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Review

An improved Lagrangian relaxation approach to scheduling steelmaking-continuous casting process

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ABSTRACT

In the steelmaking continuous-casting (SCC) process, scheduling problem is a key issue for the iron and steel production. To improve the productivity and reduce material consumption, optimal models and approaches are the most useful tools for production scheduling problems. In this paper, we firstly develop a mixed integer nonlinear mathematical model for the SCC scheduling problem. Due to its combinatorial nature and complex practical constraints, it is extremely difficult to cope with this problem. In order to obtain a near-optimal schedule in a reasonable computational time, Lagrangian relaxation approach is developed to solve this SCC scheduling problem by relaxing some complicated constraints. Owing to the existence of the nonseparability coming from the product of two binary variables, it is still hard to deal with this relaxed problem. By making use of their characteristics, the subproblems of the relaxed problem can be converted into different difference of convex (DC) programming problems, which can be solved effectively by using the concave–convex procedure. Under some reasonable assumptions, the convergence of the concave–convex procedure can be established. Furthermore, we introduce an improved conditional surrogate subgradient algorithm to solve the Lagrangian dual (LD) problem and analyze its convergence under some appropriate assumptions. In addition, we present a simple heuristic algorithm to construct a feasible schedule by adjusting the solutions of the relaxed problem. Lastly, some numerical results are reported to illustrate the efficiency and effectiveness of the proposed method.

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1. Introduction

The iron and steel industry, one of the cornerstone industries, makes a material contribution to the world economy by providing raw materials for a number of other important industries, such as, machinery manufacturing, shipbuilding, petro-chemical and construction industry. Unlike other industries, the process of iron and steel production runs at high-temperature and high-weight material flow with complicated technological processes and extensive energy consumption (Li et al., 2012). In the iron and steel industry, SCC process plays a significant role, since it is one of the largest bottlenecks in the manufacturing process. Production scheduling in the iron and steel industry has been recognized as one of the most difficult industrial scheduling problems (Harjunkoski and Grossmann, 2001). In the SCC process, two main tasks of scheduling are to determine which orders are allocated to each machine, and assign the sequence of orders allocated at each stage (Li et al., 2011; Tang et al., 2000). Due to its combinatorial nature, strict requirements on material continuity and complex practical constraints, it is extremely challenging to solve the scheduling problems of the SCC process. Optimal scheduling of the SCC process can effectively improve machine productivity, reduce material and energy consumption and minimize production cost (Li et al., 2016b; Ye et al., 2014). Therefore, it is critical to develop an effective and efficient optimization model and approach to cope with the complicated scheduling problem of the SCC process.

In recent years, most published works on optimization models and approaches for scheduling problems of the SCC process can be roughly classified into three categories: mathematical programming methods, artificial intelligence methods and heuristic methods. Using mathematical programming methods, Bellabdaoui and Teghem (2006) presented a mixed integer mathematical model for the scheduling of steelmaking continuous casting production, which can be solved by using some standard software packages. Harjunkoski and Grossmann (2001) presented a decomposition algorithm to split the large scheduling problem of steel industry into smaller subproblems that can often be solved optimally by using mathematical programming methods. Mao et al. (2014) modeled the SCC scheduling problem as a mixed-integer linear programming problem and proposed a novel Lagrangian relaxation approach to solve this problem. Mao et al. (2015) presented a time-index formulation for the SCC scheduling problem and developed an effective subgradient method and dynamic programming approach to deal with this scheduling problem. Tang et al. (2002) formulated a novel integer programming formulation with a separable structure for SCC scheduling problem and developed an improved solution method by combining Lagrangian relaxation, dynamic programming and heuristics to solve this problem. Ye et al. (2014) introduced robust optimization and stochastic programming approaches for addressing a medium-term production scheduling of the large-scale steelmaking continuous casting process under demand uncertainty. With respect to artificial intelligence methods, Atighehchian et al. (2009) investigated a novel iterative algorithm by combining ant colony optimization and nonlinear optimization methods for scheduling of the SCC production. Jiang et al. (2015) investigated a mathematic programming model for the SCC scheduling problem with controllable processing times and proposed a meta-heuristic algorithm by comparing differential evolution algorithm with a variable neighborhood decomposition search to address this problem. Li et al. (2014) formulated a realistic hybrid flowshop scheduling problem model for steelmaking casting process and developed an effective fruit fly optimization algorithm to solve the steelmaking casting problem. Li et al. (2016) proposed a hybrid fruit fly optimization algorithm and successfully applied to solve the hybrid flowshop rescheduling problem with flexible processing time in steelmaking casting systems. Long et al. (2016) studied a dynamic scheduling model with NP-hard feature for the SCC scheduling problem under the continuous caster breakdown and developed a hybrid algorithm featuring a genetic algorithm combined with a general variable neighbourhood search to solve this model. Pan (2016) addressed a new SCC scheduling problem arising from iron and steel production process, modeled this problem as a combination of two coupled sub-problems and presented a novel cooperative co-evolutionary artificial bee colony algorithm with two sub-swarms to address the sub-problems of this scheduling problem, respectively. Tang and Wang (2010) designed an improved particle swarm optimization algorithm for the hybrid flowshop scheduling problem in the integrated production process of steelmaking continuous-casting. Tang et al. (2014) studied an improved differential evolution algorithm to solve a challenging problem of dynamic scheduling in the SCC production. Zhao et al. (2011) formulated a mathematical programming model for the SCC scheduling problem and proposed a tabu search algorithm to deal with the allocation and sequencing decisions. As for heuristic methods, Missbauer et al. (2009) proposed a mixed integer linear programming model for the SCC scheduling problem and presented a three-stage heuristic solution procedure to improve the schedule by means of a linear programming model. Pacciarelli and Pranzo (2004) modeled the SCC scheduling problem by means of the alternative graph and described a beam search procedure to tackle with this problem. Yu and Pan (2012) proposed a three-stage rescheduling method including the batches splitting, forward scheduling method and backward scheduling method for solving a novel multi-objective nonlinear programming model of the SCC production process. Yu et al. (2016) considered a job start-time delay issue for the SCC rescheduling problem and carried out an effective heuristic rescheduling algorithm for the SCC production system to quickly respond to any disruption with a proper rescheduling plan.

Inspired by the above existing literatures, the motivation and main contribution of this paper are in following directions. Firstly, the optimization models for the SCC scheduling problems are usually described by adopting a big-M strategy (Harjunkoski and Grossmann, 2001; Jiang et al., 2015; Li et al., 2016a; Long et al., 2016; Missbauer et al., 2009; Mao et al., 2014; Pan, 2016; Tang et al., 2002, 2014; Tang and Wang, 2008; Ye et al., 2014), which play a significant role in improving the productivity and reducing the cost of the entire production process. In the big-M strategy, the main drawbacks are that the computation time will increase owing to the existence of redundant constraints (Tang et al., 2013; Vallada and Ruiz, 2011) and the big-M formulation usually produces much looser lower bound (Mao et al., 2015). As a result, we address a new mixed integer nonlinear mathematical model for the SCC scheduling problem without using the big-M strategy to avoid above weaknesses. Secondly, in most cases, scheduling problems of the iron and steel industry are NP-hard, which implies that no algorithm can optimally solve these problems within a reasonable computation time (Chen and Luh, 2003). In 1988, Gupta (1988) has proved that the two-stage flowshop problem with identical multiple machines at each stage is NP-hard and two-stage flowshop problem is also NP-hard even if the number of machines at one of the two stage is one. Due to the complexity, the SCC scheduling problem addressed in this paper is much more complicated than the two stages flowshop scheduling problem (Gupta, 1988), which means that the SCC scheduling problem is also NP-hard. Therefore, the SCC scheduling problem cannot be solved optimally within the reasonable computation time. Thus, Lagrangian relaxation approach is introduced to deal with the SCC scheduling problem, because this approach can provide a lower bound to evaluate the optimality of solutions and yield a near-optimal schedule in a reasonable computational time (Nishi and Hiranaka, 2013). Up to now, published works on the Lagrangian relaxation approaches have mainly focused on relaxing the compli-