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Chemical-reaction optimization for flexible job-shop scheduling problems with maintenance activity

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ABSTRACT

This paper proposes an effective discrete chemical-reaction optimization (DCRO) algorithm for solving the flexible job-shop scheduling problems with maintenance activity constraints. Three minimization objectives—the maximum completion time (makespan), the total workload of machines and the workload of the critical machine are considered simultaneously. In the proposed algorithm, each solution is represented by a chemical molecule. Four improved elementary reactions, i.e., on-wall ineffective collision, inter-molecular ineffective collision, decomposition, and synthesis, are developed. A well-designed crossover function is introduced in the inter-molecular collision, synthesis, and decomposition operators. Tabu search (TS) based local search is embedded in DCRO to perform exploitation process. In addition, the decoding mechanism considering the maintenance activity is presented. Several neighboring approaches are developed to improve the local search ability of the DCRO. The proposed algorithm is tested on sets of the well-known benchmark instances. Through the analysis of experimental results, the highly effective performance of the proposed DCRO algorithm is shown against the best performing algorithms from the literature.

1. Introduction

The flexible job-shop scheduling problem (FJSP) is a branch of the classical JSP, which is more computationally difficult than the latter because of the addition need of machine assignment for each operation [1,2]. Due to the complexity of the FJSP, meta-heuristic algorithms have become a practical alternative of solving techniques for these problems. For the FJSP with makespan criterion, many different approaches have been developed, such as tabu search (TS [2–8]), genetic algorithm (GA [9–12]), particle swarm optimization (PSO [13–16]), the parallel variable neighborhood search (PVNS [17]), the knowledge-based ant colony optimization (KBACO [18]), the artificial immune algorithm (AIA [19]), and the climbing depth-bounded discrepancy search (CDDS [20]).

In very recent years, researchers have considered the importance of the FJSPs with multiple objectives. There are mainly two kinds of approaches for solving the multi-objective FJSP: the first is to combine all objectives into one weighted objective; the second is the Pareto based method. For the first kind, many heuristics and meta-heuristics have been used, such as the hybrid GA (hGA [12]), the hybrid of PSO and simulated annealing (PSO + SA [13]), the hybrid of PSO and TS (PSO + TS [16]), the framework of local search based algorithms [21], and the hybrid TS algorithm (HTSA [22]). The Pareto based method has taken little consideration. Kacem et al. [23] proposed a Pareto based algorithm which combines evolutionary algorithms and fuzzy logic. Ho and Tay [24] developed an approach named MOEA-GLS by utilizing evolutionary algorithm and guided local search. Moslehi et al. [25] conducted a Pareto approach using PSO and local search.

Nowadays, production scheduling and maintenance planning have been received considerable attention because of their importance both in the fields of manufacturing and combinatorial research. Ma et al. [26] surveyed the scheduling problems with maintenance activity constraints during very recent years. It shows that most literature considered machine availability constraints in solving single machine problems, parallel machine problems, flow shop scheduling problems, and job shop scheduling problems. There are few literature considers the availability constraints in the FJSP context. Gao et al. [27] proposed a hybridization of GA and local search method for solving the multi-objective FJSPs with preventive maintenance (PM) tasks. Zribi et al. [28] considered the MPM job shop scheduling problem with maintenance activity constraints. Wang and Yu [29] investigated a filtered beam search (FBS) based algorithm for FJSPs with PM tasks.

Very recently, by simulating the behavior of chemical molecular reaction, an efficient chemical-reaction optimization (CRO) algorithm is proposed by Lam and Li [30–32] to optimize

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combinatorial problems. Experimental comparisons demonstrated that the performance of the CRO algorithm is competitive to other swarm intelligent algorithms. Due to its ability to escape from the local optima, CRO has been applied for solving many scheduling problems, such as grid scheduling, network scheduling optimization [30–32]. Since there is no published work to deal with the flexible job-shop scheduling problem by using the CRO algorithm, we develop a novel discrete CRO (DCRO) algorithm for solving the multi-objective FJSPs. Furthermore, both maintenance activity case and non-maintenance activity case are considered, respectively.

The rest of this paper is organized as follows: In Section 2, we briefly describe the problem formulation. Then, the chemical-reaction optimization algorithm is presented in Section 3. The proposed DCRO algorithm is shown in Section 4. Section 5 reports the experimental results and compares with other algorithms in the literature to demonstrate the superiority of the DCRO performance. Finally, the last section presents conclusions of our work.

2. Problem formulation

In FJSP, there are a set of machines $M = \{M_k\}_{1\le k\le m}$, and a set of jobs $J = F_3^* \ge (\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j})$. Each job consists of a sequence of operations O_{ij}, $j = 1, \ldots, n_i$, where O_{ij} and $F_3^* \ge \left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j}\right)$ denote the jth operation of job i and the number of operations required for job i, respectively. Each operation O_{ij} is to be processed on a machine named $F_3^* \ge \left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j}\right)$ out of a set of suitable machines called $M_{ij} \subseteq M$ with a predefined fixed processing time p_{ijk}.

The following notation is used for the formulation of FJSP.

(1) Indices and sets

i	Job index ($i = 1,\ldots,n$).
j	Operation index.
k	Machine index ($k = 1,\ldots,m$).
l	Maintenance task index.
O_{ij}	The jth operation of job i.
M_{ij}	The set of candidate machines on which operation O_{ij} can be processed ($M_{ij} \subseteq M$).
PM_{kl}	The lth maintenance task on machine k.

(2) Parameters

n	Number of jobs.
m	Number of machines.
p_{ijk}	Processing time of operation O_{ij} on machine k ($p_{ijk} \ge 0$).
L	A large number.
L_k	Total number of preventive maintenance tasks on machine k.
$F_3^* \ge \left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j}\right)$	The number of operations of J_i.
d_{kl}	Duration of the maintenance task PM_{kl}.
$[w_{kl}^E, w_{kl}^L]$	Time window associated with PM_{kl}, where w_{kl}^E represents the early starting time, while w_{kl}^L is the late completion time.

(3) Decision variables

x_{ijk}	$\begin{cases} 1, & \text{if machine } k \text{ is selected for } O_{ij} \\ 0, & \text{otherwise} \end{cases}$
s_{ij}	The starting time of operation O_{ij}.
c_{ij}	The completion time of operation O_{ij}.
f_1	Maximum completion time of all jobs.
f_2	The total workload of all machines.
f_3	Maximum workload of all machines.
z_{kl}	Completion time of the maintenance task PM_{kl}.

Under these assumptions and notations, the proposed mathematical model for the problem is defined as follows.

$$\min f_1 = \max_{1\le i\le n}\{c_{in_i}\} \tag{1}$$

$$\min f_2 = \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{n_i} x_{ijk}\cdot p_{ijk} + \sum_{k=1}^{m}\sum_{l=1}^{L_k} d_{kl} \tag{2}$$

$$\min f_3 = \max_{1\le k\le m}\left\{\sum_{i=1}^{n}\sum_{j=1}^{n_i} x_{ijk}\cdot p_{ijk} + \sum_{l=1}^{L_k} d_{kl}\right\} \tag{3}$$

s.t.

$$s_{ij} + \sum_{k\in M_{ij}}(p_{ijk}\cdot x_{ijk}) \le s_{i(j+1)} \quad \text{for } j = 1,\ldots,n_i-1; i = 1,\ldots,n; \tag{4}$$

$$\sum_{k\in M_{ij}} x_{ijk} = 1 \quad \text{for } j = 1,\ldots,n_i; \quad i = 1,\ldots,n; \quad k = 1,\ldots,m; \tag{5}$$

$$(z_{kl} - d_{kl} - c_{ij})\cdot x_{ijk} \ge 0] \vee [(c_{ij} - z_{kl} - p_{ijk})\cdot x_{ijk} \ge 0] \forall (i,j)(k,l) \tag{6}$$

$$w_{kl}^E + d_{kl} \le z_{kl} \le w_{kl}^L \quad \forall (k,l) \tag{7}$$

$$s_{ij} \ge 0 \quad \text{for } j = 1,\ldots,ni; \quad i = 1,\ldots,n; \tag{8}$$

$$p_{ijk} \ge 0 \quad \text{for } j = 1,\ldots,ni; \quad i = 1,\ldots,n; \quad k = 1,\ldots,m; \tag{9}$$

$$x_{ijk} \in \{0,1\} \quad \text{for } j = 1,\ldots,ni; \quad i = 1,\ldots,n; k = 1,\ldots,m; \tag{10}$$

$$w_{kl}^E, w_{kl}^L \ge 0 \,\forall (k,l) \tag{11}$$

Constraint (4) ensures that the precedence relationships between the operations of a job are not violated, i.e. the operation $F_3^* \ge \left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j}\right)$ cannot be started until its predecessor $F_3^* \ge \left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\delta_{i,j}\right)$ has been completed. Constraint (5) makes sure that each operation is assigned to only one machine from its candidate machines set. Constraint (6) forces the un-overlapping constraints between preventive maintenance tasks and operations, while constraint (7) ensures that the PM tasks have to be completed within their time windows.

3. Chemical-reaction optimization

3.1. The basic concept of CRO

CRO is introduced by Lam and Li [30] in 2010, which loosely mimics what happens to molecules in a chemical reaction system and tries to capture the energy in the reaction process. The molecules represent the solution for the considered problem, which have some properties. A molecule is composed of several atoms and characterized by the atom type, bond length, angle, and torsion [30]. Any change in the atom type, bond length, angle, or torsion will make the molecules different with each other. Thus, the change in molecular structure is tantamount to switching to another feasible solution. Each molecule possesses two kinds of energies, i.e., *PE* (potential energy) and *KE* (kinetic energy). *PE* corresponds to the objective function of a molecule while the *KE* of a molecule symbolized its ability of escaping from a local minimum. Given a molecule ω, the formulation of *PE* is shown as follows.

$$PE_\omega = f(\omega) \tag{12}$$