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Robust optimization and stochastic programming approaches for medium-term production scheduling of a large-scale steelmaking continuous casting process under demand uncertainty

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ABSTRACT

Scheduling of steelmaking-continuous casting (SCC) processes is of major importance in iron and steel operations since it is often a bottleneck in iron and steel production. In practice, uncertainties are unavoidable and include demand fluctuations, processing time uncertainty, and equipment malfunction. In the presence of these uncertainties, an optimal schedule generated using nominal parameter values may often be suboptimal or even become infeasible. In this paper, we introduce robust optimization and stochastic programming approaches for addressing demand uncertainty in steelmaking continuous casting operations. In the robust optimization framework, a deterministic robust counterpart optimization model is introduced to guarantee that the production schedule remains feasible for the varying demands. Also, a two-stage scenario based stochastic programming framework is investigated for the scheduling of steelmaking and continuous operations under demand uncertainty. To make the resulting stochastic programming problem computationally tractable, a scenario reduction method has been applied to reduce the number of scenarios to a small set of representative realizations. Results from both the robust optimization and stochastic programming methods demonstrate robustness under demand uncertainty and that the robust optimization-based solution is of comparable quality to the two-stage stochastic programming based solution.

1. Introduction

Scheduling of steelmaking-continuous casting (SCC) processes is of major importance in iron and steel operations since the SCC process is often a bottleneck in iron and steel production (Tang et al., 2002). Optimal scheduling of SCC processes can increase profit, minimize production cost, reduce material and energy consumption, and improve customer satisfaction. Scheduling of SCC processes is challenging because of its combinatorial nature, complex practical constraints, strict requirements on material continuity and flow time, as well as technological requirements to ensure practical feasibility of the resulting scheduling. Many different models and solution approaches have been proposed to generate optimal schedules for scheduling of SCC processes. These approaches can be classified into linear optimization (LP) and mixed-integer linear optimization (MILP) (Harjunkoski and Grossmann, 2001; Bellabdaoui and Teghem, 2006; Missbauer et al., 2009), heuristics (Pacciarelli and Pranzo, 2004; Atighehchian et al., 2009), artificial intelligence, and simulation methods. Detailed reviews on those methods can be found in the papers of Tang et al. (2001), Dutta and Fourer (2001), and Basu et al. (2014).

Recently, Li et al. (2012a) developed a novel and effective unit-specific event based continuous-time formulation for this process and extended the rolling-horizon approach (Lin et al., 2002; Janak et al., 2006a,b) to decompose the entire MILP problem. The computational results show that the extended rolling horizon approach reduced the computational time and generated the same or better feasible solutions than those without using the rolling horizon approach. This proposed model assumed that all the parameters are deterministic in nature.

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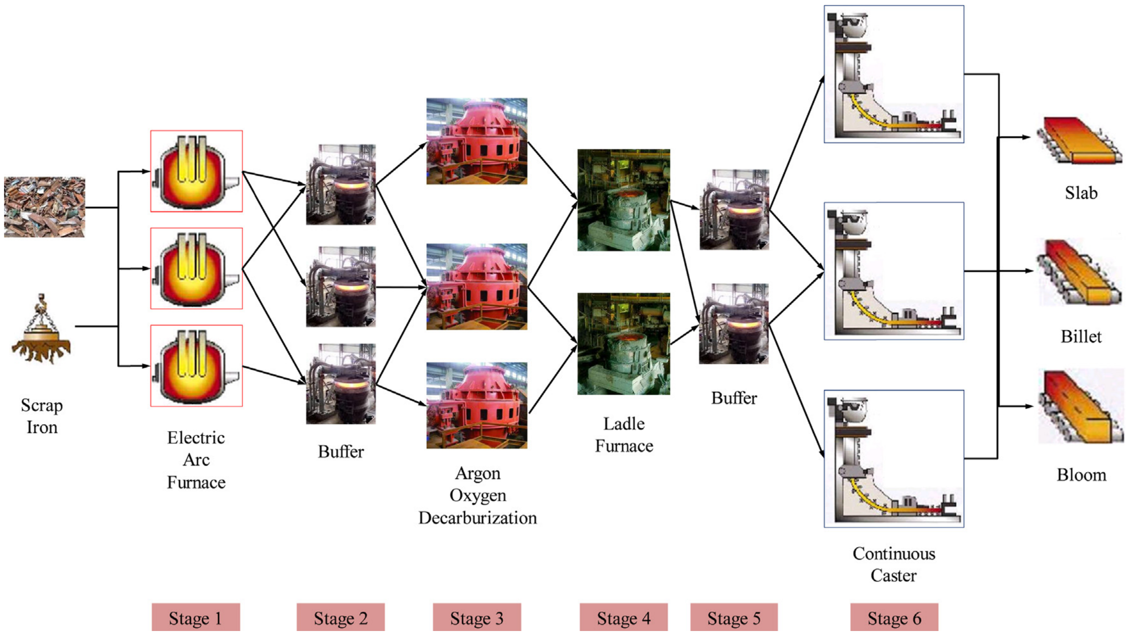

Fig. 1. Schematic of steelmaking continuous casting processes.

However, several uncertainties such as demand fluctuation, and processing time uncertainty frequently happen during the realistic operations. In the presence of these uncertainties, the nominal schedule may often be suboptimal or even become infeasible. In general, two approaches can be used to address those uncertainties: reactive scheduling and preventive scheduling (Verderame et al., 2010). While reactive scheduling is a process to revise the generated schedule from nominal parameters when a disruption has occurred during the actual execution of the schedule, preventative scheduling seeks systematic ways to accommodate future uncertainty. The uncertainty can be explicitly taken into account through preventive approaches such as two-stage stochastic programming, parametric programming, fuzzy programming, chance constraint programming, robust optimization techniques, and conditional value at risk (Verderame et al., 2010). Uncertain parameters are often represented by scenarios in approaches such as two-stage stochastic programming and conditional value at risk, or by avoiding the use of scenarios and addressing the whole uncertainty space via approaches such as robust optimization. The detailed reviews on planning and scheduling under uncertainty can be referred to Li and Ierapetritou (2008) and Verderame et al. (2010).

In steelmaking and continuous casting process, reactive scheduling is often used for handling different types of disruptions such as machine breakdowns, rush orders, defect problems, and order cancellations (Tang and Wang, 2008; Worapradya and Buranathiti, 2009; Hou and Li, 2012). Yu et al. (2009) used a fuzzy programming approach to address uncertain processing time in the steelmaking and continuous casting production process. The uncertain processing times were denoted by triangular fuzzy numbers.

In this paper, we first employ the robust optimization framework from Lin et al. (2004), Janak et al. (2007) and Li et al. (2011, 2012b) to develop a deterministic robust counterpart optimization model for demand uncertainty during steelmaking continuous casting operations. The robust solution from the robust optimization framework is guaranteed to be feasible for the whole space of the uncertain demand parameters. While the robust optimization framework aims at finding a single schedule that is immune to all possible uncertainty realizations within an uncertainty set, a two/multi-stage stochastic programming method provides flexibility of implementing different operational decisions after the realization of uncertainty. A scenario based two-stage stochastic programming framework was also studied for the scheduling of steelmaking and continuous operations under demand uncertainty. To make the resulting stochastic programming problem computationally tractable, a novel scenario reduction method (Li and Floudas, 2013a,b) has been introduced to reduce the huge number of scenarios to a small set of representative realizations. The selected scenarios are incorporated into the stochastic programming model, which is further reformulated into its deterministic equivalent model and solved.

2. Problem statement

Fig. 1 shows a schematic of a typical stainless steel production process. The process involves four stages, each of which has several parallel processing units including electric arc furnaces (EAF), argon oxygen decarburization units (AOD), ladle furnaces (LF), and continuous casters (CC). Between EAF and AOD, there is one buffer that can hold one or several ladles. Similarly, another buffer also exists between LF and CC, which can hold one or several ladles. The entire process can be briefly described as follows:

In the beginning, scrap irons are loaded into one or several EAFs for melting. The total time in an EAF includes melting, setup, and maintenance time. Then, the liquid steel is poured into ladles that can be transported by a crane. The ladles can be immediately transported to AOD units or can be stored temporarily in a buffer. In an AOD unit, the liquid steel is subject to decarburization, reduction, and desulphurization. Leaving from the AOD units, the ladles are put into one or several LFs to maintain their proper temperature and add several alloying materials such as manganese, chromium, and vanadium to meet its chemical specification properties required by customers. Each LF can host at most two ladles and the time needed in each LF cannot exceed 30 min. The ladles from the LFs can go directly into one or several continuous casters (CCs) for casting or stay in a buffer before entering continuous casters. To prevent the liquid steel cooling down, a ladle can stay in the buffer (before casters) for some maximum time (e.g., 10 min). In the casters (CCs), the liquid steel is cast and cooled