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Multi-factory parallel machine problems: Improved mathematical models and artificial bee colony algorithm ☆

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A B S T R A C T

This paper considers the problem of multi factory parallel machine problems. This problem is already studied in the literature and there is a mathematical model and a genetic algorithm for the problem. We analyzed the model and algorithm, and showed that they suffer from serious shortcomings. Then, we propose three mathematical models for makespan and total completion time objectives. The proposed models are compared with the available model in both size and computational complexities. The available model is significantly outperformed. Moreover, we propose three effective metaheuristics based on artificial bee colony algorithms. The proposed metaheuristics are compared against the four available algorithms on both small and large instances. The proposed metaheuristics perform much more effectively.

1. Introduction

In today's world, the centralized manufacturing seems deficient to respond to the market requirements. Therefore, many organizations are showing increasing interest for utilizing a decentralized structure in manufacturing. Hence, a new concept called distributed manufacturing has been introduced in which several factories are integratedly planned in order to gain competitive advantages in the international economic area (Alvarez, 2007). Kanyalkar and Adil (2005) state that the single- and multi-factory production systems have some basic differences. In the single-factory production, products are manufactured by a single entity and then delivered to the market. However, in the multi-factory production, products are manufactured in several factories, maybe located in different geographical places. Therefore, some might be closer to customers and some might be far away. Moreover, not all factories are able to carry out all job types. In other words, there is the factory eligibility.

According to Kreipl and Pinedo (2004), a multi-factory model schedules all the jobs in different factories and at the same time satisfies the precedence constraints and sometimes time windows. Thoney, Hodgson, King, Taner, and Wilson (2002) considered scheduling of multi-factory supply chains and studied a model of batch processing with internal and external bulk transportation and solved industrial-sized problems. Moon, Seo, Yun, and Gen (2006) proposed a scheduling model and an advanced process planning for the multi factory production to minimize the makespan and operation sequences with machine selections considering the precedence constraints, flexible sequences, and alternative machines.

Wilkinson, Cortier, Shah, and Pantelides (1996) studied a real life application of multi factory scheduling. In their study they considered a production system with three factories placed in different countries and supply products for European consumers. In order to model the problem, they considered equipment changeovers and limited intermediate storage as some features of real world. They also divided the problem into smaller subproblems by combining constraints. Some other case studies include Gnonia, Iavagnilioa, Mossaa, Mummoloa, and Di Leva (2003) in the automotive factories, Sambasivan and Yahya (2005) in the steel corporation, Westfield (1955) in the electric power generating industries, Leung, Wu, and Lai (2003) in the lingerie company, Chen and Lin (2004) in the production of thin film transistor-liquid crystal display, Timpe and Kallrath (2000) in the food or chemical process industry and others. Cheng and Sin (1990) provides an excellent review of these types of problems.

More recently, Behnamian and Fatemi Ghomi (2013) consider a multi-factory model where each factory has multiple identical

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machines in parallel. Machines in each factory may have different processing speeds. Thus, the processing time of the same job in different factories varies. The objective is to minimize the general makespan (i.e., the maximum makespan among factories). This problem can be viewed as group unrelated parallel machines where machines within a group are identical; yet, machines of a group comparing with machines of other groups are unrelated. They propose a mathematical model for the problem. Moreover, they develop a genetic algorithm to solve the problem.

There are some serious drawbacks in their model and algorithm. These drawbacks cause the model and algorithm be completely ineffective. Hence, we have been thinking of improving both model and solution algorithm. We study the problem of multi-factory parallel machines once to minimize the makespan and once to minimize the total completion time. Because this problem is significantly influenced by the objective considered. We first propose three mathematical models, one for makespan minimization and the two others for total completion time minimization. The proposed models are compared for performance with the available model (Behnamian & Fatemi Ghomi, 2013) in both size and computational complexities. As the research problem belongs to the NP-hard category, exact methods can solve only small sized instances. Hence, we then propose novel metaheuristics based on artificial bee colony algorithms to minimize makespan and total completion time. The proposed algorithms are compared against the available genetic algorithm proposed by Behnamian and Fatemi Ghomi (2013).

The rest of this paper is organized as follows. Section 2 proposes two mixed integer linear programming models for the problem. Section 3 develops two artificial bee colony algorithms. Section 4 explains parameter setting. Section 5 evaluates the models and the algorithms using numerical experiments. Section 6 summarizes the research findings and suggests future studies.

2. Problem definition and formulation

The paper considers the problem of scheduling multi-factory parallel machines (MFPM). This problem with the objective of makespan minimization is already studied by Behnamian and Fatemi Ghomi (2013). In this problem, it is assumed that there are f parallel factories. In each factory, we have $m_k(k = 1, 2, \ldots, f)$ machines in parallel. The machines inside each factory are identical while machines of different factories are different. They process the same job with different speed. Therefore, the processing time of a job in different factories varies. There are n independent jobs $(j = 1, 2, \ldots, n)$ ready at time zero. It is also assumed that at any time, each job can only be processed by at most one machine and each machine can process only one job. Jobs and machines are continuously available. Preemption is not allowed; In other words, once a job started on a machine it cannot be interrupted.

There are two decisions, (1) assign jobs to factories and (2) sequence jobs of each factory. Developing mathematical programming models is one of the basic steps to deal with an optimization problem. Thus, in this paper we provide two mathematical models for each problem. The following notations are used in both mathematical models:

- n the number of jobs, $j = \{1, 2, \ldots, n\}$
- f the number of factories, $k = \{1, 2, \ldots, f\}$
- m_k the number of machines in factory , $i = \{1, 2, \ldots, m_k\}$
- v_k the speed of machines in factory k
- p_j the base processing time of job j
- $p_{j,k}$ the processing time of job j on machines of factory k $(p_{j,k} = \frac{p_j}{v_k})$

2.1. Makespan minimization

In case of makespan minimization, we have the following property.

Property 1. *Regarding the problem of MFPM, makespan is independent of sequencing decisions.*

Proof. Let us denote makespan and finishing time of all jobs assigned to machine i of factory k by C_{max} and F_{ik}, respectively. We know

$$C_{max} = \max_{k,i}\{F_{i,k}\}$$

We have

$$F_{i,k} = \sum_{j \in J_{i,k}} p_{j,i,k}$$

where $J_{i,k}$ is the set of jobs assigned to machine i of factory k. Therefore, $F_{i,k}$ is independent of sequence of jobs in set $J_{i,k}$. □

The available model proposed by Behnamian and Fatemi Ghomi (2013), although for makespan minimization, is developed so as to consider both assigning and sequencing. In this case, the model consists of many unnecessary binary variables and constraints for sequencing decision. This fact makes the model and their algorithm completely ineffective. The available model solves the makespan problem, although the problem is easier, at expense of both assignment and sequencing decisions.

We now present the mathematical model of makespan minimization. The variables applied in the first model are as follows.

- $X_{j,k,i}$ binary variable taking value 1 if job j is processed at factory k on machine i; and 0 otherwise
- C_{max} continuous variable for the makespan

As can be seen, the decision variables merely express the assignment part. The model is as follows.

Objective:

$$\text{Min } C_{max} \tag{1}$$

Subject to:

$$\sum_{k=1}^{f} \sum_{i=1}^{m_k} X_{j,k,i} = 1 \quad \forall_j \tag{2}$$

$$C_{max} \geqslant \sum_{j=1}^{n} p_{j,k} \cdot X_{j,k,i} \quad \forall_{k,i} \tag{3}$$

$$X_{j,k,i} \in \{0,1\} \tag{4}$$

Eq. (1) is the objective. Constraint set (2) assures that job j is assigned to exactly one machine of one factory. Constraint set (3) calculates the makespan which is equal to maximum finishing time of all machines. Constraint set (4) defines the decision variables.

2.2. Total completion time minimization

Note that the objective in the problem of MFPM with total completion time minimization depends on both decisions of assigning and sequencing. This fact causes that this problem with makespan minimization differs from the problem with total completion time minimization. Since the available model and genetic algorithm determine both assigning and sequencing, they can solve problem with total completion time. Even for this problem, we believe that