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A multi-objective artificial bee colony algorithm for parallel batch-processing machine scheduling in fabric dyeing processes

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ABSTRACT

Fabric dyeing is a critical production process in the clothing industry. Characterized by high energy consumption and water pollutant emission, dyeing processes need careful scheduling in order to reduce the relevant direct and indirect costs. In this paper, we describe the dyeing process scheduling problem as a bi-objective parallel batch-processing machine scheduling model, in which the first objective function reflects the tardiness cost and the second objective function concerns the utilization rate of dyeing vats. To obtain satisfactory schedules within reasonable time, we propose an efficient multi-objective artificial bee colony (MO-ABC) algorithm to solve the scheduling problem. The proposed algorithm features a specialized encoding scheme, a problem-specific initialization technique and several unique functions to deal with multi-objective optimization. After preliminary tuning of parameters, we use a set of 90 instances with up to 300 jobs to test the MO-ABC algorithm. Extensive experiments show that the MO-ABC outperforms a generic multi-objective scheduling algorithm in terms of both solution quality and computational time robustness.

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1. Introduction

A clothing factory typically consists of three sequential departments, i.e., the weaving workshop, the dyeing workshop and the sewing workshop. Among the three production stages, dyeing is often the most critical process (bottleneck) that dominates the entire production progress because it is time-consuming and technologically demanding. Therefore, scheduling of the dyeing processes is of great significance to maintaining high product quality and on-time delivery rate for a clothing firm. In addition, since dyeing processes inevitably generate high emissions of water and air pollutants, scheduling plays an important role in controlling the cost of pollution by means of increasing the utilization rate of dyeing equipment.

Dyeing process scheduling needs to consider the following factors. Each job is characterized by three attributes (i.e., color, weight and due date). Jobs with the same color belong to a family and have an identical processing time. Several jobs from the same family can be processed as a batch in the same vat (dyeing machine) as long as the total weight does not exceed the capacity of the vat. However, jobs from different families can never be processed together in the same vat (they are called incompatible). The available dyeing vats in the workshop have different capacities and can be utilized in a simultaneous manner.

1.1. The batch-processing machine scheduling problem

The scheduling model that best fits the characteristics of dyeing processes is known as the batch-processing machine scheduling problem in literature. A batch-processing machine can process several jobs simultaneously as a batch (subject to limit capacity). Therefore, batch-processing machine scheduling models inherently integrate the batching problem and the sequencing problem, and thus are more difficult to solve than ordinary scheduling problems that require only sequencing decisions. outlookIt has been shown in [1] that makespan minimization on a single batch-processing machine with non-identical job sizes is equivalent to a bin-packing problem which is $\mathcal{NP}$-hard in the strong sense. In addition, given the fact that scheduling of ordinary parallel machines for makespan minimization is also $\mathcal{NP}$-hard (even for two machines) and the fact that makespan minimization can be reduced to (and thus can be regarded as a special case of) total tardiness minimization [2], we may conclude that parallel batch-processing machine scheduling with total tardiness criterion, as discussed in this paper, is a highly complex and challenging problem.

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From the perspective of real-world applications, we could notice that there has been increasing interest in parallel batch-processing machine scheduling problems because of their considerable application potential. Such scheduling problems are often encountered in contemporary manufacturing industries, such as chemical and mineral processing, pharmaceutical and mechanical production, semiconductor manufacturing, etc. [3]. To get a glimpse of the literature, some representative works are introduced below as examples of research in this line.

An ant colony optimization meta-heuristic is proposed in [4] to schedule a single batch-processing machine with arbitrary job sizes and incompatible job families for minimizing total weighted completion time. A fuzzy goal programming approach is presented in [5] for integrated loading and scheduling of a batch-processing machine considering both short-term and long-term objectives. A combined scheduling algorithm based on simulation and integer programming is proposed in [6] to address the problem of minimizing total weighted tardiness on a re-entrant batch-processing machine with incompatible job families in semiconductor wafer fabrication processes. A genetic algorithm is designed in [7] to schedule a set of identical batch-processing machines in parallel with the aim of minimizing makespan. A genetic algorithm, an ant colony optimization approach and a large neighborhood search approach are described in [8] for solving a scheduling problem for parallel identical batch-processing machines with incompatible job families to minimize the total weighted tardiness. A linear-programming algorithm, an integer-programming algorithm and a heuristic algorithm are proposed in [9] to schedule non-homogenous parallel batch-processing machines with non-identical job sizes and incompatible job families in semiconductor manufacturing systems. An online version of the scheduling problem for unbounded parallel batch-processing machines and equal-length jobs is studied in [10] with the objective of minimizing makespan. outlook Besides genetic algorithm, other meta-heuristics such as discrete particle swarm optimization [11], discrete differential evolution [12], and max–min ant system [13] have also been applied to parallel batch-processing machine scheduling problems.

All of the above works deal with single-objective optimization models for batch-processing machine scheduling. In fact, quite few publications are concerned with multi-objective versions of the scheduling problem. In [14], the authors propose two hybrid multi-objective genetic algorithms based on different representation schemes to address a single batch-processing machine scheduling problem with bi-criteria of makespan and maximum tardiness. In [15], the authors design an ant colony optimization algorithm to solve a parallel batch-processing machine scheduling problem with incompatible job families and dynamic job arrivals while taking into account two objective functions, namely, total weighted tardiness and makespan. In [16], the authors present a multi-objective imperialist competitive algorithm for scheduling identical parallel batch-processing machines with arbitrary job sizes and unequal release times in order to minimize the makespan and the total weighted earliness and tardiness of jobs (JIT). outlookIn [17], the authors develop an efficient meta-heuristic algorithm based on tabu search with multi-level diversification to address a batch scheduling problem on a set of unrelated parallel machines with the objective of minimizing a linear combination of total weighted completion time and total weighted tardiness.

As can be seen from above, batch-processing machine scheduling problems can be divided into several subclasses according to the specifics of machines and jobs. In terms of machines, we can differentiate between the *single machine* setting and the *parallel machines* setting. When discussing parallel machines, we can further differentiate between *identical parallel machines* and *non-identical/heterogeneous parallel machines*. In terms of jobs, we can distinguish between the case of *identical/equal job sizes* and the case of *arbitrary/unequal job sizes*, and we can also distinguish between the case of *compatible job families* and the case of *incompatible job families*. In each pair of classifications stated above, it is apparent that the latter type represents a higher level of complexity for scheduling than the former type. In this way, it is easily seen that the dyeing process scheduling problem belongs to the most complex category, i.e., parallel batch-processing machine scheduling problem with heterogeneous parallel machines, arbitrary job sizes and incompatible job families.

1.2. The artificial bee colony optimization algorithm

To solve large-scale scheduling problems with $\mathcal{NP}$-hard complexity, most researchers nowadays would resort to meta-heuristic algorithms because of their computational efficiency and controllable precision. Among various types of meta-heuristics, the artificial bee colony (ABC) optimization algorithm is a relatively new one but it has been applied to many engineering optimization problems with noticeable success. The ABC algorithm, originally proposed by Karaboga in 2005 for optimizing multi-variable and multi-modal continuous functions [18], simulates the cooperative foraging behavior of a swarm of honey bees [19]. Later research has revealed some good properties of the ABC [20–22]. In particular, the ABC involves much fewer control parameters than many other population-based meta-heuristics, which makes it easier to implement and more reliable for engineering purposes. Therefore, the ABC has become a popular algorithm in the optimization community for solving problems such as production scheduling [23,24], vehicle routing [25], transit route design [26], land-use allocation [27], portfolio selection [28], and dynamic optimization problems [29].

In real-world applications, optimization problems often involve more than one objectives which have to be optimized simultaneously. Extensive research efforts have been made to address such problems. For example, an approximate algorithm has been proposed in [30] for solving fuzzy multi-objective linear programming problems with fuzzy parameters in both objective functions and constraints, and a decision support system (DSS) has been developed based on the algorithm. Focusing on meta-heuristics, we could see that a number of efforts have been made to adapt the ABC algorithm for multi-objective optimization problems. In [31], a multi-objective artificial bee colony (MOABC) algorithm is proposed, which features a grid-based approach to adaptively assess the Pareto front maintained in an external archive. The external archive is used to control the flying behaviors of the bees and the structure of the bee colony. The vector evaluated artificial bee colony (VEABC) algorithm proposed in [32] organizes multiple bee colonies based on the number of objectives to be optimized. Each colony separately evaluates one single objective and they exchange information so as to obtain the optimal solution set. In [33], the author proposes three multi-objective ABC algorithms based on synchronous/asynchronous models and Pareto non-dominated sorting, called A-MOABC/PD, A-MOABC/NS and S-MOABC/NS, respectively. These algorithms have been evaluated on 10 unconstrained test functions and compared with three algorithms in terms of different performance metrics. An elitism based multi-objective artificial bee colony (eMOABC) algorithm is proposed recently [34], which uses a fixed-size archive maintained on the basis of crowding-distance to store the non-dominated solutions found during the search process. In the algorithm, an improved elitism strategy is utilized for the purpose of avoiding premature convergence. It is worth pointing out that another multi-objective ABC algorithm based on similar ideas (elite-guided) is presented in [35]. In the so-called EMOABC algorithm, a novel elite-guided solution generation strategy is proposed to accelerate the convergence

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