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Robust optimization for integrated scrap steel charge considering uncertain metal elements concentrations and production scheduling under time-of-use electricity tariff

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ABSTRACT

Under the background of time-of-use electricity tariff, the problems of scrap steel charge optimization considering metal elements concentrations uncertainty and scrap steel melt shop production scheduling optimization are integrally studied in this paper using robust optimization approaches. First, taking the parallel electric arc furnaces melt shop as the research object, this paper constructs a robust optimization model about integrated scrap steel charge considering uncertain metal elements concentrations and production scheduling under time-of-use electricity tariff applying a block modeling method. Then, based on the assumptions that the random parameter values of scrap steel metal elements concentrations are distributed in the "bounded uncertainty" set and "bounded symmetric uncertainty" set respectively, the robust optimization model is transformed into two deterministic counterpart models. Finally, Cplex software is used to solve the nominal model and two deterministic counterpart models, the results of which are also compared with two-stage optimization strategy results, indicating the feasibility and effectiveness of the models. Meanwhile, the impacts of uncertainty of metal elements concentrations on production costs, the impacts of time-of-use electricity tariff on production scheduling, and the impacts of electricity tariff fluctuations on the consumption of scrap steels and ferroalloys and the number of setups are analyzed.

1. Introduction

Scrap steel is a kind of recyclable resource, and it can be returned to steel plants through various recycling channels for re-melting in the electric arc furnaces (Ohno et al., 2015). The sources of scrap steel used for re-melting are very wide. And the metal elements concentrations may be quite different from each other among the scrap steels from different sources (Rong and Lahdelma, 2008). It can cause the metal elements concentrations of the scrap steels to be uncertain in the process of classification before the scrap steels loaded into the furnaces to be melted, which not only brings difficulties to the work of scrap steel charge, but also some impacts on the subsequent production scheduling.

In recent years, with the shortage of global resources and the increasing demands for energy, energy costs increase sharply, influencing the production operation management in the energy-intensive enterprises seriously. And energy production scheduling problem has caught attention in academia and industry widely. Merkert et al. (2015) discussed the challenges and opportunities in energy scheduling problem in industry. Yan et al. (2016) and Liu et al. (2017) studied flow shop energy scheduling problem. Giglio et al. (2017) considered a job shop energy scheduling problem in manufacturing/remanufacturing systems. In addition, the demands of electricity as a kind of energy widely used are increasing rapidly. In order to balance the load of the power grids, the power plants mostly adopt “time-of-use electricity tariff” policy (Perković et al., 2017). Under this policy, the power plants divide 24 h a day into several time periods to charge different electricity prices, such as low periods, medium periods and peak periods, so as to use economic measure to encourage the power consumption enterprises to rationally arrange their production activities and improve power efficiency. The impacts of time-of-use electricity tariff on scheduling have been explored. Mikhaylidi et al. (2015) and Che et al.

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(2016) researched single machine scheduling problem under time-of-use electricity tariffs. Che et al. (2017) studied the impacts of time-of-use electricity tariff on unrelated parallel machine scheduling problem. And Sharma et al. (2015) investigated flow shop scheduling problem with time-of-use electricity tariff consideration. Furthermore, scrap steels are melted mainly in the electric arc furnaces, which needs to consume a lot of electricity to produce high temperature. The time-of-use electricity tariff policy has very great impacts on high power consumption enterprises, such as steel plants.

Therefore, this paper researches the problem of integrated scrap steel charge considering uncertain metal elements concentrations and production scheduling under time-of-use electricity tariff.

Similar to the study of Rong and Lahdelma (2008), in this paper, the problem of scrap steel charge optimization considering uncertain metal elements concentrations means to optimize the consumption of scrap steels and ferroalloys, in the case of metal elements concentrations uncertainty in the process of classification of scrap steels, so as to reach the metal elements concentrations requirements of the final steel products spending the lowest raw materials cost. At present, this problem has been studied in only several papers based on stochastic chance constrained linear programming (Sakall et al., 2011) or fuzzy chance constrained linear programming (Rong and Lahdelma, 2008). The former case assumed the random parameter values of scrap steel metal elements concentrations obeyed the normal distribution, and the latter case defined them as triangular fuzzy numbers. However, these two assumptions are too idealized, and there are big gaps between the assumptions and production practice. Robust optimization is another method to deal with the uncertain problems in addition to stochastic optimization and fuzzy optimization. In the robust optimization method, a set is usually used to describe the random parameters. Approaching the robust optimization method, the uncertain problems can be well solved in the case of probability distribution information of the random parameters unknown or only part of the probability distribution information of random parameters known. Therefore, robust optimization is more applicable compared to stochastic optimization and fuzzy optimization. Different from the existing researches (Sakall et al., 2011; Rong and Lahdelma, 2008), the problem of scrap steel charge optimization considering uncertain metal elements concentrations in this paper is studied based on the relevant theories of robust linear programming. And there has been some literature on the study of robust linear programming. Soyster (1973) proposed robust linear programming firstly, and obtained a counterpart form. Although the counterpart form retained the linear characteristics, and was easy to solve, it was too conservative. For this reason, some scholars conducted relevant study from the perspective of balancing computational complexity and conservatism of robust counterpart form based on various kinds of uncertain sets. Bertsimas et al. (2004) used norm set to study the robust linear programming. Ben-Tal and Nemirovski (2000) considered the robust linear programming in "bounded uncertainties" set and "bounded symmetric uncertainties" set. Subsequently, Lin et al. (2004) extended the above situations to robust mixed integer linear programming, and then Chen et al. (2007) considered a "bounded asymmetric uncertainties" set. Li et al. (2011) further studied robust hybrid integer linear programming in various mixed uncertain sets (such as "interval + ellipsoid" uncertain set). These studies on robust linear programming provide reference for the construction and solution of the robust model in this paper.

The current study about steel production scheduling problem is mainly focused on the steelmaking and continuous casting (SCC) stages. And mostly it is reduced into a shop scheduling problem with special constraints (such as limited waiting time, continuous casting, etc.), and is studied from the perspectives of both algorithm and model. From the view of the algorithm, Mao et al. (2015) designed a Lagrangian relaxation algorithm to relax the "hard" constraints in the steelmaking-continuous casting production model and proposed an improved subgradient method to solve the sub-problem, and they also adopted Lagrangian relaxation algorithm to explore rescheduling SCC problem (Mao et al., 2014). Tang et al. (2014) integrated charge batching problem at steelmaking stage and casting width selection problem at the continuous casting stage, and designed the appropriate column generation algorithm for it. Jiang et al. (2015) used hybrid differential evolution algorithm combined with a variable neighborhood decomposition search algorithm to study steelmaking-continuous casting problem involving controllable processing times. Pan (2016) adopted the improved artificial bee colony intelligent algorithm to solve SCC problem. Long et al. (2016) used a hybrid multi-objective evolutionary algorithm based on NSGA-II for SCC scheduling considering release times. Mori and Mahalec (2017) used simulated annealing and shuffled frog-leaping intelligent algorithms to solve continuous casting problem. Long et al. (2017) designed a genetic algorithm combined with a variable neighborhood search method to solve dynamic scheduling in steelmaking-continuous casting production for continuous caster breakdown. From the point of model, Castro et al. (2013) built a steelmaking-continuous casting RTN (resource–task network) model based on the discrete time presentation method. Sbihi et al. (2014) studied the hybrid integer linear programming model of steelmaking-continuous casting production scheduling problem considering the setup factor. Song (2014) used multi-layer network representation to generate integrated formulation for hierarchical cast design problem. Mattik et al. (2014) applied the block modeling method to solve the problem of integrated scheduling of continuous casting and hot rolling, and obtained excellent computing results. Ye et al. (2014) studied steelmaking and continuous casting production scheduling model with demand uncertainty consideration using robust and stochastic programming modeling approaches. And in this paper, the authors explore and analyze their problem from the perspective of model.

Some studies have further explored steelmaking-continuous casting production scheduling under time-of-use electricity tariff. Ashok (2006) first considered the cost of time-of-use electricity tariff in steel production and operation management. Castro et al. (2013) studied steelmaking continuous casting production scheduling problem with time-of-use electricity tariff consideration applying the discrete time presentation RTN modeling method. Tan and Liu (2014) studied the problem by using constraint propagation technique. Hadera et al. (2015) studied steelmaking-continuous casting scheduling under the sensitive time-of-use electricity tariff based on a continuous-time presentation modeling method. Gajic et al. (2017) developed a continuous-time mixed-integer linear programming model for melt shop production scheduling under time-of-use electricity tariff, and a heuristics algorithm was design to solve the problem.

However, most literature treats the charges in the steelmaking and continuous casting processes as discrete jobs and assumes that the processing time for each job is known at all stages without considering the impacts of time-of-use electricity tariff on the consumption of raw materials (the consumption of scrap steels and ferroalloys), and then the effects of which on the processing time and the production scheduling. Namely, in the studies mentioned above, the scrap steel charge optimization and production scheduling optimization are considered as two separate optimization processes, while in fact there is a deep connection between them under time-of-use electricity tariff environment.

Above all, the study of integrated scrap steel charge considering uncertain metal elements concentrations and production