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A bi-layer optimization approach for a hybrid flow shop scheduling problem involving controllable processing times in the steelmaking industry ☆

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ABSTRACT

A steelmaking-continuous casting (SCC) scheduling problem is an example of complex hybrid flow shop scheduling problem (HFSSP) with a strong industrial background. This paper investigates the SCC scheduling problem that involves controllable processing times (CPT) with multiple objectives concerning the total waiting time, earliness/tardiness and adjusting cost. The SCC scheduling problem with CPT is seldom discussed in the existing literature. This study is motivated by the practical situation of a large integrated steel company in which the just-in-time (JIT) and cost-cutting production strategy have become a significant concern. To address this complex HFSSP, the scheduling problem is decomposed into two subproblems: a parallel machine scheduling problem (PMSP) in the last stage and an HFSSP in the upstream stages. First, a hybrid differential evolution (HDE) algorithm combined with a variable neighborhood decomposition search (VNDS) is proposed for the former subproblem. Second, an iterative backward list scheduling (IBLS) algorithm is presented to solve the latter subproblem. The effectiveness of this bi-layer optimization approach is verified by computational experiments on well-designed and real-world scheduling instances. This study provides a new perspective on modeling and solving practical SCC scheduling problems.

1. Introduction

The hybrid flow shop scheduling problem (HFSSP), which is also referred to as the flexible flow shop scheduling problem (FFSSP) or flow shop with multiple processors scheduling problem (FSMPSP), has attracted the attention of numerous researchers (Ribas, Leisten, & Framiñan, 2010; Ruiz & Vázquez-Rodríguez, 2010). It is a complex problem that is applied in many industry fields, such as the chemical industry, the paper-making industry, the food industry, and the metallurgical industry (Hakimzadeh Abyaneh & Zandieh, 2011). Fig. 1 illustrates the production process flow in a steelmaking plant.

The general steelmaking process always involves three stages: (1) The steelmaking stage, in which the pig iron and the scrap steel are converted into liquid steel in the basic oxygen furnace (BOF) or electric arc furnace (EAF). The liquid steel is poured into a ladle and transferred to the next stage with an idle crane. (2) The refining stage, in which the chemical composition and the temperature of liquid steel are adjusted to the predetermined level in a refining machine, such as a ladle furnace (LF) and a Rheinstahl–Heraeus (RH). For some high-precision steel grades, more than one refining machine is employed. (3) The casting stage, in which the liquid steel is cast and cut into slabs or bullets through continuous casting machines (CCM) operated continuously. In some practical situations, the processing speed of each CCM can be controlled to satisfy the continuity constraint of the CCM and to stabilize the temperature (Missbauer, Hauber, & Stadler, 2009).

With regard to an integrated steel company, the steelmaking-continuous casting (SCC) is pivotal for boosting productivity, reducing production costs and achieving sustainable scheduling of manufacturing systems. However, it is also the bottleneck between ironmaking and rolling mills. This paper addresses the previously mentioned concerns and presents the results of our industrial scheduling work using a bi-layer optimization approach. The remaining contents are organized as follows. In Section 2, the literature about scheduling problems related to the SCC production and controllable processing times (CPT) is reviewed. In Section 3, the mathematical model of the SCC scheduling problem is provided. In Section 4, a hybrid differential evolution (HDE) algorithm enhanced by a variable neighborhood decomposition search

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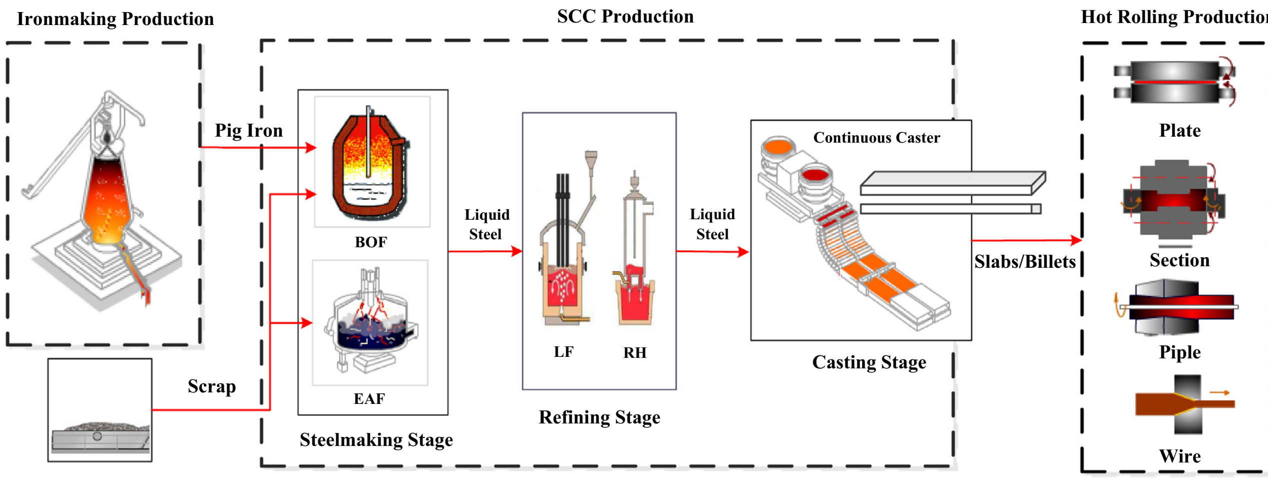

Fig. 1. The process flow diagram for a steelmaking plant.

(VNDS) is proposed after the essential elements are discussed in details. In Section 5, a novel heuristic approach, named iterative backward list scheduling (IBLS), is presented for the scheduling problem in the upstream stages. To obtain appropriate performance of the algorithm, the parameters of HDE-VNDS are tuned by the Taguchi method in Section 6. The experimental results and comparisons are listed and analyzed in this section. Section 7 provides some conclusions from this paper. All involved algorithms are coded by Visual C++ 2012 and run on a PC- with an Intel® Core™ i5 CPU and 8 GB RAM, using Gurobi 6.0 for solving linear programming problems.

2. Literature review

2.1. Steelmaking-continuous casting scheduling problem

The SCC scheduling problem, which is regarded as a special HFSSP with strong constraints, is an important research topic extensively investigated in academic and industrial communities. Various algorithms for the SCC scheduling problem have been discussed in the literature. They can be categorized into three types: the exact method, the heuristic method and the meta-heuristic method.

According to the just-in-time (JIT) production strategy, Tang, Liu, Rong, and Yang (2000) developed a nonlinear model, and converted it into a linear programming model. Focusing on a model derived from a real-world application, Bellabdaoui and Teghem (2006) developed a mixed-integer linear programming formulation. After some constraints are relaxed, both of these models can be solved by standard software packages. Tang, Xuan, and Liu (2006) and Xuan and Tang (2007) decomposed the SCC scheduling problem into batch-based subproblems by the Lagrangian relaxation method. A dynamic programming approach is developed to solve these subproblems. Mao, Pan, Pang, and Chai (2014) decomposed the SCC scheduling problem into two tractable subproblems by relaxing the machine capacity constraints, and proposed an improved subgradient level algorithm. Pacciarelli and Pranzo (2004) proposed an alternative graph model to describe all constraints of the SCC scheduling problem and designed a beam search algorithm. Atighehchian, Bijari, and Tarkesh (2009) presented a hybrid algorithm named HANO, which combined an ant colony optimization (ACO) algorithm and a nonlinear optimization method for the three-stage SCC scheduling problems. Tang and Wang (2010) presented an improved particle swarm optimization (PSO) algorithm to minimize the total weighted completion time of an HFSSP, which exhibits a steelmaking industry background. According to some problem-specific characteristics, Pan, Wang, Mao, Zhao, and Zhang (2013) designed a job-permutation-based artificial bee colony (ABC) algorithm that incorporates several improved heuristic procedures. Tang, Zhao, and Liu (2014) proposed an improved differential evolution (PIDE) algorithm based on incremental mechanism to solve a dynamic SCC scheduling problem. To solve the realistic SCC scheduling problem, Li, Pan, Mao, and Suganthan (2014) presented an effective fruit fly optimization algorithm (FOA) in which the solution representation is decoded with forward list scheduling (FLS) method.

2.2. Scheduling problems involving CPT

The original study of scheduling problems involving CPT was completed by Vickson (1980). Shabtay and Steiner (2007) reviewed studies of scheduling problems with CPT completed before 2007. Recently, a greater number of researchers have focused their attention on this field. Mokhtari, Abadi, and Cheraghalikhani (2011) presented hybrid discrete differential evolution (HDDE) and a variable neighborhood search (VNS) algorithms to solve a multi-objective flow shop scheduling problem with resource-dependent processing times. Mokhtari, Abadi, and Zegordi (2011) devised a two-phase genetic algorithm (GA) for a no-wait job shop scheduling problem with CPT. Shabtay, Bensoussan, and Kaspi (2012) presented a pseudo-polynomial time algorithm for a JIT flow shop scheduling system in which the processing times are controllable by the allocation of resources. Behnamian and Fatemi Ghomi (2011) proposed a hybrid approach based on GA and VNS for an HFSSP with resource-dependent processing times. Kayvanfar, Mahdavi, and Komaki (2013) presented a net benefit compression-net benefit expansion (NBC–NBE) heuristic to optimize processing times for single machine scheduling problems with a given sequence. To solve the unrelated parallel machine scheduling problem (PMSP) with CPT, Kayvanfar, Komaki, Aalaei, and Zandieh (2014) proposed a parallel net benefit compression-net benefit expansion (PNBC–NBE) heuristic for optimizing the job processing times, and some evolutionary algorithms for optimizing the job sequence on each machine.

In existing studies on the SCC scheduling problem, the processing times of jobs were treated as fixed parameters. However, in the practical production environment, the processing times in the casting stage can be controlled by adjusting the slab width or the strand number. The SCC scheduling problem that involves CPT in the casting stage has only been discussed by Missbauer et al.