandez-Gaucherand, Fu, & Marcus, 2004), integration of machine maintenance and scheduling has also appeared in many researches in the last two decades (Xu, Wan, Liu, & Yang, 2015).

This integration has been proposed for different configurations of manufacturing environments such as single machine, flow shop, parallel machine, job shop, or flexible flow shop, and based on different objective functions such as minimizing makespan, total (expected) completion time, total workload of machines, total workload of critical machines, tardiness, or a combination of them (Wang & Liu, 2014). In this paper, integration of maintenance and operations scheduling in flow shop is presented where the objective function is to minimize the total maintenance and tardiness costs. In some industries such as heavy construction projects, the maintenance costs form a significant portion of the overall costs (Yip, Fan, & Chiang, 2014). Therefore, it is important to consider the maintenance cost in the objective function along with conventional scheduling criteria such as tardiness.

Flow shop scheduling refers to the problem of determining the optimum permutation of a series of independent jobs which are to be processed by a set of machines. When all the jobs are assumed to go through the same sequence of machines, the problem is called permutation flow shop, and otherwise, non-permutation flow shop. After a job is processed on a machine, and before it proceeds with the next machine, if the next machine is busy with another job, the job can wait in the buffer between the consecutive machines. If the buffer has zero capacity the problem is called blocking flow shop in which case when the next machine is busy the job has to be blocked on the current machine (Abdollahpour & Rezaeian, 2015).

Scheduling falls into optimization class of problems where the objective function is to be minimized or maximized; for example, minimizing the total completion time of all the jobs (makespan). From a computational complexity point of view, it is proved that, even with two machines, flow shop scheduling problem is NP-hard (Papadimitriou & Kanellakis, 1980). That is, the growth of

* Corresponding author. Tel.: +1 (931) 393 7529.
E-mail address: ajyu@utk.edu (A.J. Yu).

http://dx.doi.org/10.1016/j.cie.2016.03.024
0360-8352/

the time for solving the corresponding decision problem is not a polynomial function of the size of the problem. As a result, when the number of jobs is relatively high, the time for finding the exact optimal solution is not justifiable. Most of the literature related to flow shop scheduling deals with proposing new heuristic or meta-heuristic algorithms that can yield near-optimal solutions in a relatively short amount of time. See for examples in Abdollahpour and Rezaeian (2015), Ronconi (2004), Ying (2008), Norman (1999), Smutnicki (1998), Nowicki (1999), Brucker, Heitmann, and Hurink (2003), and Hsieh, You, and Liou (2009).

The literature related to integration of maintenance planning and scheduling was classified differently by Xu et al. (2015) and Aramon Bajestani and Beck (2015). Xu et al. (2015) considered the literature to fall into two categories based on the maintenance duration. In the first category, the duration is prefixed. These research works consider the maintenance times as availability constraints (times at which the machine is not available). In the surveys by Sanlaville and Schmidt (1998), Schmidt (2000), Ma, Chu, and Zuo (2010), and Gordon, Strusevich, and Dolgui (2012), this kind of works are identified and further categorized. In the second category, maintenance duration may change based on some factors that are dependent on the scheduling. For example, if the production schedule forces a maintenance activity to be performed at a later time, it takes more time to perform. In short, the duration is a function of the start time of the activity. Xu et al. (2015) also discussed the subtle differences between these functions as appeared in the works of Yang and Yang (2010), Cheng, Yang, and Yang (2012), Mor and Mosheiov (2012), Luo and Ji (2015), Xu, Yin, and Li (2010), Yang (2012), and Yang (2013). In this paper, we will consider prefixed duration for maintenance activities.

Aramon Bajestani and Beck (2015) also divided the literature in two categories. The first category was the same as the first category determined by Xu et al. (2015). The second category, however, is different and addresses those research works which assume that the processing times of the jobs varies based on the maintenance. In the models presented in these literatures, a rate, which is dependent on maintenance activities, is applied to the processing times of the jobs (Lee & Leon, 2001). Since we do not have such assumption for processing times, we will not further discuss the related works in the second category.

In this paper we will model and optimize a flow shop scheduling problem integrated with diverse and flexible maintenance activities. Most of the related works consider a single machine. However, there are some works such as Allaoui and Artiba (2004) in which the integration of maintenance planning and production scheduling has been extended to flow shop setting. They considered a hybrid (non-permutation) flow shop with different objective functions while also considering setup, cleaning and transportation times. They proposed a combination of simulation and one of the meta-heuristic algorithms (simulated annealing) as the solution approach. Other meta-heuristic solution approaches such as genetic algorithm and tabu search have been utilized by Aggoune (2004) and Ruiz, Carlos García-Díaz, and Maroto (2007), and a detailed review of all the approaches along with a variable neighborhood search was presented by Naderi, Zandieh, and Fatemi Ghomi (2009).

What distinguishes this paper from the related works is flexibility and diversity of maintenance activities. Flexibility means that we are not limited to perform maintenance activities at fixed intervals. Diversity means that we have different set of maintenance activities for a machine. One downside of fixed-interval preventive maintenance (PM) activities is that we do not know if the oil or bearing which are to be replaced, for example, have been fully utilized. Condition based maintenance (CBM) involves monitoring equipment's health and replacements or other maintenance actions that are performed only when they are necessary. The cost of conducting condition monitoring, however, is not always justifiable and there are researches dedicated solely to cost-wise justification of running a CBM program (Azadeh, Asadzadeh, & Seif, 2014). Flexible maintenance activities try to imitate CBM without monitoring, that is, by estimating the remaining useful life of a system based on the known deterioration rate that each job incurs in the system. Job-dependent deterioration of machine means that in environments analogous to manufacturing, when different jobs are processed by a machine, we can expect the health of a machine to be deteriorated with different rates when different jobs are processed. Having these deterioration rates available, a more economic maintenance plan can be achieved in which maintenance activities are not necessarily performed with fixed intervals (in the literature, general, flexible, or noncyclical PMs are also used with the same meaning).

Bock, Briskorn, and Horbach (2012) tried to extend classic machine scheduling problems by taking machine deterioration and maintenance activities (MAs) into account. They described health of a single machine by a bounded maintenance level (ML) which is deteriorated as jobs are processed. They assumed that the deterioration is a linear function of the processing time of the jobs and each job has its own coefficient (failure rate). They considered pure scheduling objective functions such as minimization of completion times, makespan, and tardiness. Majority of their work is dedicated to the determination of computational complexity of the problems introduced in their paper.

Diversity of maintenance activities has not been observed in flow shop literature. As for the objective function, the main focus of our model is on minimizing the maintenance cost (unlike most of the discussed research works) because in some flow shop settings such as in a petrochemical plant or a construction project, the maintenance cost forms the main portion of the expenses.

In many of the existing research works, the maintenance cost is usually considered as a whole along with other production costs (Aghezzaf & Najid, 2008). In addition, some practical considerations have never been taken into account. One of such considerations is that a machine usually has more than one type of MA. Because terms like "multi-maintenance activities" and "multiple maintenance activities" appeared in the literature (Shi & Xu, 2014; Sun & Li, 2010; Zarook, Rezaeian, Tavakkoli-Moghaddam, Mahdavi, & Javadian, 2014) do not refer to different types of maintenance activities, we have adopted the term "diverse maintenance activities" in order to more distinctively represent the problem.

Note that some works that integrated preventive maintenance planning and production might not be comparable with this research as they are basically focusing on production planning, not jobs scheduling. For example, Aghezzaf, Jamali, and Ait-Kadi (2007) integrated maintenance, repair, and inventory in their models. Their model was to find the best production quantity for different products along with the optimum PM interval that minimizes total cost. Aghezzaf et al. (2007) and a few other researchers have considered maintenance cost in their works but unlike the presented research, they did not incorporate the maintenance resource cost into the maintenance planning. Instead, they considered the maintenance and repair cost as a fixed value multiplied by the frequency of maintenance activities. In our proposed model, we break the maintenance cost into various costs of resources and optimize the jobs schedule in a way that minimum resource is used.

There are some researches that consider both corrective (and unplanned) maintenance (CM) and PM. Aghezzaf and Najid (2008), also, tried to find the optimum length for PM cycles with minimal repair at failure for different machines working in a parallel setting with almost the same objective function as their previous work. They also integrated maintenance with production planning and suggested an approximation Lagrangian decomposition to solve their problem for both cyclic and noncyclic (flexible) cases.