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Discrete Optimization

An effective co-evolutionary artificial bee colony algorithm for steelmaking-continuous casting scheduling

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ABSTRACT

This paper addresses a new steelmaking-continuous casting (SCC) scheduling problem from iron and steel production processing. We model the problem as a combination of two coupled sub-problems. One sub-problem is a charge scheduling problem in a hybrid flowshop, and the other is a cast scheduling problem in parallel machines. To solve this SCC problem, we present a novel cooperative co-evolutionary artificial bee colony (CCABC) algorithm that has two sub-swarms, with each addressing a sub-problem. Problem-specific knowledge is used to construct an initial population, and an exploration strategy is introduced to guide the CCABC to promising regions during the search. To adapt the search operators in the classical artificial bee colony (ABC) to the cooperative co-evolution paradigm, an enhanced strategy for onlookers and a self-adaptive neighbourhood operator have been suggested. Extensive experiments based on both synthetic and real-world instances from an SCC process show the effectiveness of the proposed CCABC in solving the SCC scheduling problem.

1. Introduction

There has been growing interest in solving real-world scheduling problems in recent years (Tang, Guan, & Hu, 2010). This paper considers a realistic and typical scheduling problem that integrates a charge scheduling problem in a hybrid flowshop and a cast scheduling problem in parallel machines. The problem is found in a very important industrial process of the world economy, which is the steelmaking-continuous casting (SCC) process. The SCC process includes three consecutive production stages, namely steelmaking, refining, and continuous casting, and it is usually the bottleneck in iron and steel production (Tang, Liu, Rong, & Yang, 2001, Tang, Wang, & Chen, 2014). Effective scheduling methods for the SCC process are crucial to improving the productivity of the modern iron and steel industry (Chang, Chang, & Hong, 2000, Cowling and Rezig 2000, Tang, Liu, Rong, & Yang, 2000, Tang, Lub, Liu, & Fang, 2002).

SCC scheduling is known to be one of the most difficult industrial scheduling problems. Researchers and practitioners have approached SCC scheduling problems mostly by mathematical programming and artificial intelligence (Pacciarelli & Pranzo, 2004). For mathematical programming methods, Tang et al. (2002) presented a combination of Lagrangian relaxation, dynamic programming and heuristics for an SCC problem, to ensure continuity of the production process and just-in-time delivery of the final products. Bellabdaoui and Teghem (2006) presented a mixed-integer programming model to minimize the total completion time of the sequences for scheduling an SCC process with two parallel machines at each stage in Arcelor Group in Liege, Belgium. Xuan and Tang (2007) established an integer programming model and presented a batch decoupling based on a Lagrangian relaxation algorithm for an SCC scheduling problem, to minimize a given criterion with respect to the completion time. Missbauer, Hauber, and Stadler (2009) introduced a computerized scheduling system for an SCC process from a steel plant in Austria, where a schedule is improved by a linear programming model. Sun and Wang (2013) proposed a scheduling method that consists of an equipment assignment algorithm based on a dynamic programming technique and a conflict elimination algorithm based on a linear programming technique, to guarantee that the charges are continuously processed on the same caster. Recently, Mao , Pan, Pang, and Chai (2014a) studied an SCC scheduling problem for minimizing the total weighted earliness/tardiness penalties and job waiting and presented a Lagrangian relaxation approach while relaxing the machine capacity constraints. Mao , Pan, Pang, and Chai (2014b) addressed an SCC rescheduling problem with machine break-down and processing time variations and developed a time-index formulation and an effective Lagrangian relaxation approach with machine capacity relaxation.

Using artificial intelligence methods, Pacciarelli and Pranzo (2004) formulated the scheduling of stainless ingots in a production line in central Italy by an alternative graph and solved the

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problem using a beam search procedure. Kumar, Kumar, Tiwari, and Chan (2006) developed a combinatorial auction-based approach to resolve an SCC scheduling problem for minimizing the waiting time and maximizing the number of steel slabs that are produced. Atighehchian, Bijari, and Tarkesh (2009) investigated an SCC scheduling problem from Mobarakeh Steel Company in Isfahan with the objective of minimizing the casting interruption cost, molten steel temperature drop cost, cost of poor quality and maximum completion time cost, and they presented a hybrid algorithm based on ant colony optimization and non-linear optimization methods. Zhu, Zheng, and Gao (2010) proposed an optimization model that is combined with a parallel-backward inferring algorithm and genetic algorithm to improve the efficiency and performance of production scheduling in an SCC process. Recently, Pan, Wang, Mao, Zhao, and Zhang (2013) considered an SCC scheduling problem to minimize the penalty caused by sojourn time and the earliness/tardiness of cast starting, using an artificial bee colony algorithm. Later, Li, Pan, Mao, and Suganthan (2014) presented an effective fruit fly optimization algorithm to solve the same SCC scheduling problem, and they improved the results. More recently, Tang, Zhao, and Liu (2014) presented an improved differential evolution algorithm with a real-coded matrix representation to re-optimize the assignment, sequencing, and timetable of a set of existing and new jobs among various production stages for a new environment in which unforeseen changes occurred in the production system.

In the above literature, one of the basic assumptions is that the assignment and sequencing of the casts (i.e., a given sequence of charges) in the continuous casting stage are fixed in advance and remain unchanged, and the researchers concentrated on the sequence and scheduling of the charges in the steelmaking and refining stages and the timing of the charges on casters in the continuous casting stage. Unlike the above studies, this paper assumes that the schedule of the casts are not given in advance and to be determined by the scheduling algorithm. That is, we address a new SCC scheduling problem that optimizes charge scheduling in the steelmaking and refining stages and cast scheduling in continuous casting stage simultaneously to minimize the makespan and charge waiting times over the whole SCC process. This approach will lead to a much higher degree of flexibility, which can significantly enhance the productivity. Furthermore, we consider multiple refining phases in the refining stage, which is an approach that has a much wider application to real-world problems.

Artificial bee colony (ABC) is a fairly new optimizer that has been shown to be as competitive as other population-based algorithms for continuous function optimization, but it has the advantage of employing fewer control parameters (Karaboga & Akay, 2009). It has gradually become more and more popular and has been successfully used in scheduling problems, including the lot-streaming flowshop (Pan, Suganthan, Tasgetiren, & Chua, 2011), flexible job shop (Li et al. 2011), and many others. In our previous work (Pan et al., 2013), we presented an effective ABC algorithm for solving a three-stage SCC scheduling problem with the assumption of a fixed cast schedule at the continuous casting stage. Whereas, this paper applies ABC to the new SCC scheduling problem, which consists of two coupled subproblems: a charge scheduling problem in the steelmaking and refining stage and a cast scheduling problem in the continuous casting stage. We extend the ABC to a cooperative co-evolutionary paradigm by dividing the artificial bees into two sub-swarms, each addressing a scheduling problem. Furthermore, we introduce new techniques to enhance the performance of the cooperative co-evolution ABC (CCABC), including a problem-specific knowledge-based initialization, a new exploration mechanism, and a self-adaptive neighbourhood operator. Extensive simulations and comparisons demonstrate the effectiveness of the CCABC for the new SCC problem.

The remainder of this paper is organized as follows. In Section 2, a realistic SCC scheduling problem is formulated. Section 3 introduces the basic ABC briefly, which is followed by a description of the presented CCABC in Section 4. The simulation results and empirical comparisons are provided in Section 5. Finally, Section 6 concludes the paper and suggests some future work.

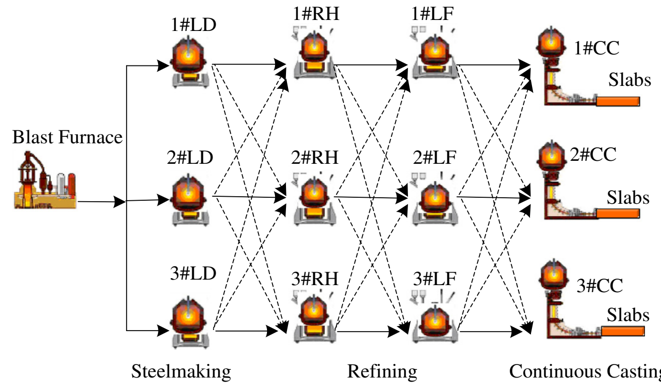

Fig. 1. A typical SCC process.

2. The steelmaking-continuous casting (SCC) scheduling problem

2.1. The SCC process

Basically, an SCC process consists of three consecutive production stages: steelmaking, refining, and continuous casting (see Fig. 1).

In the steelmaking stage, hot molten iron is turned into molten steel by a Linz–Donawitz–Verfahren converter (‘LD’ in Fig. 1), which reduces the carbon, sulphur, silicon, and other impurity content to desirable levels. In the refining stage, the impurities are further eliminated, and the required alloy ingredients are added to the molten steel. To produce high grade steel, multiple refining stages always exist, such as the Ruhrstahl Heraeus (‘RH’ in Fig. 1) and Ladle Furnace (‘LF’ in Fig. 1). Charges are the basic production units in the steelmaking and refining stages, which refers to concurrent smelting in the same furnace. The continuous casting stage is responsible for casting the liquid steel into solid slabs. At this stage, a sequence of charges must be continuously cast on the same continuous caster (‘CC’ in Fig. 1) in accordance with a given precedence and without a break. Thus, a sequence of charges (or a cast) is the basic production unit. To accelerate the production and to balance the interflow of the charges, identical parallel machines are configured at each stage.

2.2. The SCC scheduling problem

Following Atighehchian et al. (2009), Tang et al. (2002), and many others, we consider the situation in which all of the charges follow the same process route: steelmaking, refining, and then continuous casting. In the refining stage, the charges undergo refining stage one and then refining stage two, until the last refining stage. A charge or cast can be processed on any one of the parallel machines at the same stage. The production process is a complex hybrid flowshop, which is very common in modern iron and steel enterprises in China. The other cases in which the charges have different refining routes, for example, some from RH to LF, others from LF to RH, or a charge goes through some refining stage twice will be studied in the future.

A sequence-independent and separable setup time is needed when a new cast is prepared for processing. However, no setup time is required between the adjacent charges in a cast. The transportation times between the stages must be considered. We address the static scheduling problem in this paper and assume that the processing times of all of the charges, the transportation times between stages, and the setup times of all of the casts are known, deterministic, and uninterrupted. The dynamic scheduling problem, which