Int. J. Production Economics 158 (2014) 256–266

Contents lists available at ScienceDirect

Int. J. Production Economics

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

Modeling and scheduling no-wait open shop problems

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ARTICLE INFO

Article history:
Received 21 September 2012
Accepted 4 January 2014
Available online 4 July 2014

Keywords:
Scheduling
Open shop
No-wait
Mixed integer linear programming
Genetic algorithm
Variable neighborhood search

ABSTRACT

This paper studies the problem of scheduling open shops with no intermediate buffer, called no-wait open shops under makespan minimization. No-wait scheduling problems arise in many realistic production environments such as hot metal rolling, the plastic molding, chemical and pharmaceutical, food processing and several other industries. To tackle such problems, we first develop three different mathematical models, mixed integer linear programs, by which we can solve the problem to optimality. Besides the models, we propose novel metaheuristics based on genetic and variable neighborhood search algorithms to solve the large-sized problems in an acceptable computational time. The key point in any scheduling solver is the procedure of encoding and decoding schemes. In this paper, we propose a simple yet effective tailor-made procedure of encoding and decoding schemes for no-wait open shop problems. The operators of the proposed metaheuristics are designed so as to consider the specific encoding scheme of the problem. To evaluate the performance of models and metaheuristics, we conduct two computational experiments. The first includes small-sized instances by which we compare the mathematical models and assess general performance of the proposed metaheuristics. In the second experiment, we further evaluate the potential of metaheuristics on solving some benchmarks in the literature of pure open shops. The results show that the models and metaheuristics are effective to deal with the no-wait open shop problems.

1. Introduction

In general, scheduling problems can be described by a set of n jobs that need to be processed by a set of m machines. The problem is called a flow shop if all the jobs follow the same processing route through the machines, i.e., they are first processed on machine 1, then on machine 2, and so on until machine m. If each job has its own processing route to go through machines, the problem is a job shop. Now, if there are no predetermined processing routes for the jobs, the problem becomes an open shop. In other words, in open shops, there are two decisions to make, the determination of the processing routes of the jobs as well as job sequence on each machine (Pinedo, 2008). The following assumptions are usually characterized to open shops. All the jobs are independent and available for their process at time 0. All machines are continuously available. Each machine can at most process one job at a time. The process of a job on a machine cannot be interrupted. There are infinite buffers between all machines. There is no transportation time between machines. The objective function is the minimization of makespan.

Some of the common assumptions in open shop scheduling impede many of the possible practical applications of this important problem. For example, the existence of an infinite storage capacity between machines is one of these assumptions (Pang, 2013). This is, jobs can unlimitedly wait for machines to be available. In many scheduling environments, however, due to characteristics of the jobs or the processing technology, the operations of a job must be performed without any interruption between machines, which is known as no-wait restriction. Typical application of no-wait scheduling problems arises in hot metal rolling industries, where the heated metal has to undergo a set of operations at continuously high temperatures before it is cooled in order to prevent defects. Similarly, in the plastic molding and silverware production industries, a set of operations must be performed to immediately follow one another to prevent degradation. Other examples include chemical and pharmaceutical industries, food processing industries, and advanced manufacturing environments. For a detailed explanation of the applications on no-wait scheduling problems, the papers by Goyal and Sriskandarajah (1988), Hall and Sriskandarajah (1996) could be good references. In spite of its practical applications and

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http://dx.doi.org/10.1016/j.ijpe.2014.06.011
0925-5273/

theoretical issues, as shown in the survey paper by Hall and Sriskandarajah (1996), no-wait open shop scheduling (NW-OSS) has given far less attention than the other scheduling problems such as no-wait flow shops. According to three folds notation of Graham et al. (1979), the problem of no-wait open shop scheduling to minimize makespan can be classified as $O/nwt/C_{max}$.

Adiri and Amit (1984) consider NW-OSS where all operations have equal processing times and present a dispatching rule to minimize total completion time. Sidney and Sriskandarajah (1999) study two-machine NW-OSS and introduce a heuristic to solve the problem. As cited by Liaw et al. (2005), Yao and Soewandi (2000) and Yao and Lai (2002) address the problem of two-machine NW-OSS and propose a heuristic and a genetic algorithm, respectively. Liaw et al. (2005) also consider the same problem of two-machine NW-OSS. They propose a branch-and-bound armed with some dominance rules as well as a two-phase heuristic. Lin et al. (2008) study NW-OSS with movable dedicated machines. The objective is the minimization of total occupation time of all the machines. They introduce a mixed integer program, however unfortunately non-linear, to formulate the problem. They also propose a two-phase heuristic whose first phase constructs an initial sequence and the second phase improves that sequence. As far as we reviewed and as summarized by Table 1, almost none of the existing papers consider classical multi-machine NW-OSS. There is almost no attempt to linearly model the problem. There is no systematic encoding and decoding schemes for NW-OSS. Only one paper presents a metaheuristic for a relevant problem, not similar one.

It is known that the problem of two-machine no-wait open shop scheduling is strongly NP-hard (Sahni and Cho, 1979). Since this problem is a specific case of NW-OSS where $m=2$, we can conclude general multi machines NW-OSS is also NP-hard. Two common approaches to tackle the scheduling problems are the utilization of mathematical programming and heuristic approaches (Stafford Jr. et al., 2005). Due to the great advance recently obtained in capacity of computers and creation of fast optimization software, presentation of MILP models is becoming more and more interesting among the researchers. We develop a total of three different MILP models to formulate the no-wait open shops. We also carry out an experiment to analyze and compare the performance of the proposed models.

As we earlier mentioned, the second common way to solve such a problem is heuristic approaches which can be divided into two main groups: constructive and improvement heuristics. Constructive heuristics are those build a sequence quickly by a fixed predetermined rule. Therefore, they always yield the same results for a given instance. Improvement heuristics (so-called metaheuristics) are those iteratively improve a (or some) sequence(*s*) produced by random or by the constructive heuristics. Besides the presentation of models, we aim at providing tools to solve the large-sized problems. To do so, we need to establish a procedure to encode and decode solutions. The encoding and decoding schemes are almost the key point in the success of any algorithm, and the most problem-specific feature of any algorithm in the production scheduling problems. It should be designed in such a way that it has high adaptability to any operator and great simplicity to code. It also should avoid infeasible solutions in order to save the algorithms' computational time by searching only feasible space. No-wait scheduling problems need more meticulous care than pure problems due to high possibility of generating infeasible solutions. The situation becomes even more vital in open shop problems in comparison with the other scheduling problems. This paper establishes a tailor-made procedure of encoding and decoding schemes for no-wait open shop problems that keeps all above-mentioned characteristics. Afterwards, we propose three high performing metaheuristics based on variable neighborhood search (VNS) and genetic algorithm (GA). VNS is known to be a powerful, yet simple to understand and code metaheuristic. In this paper, we develop two different VNSs centered on curtailed and greedy fashions. Besides the VNSs, we apply an GA incorporating with some powerful operators. Model's efficiency and metaheuristics' capability to solve the problem studied here are investigated on two computational evaluations including small- and large-sized instances.

The rest of paper is organized as follows. Section 2 develops three different mixed integer linear programs. Section 3 presents a novel procedure of the encoding and decoding schemes. Section 4 introduces the proposed metaheuristics. Section 5 describes the experimental design to evaluate the posed methods including the mathematical models and algorithms. Finally, Section 6 gives some interesting conclusions and future studies.

2. Problem formulation

Even though MILP models might not be an efficient solution method for all problem sizes, they are a natural way to attack scheduling problems (Stafford Jr. et al., 2005). This section presents three different MILP models to formulate no-wait open shop problems based on three different variables. We analyze differences between the models. For example, we compare the number of binary and continuous variables as well as the number of constraints required for each model to formulate the same sized problem; also, we study their possible impact on performance of the models. We have the following similar notations in all the three models:

Parameters

n The number of jobs
m The number of machines
$O_{j,i}$ The operation of job j on machine i
$P_{j,i}$ The processing time of $O_{j,i}$

Table 1
Papers in literature of no-wait open shops.

Author	Year	Problem description	Model	Algorithm			Algorithm description
				Exact	Heuristic	Metaheuristic	
Adiri and Amit	1984	The same processing times for all jobs			✓		Dispatching rule
Sidney and Sriskandarajah	1999	Two-machine			✓		Approximation algorithm
Yao and Soewandi	2000	Two-machine			✓		–
Yao and Lai	2002	Two-machine				✓	Genetic algorithm
Liaw et al.	2005	Two-machine		✓			Branch and bound
Lin et al.	2007	Movable dedicated machines and minimization of total occupation time of all machines	✓			✓	An iterative improvement