European Journal of Operational Research 244 (2015) 966–979

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

A soft-decision based two-layered scheduling approach for uncertain steelmaking-continuous casting process

Jinghua Hao, Min Liu*, Shenglong Jiang, Cheng Wu

Tsinghua National Library for Information Science and Technology (TNList), Department of Automation, Tsinghua University, Beijing, 100084, China

ARTICLE INFO

Article history:
Received 6 January 2014
Accepted 11 February 2015
Available online 6 March 2015

Keywords:
Steelmaking
Continuous casting
Uncertainty
Scheduling
Soft decision

ABSTRACT

Strong uncertainties is a key challenge for the application of scheduling algorithms in real-world production environments, since the optimized schedule at a time often turns to be deteriorated or even infeasible during its execution due to a large majority of unexpected events. This paper studies the uncertain scheduling problem arising from the steelmaking-continuous casting (SCC) process and develops a soft-decision based two-layered approach (SDA) to cope with the challenge. In our approach, traditional scheduling decisions, i.e. the beginning time and assigned machine for each job at each stage, are replaced with soft scheduling decisions in order to provide more flexibility towards unexpected events. Furthermore, all unexpected events are classified into two categories in terms of the impact degree on scheduling: critical events and non-critical events. In the two-layered solution framework, the upper layer is the offline optimization layer for handling critical events, in which a particle swarm optimization algorithm is proposed for generating soft scheduling decisions; while the lower layer is the online dispatching layer for handling non-critical events, where a dispatching heuristic is designed to decide in real time which charge and when to process after a machine becomes available, with the guidance of the soft schedule given by the upper layer. Computational experiments on randomly generated SCC scheduling instances and practical production data demonstrate that the proposed soft-decision based approach can obtain significantly better solutions compared to other methods under strongly uncertain SCC production environments.

1. Introduction

1.1. Background

Production scheduling is a complex decision-making process that plays an important role in most of production systems, especially in complex and capital-intensive industries such as iron and steel, wafer fabrication, automobile, etc. Effective scheduling can significantly improve throughput, customer satisfaction, inventory costs, bottleneck utilization, and other key performance indices for enterprises. The iron and steel industry is a typical capital-intensive industry, which is essential to many important industries in the world, such as automobile, construction, aircraft and ship manufacturing (Tang, Liu, Rong, & Yang, 2001; Tang, Luh, Liu, & Fang, 2002). This paper investigates a challenging scheduling problem arising from real-life steelmaking-continuous casting process in the iron and steel industry. The steelmaking-continuous casting (SCC) process mainly includes stages of steelmaking, refining and casting (Tang & Liu, 2007; Xuan & Tang, 2007), as shown in Fig. 1.

The SCC production process we studied is briefly described as follows. Firstly, undesired substances in the molten iron, such as silicon, phosphorus and carbon, are partially removed through injections of oxygen in a basic oxygen furnace (BOF) of the steel-making stage. The molten steel processed together in a BOF is called a charge, a basic unit of the SCC production. Secondly, molten steel is poured into a transfer ladle and then transported to a refining furnace by a crane where it is de-slagged and de-sulphurized (Missbauer, Hauber, & Stadler, 2009). In this processing stage, high-precision adjustment for the chemical compositions of the steel is carried out so as to produce specific steel grades. There are two types of refining furnaces, including ladle furnaces (LF), Ruhrstahl-Hausen vacuum refining furnaces (RH). Finally, graded liquid steel from the refining furnace is taken to a continuous caster (CC) which can process multiple charges consecutively in the form of a cast or a batch. In this stage, the ladle is raised onto a turret that rotates the ladle on the casting position above the tundish. Liquid steel flows out from the tundish and into the crystallizer. At the bottom of the caster, the steel is completely solidified into blooms, slabs or billets with the required rolling lengths (Tang et al., 2002; Xuan & Tang, 2007).

Each charge is defined by the corresponding steel grade and the gauges of products that the charge will be used to produce (Atighehchian, Bijari, & Tarkesh, 2009). There is a special constraint

* Corresponding author.
E-mail address: lium@tsinghua.edu.cn (M. Liu).

http://dx.doi.org/10.1016/j.ejor.2015.02.026
0377-2217/

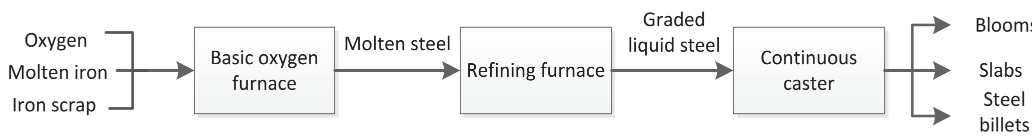

Fig. 1. The steelmaking-continuous casting process.

with SCC process that, charges at the casting stage need to be consecutively cast one by one on the same intermediate ladle and on the same caster without any idle time of the caster. Such a group of charges forms a cast or a batch. This is because charges in the same cast share a common tundish, and when a cast ends production or is interrupted, the current common tundish will be disassembled from the continuous caster, and cannot be used any more. If charges in a cast are not processed consecutively, we call that a cast interruption happens. Therefore, it is an important task to improve the life span of tundishes so as to decrease the unit cost of each charge in the process of planning and scheduling. Besides that, as the temperature of hot metal will cool down quickly in steel ladle, it is necessary to reduce the waiting time of charges before each stage so as to save energy.

Generally, the factory planning level releases a production plan every day for the SCC shop and the hot-rolling shop based on customer orders. In the production plan, detailed information of casts are given including the number of charges in each cast, the processing route, steel grade and estimated processing times of each charge and some technique constraints. Generally, two main steps need to be done in the planning level (Tang, Wang, & Chen, 2014): order batching (to form charges) and charge batching (to form casts). In some SCC plants, even the allocation of casts to continuous casters and sequence of casts are also given in the SCC production plan in order that the plan can be coordinated with hot rolling plan (hot charging to save energy) (Missbauer et al., 2009). There are a large number of researches focused on the field of production planning for the SCC process, details can be found in Tang, Wang, and Chen (2014), and Tang and Wang (2008).

Given the production plan for the SCC shop, one needs to make out a timetable plan (i.e. the starting times and the assigned machines for each charge at each processing stage) for a given scheduling period (usually a shift or a day), this problem is often termed as the *static scheduling problem* in literature. During the execution of the timetable plan, some unpredicted real-time events may happen and thus cause the initially good timetable plan to become poor and even infeasible. Tang et al. (Tang, Zhao, & Liu, 2014) have summarized some typical unexpected events such as machine breakdown, operator illness, job cancellation, arrival of urgent charges, etc. It is necessary to adjust the timetable plan in this case, and this problem is usually termed as the *dynamic scheduling problem* in literature. Lastly, due to the presence of uncertainty (e.g. uncertain charge arriving time, processing time and transportation time, short-term machine failure), the timetable plan cannot be executed precisely, therefore in practice, one needs to decide in real time based on the timetable plan which charge and when to process when a machine becomes available, and this problem is often termed as the *real-time scheduling problem*. A typical schedule of the SCC process in practice, also known as "Gantt diagram", is shown in Fig. 2.

1.2. Literature review

Efficient scheduling of the SCC process can bring considerable improvement for criterions such as Cast Interruption Ratio (CIR) and Average Weighted wait Time of charges (AWT), therefore decreasing the overall production cost and improving productivity. Much research effort has been focused on the static SCC scheduling problem since the late 1990s, most of which in literature formulate a mathematical model for the SCC scheduling problem, usually an MIP model, and then suggest a customized solution procedure. Harjunkoski and Grossmann (2001) propose a decomposition scheme that generates smaller programs that can often be solved to global optimality. In their approach the original SCC problem is split into subproblems in a natural way using the special features of steelmaking and avoiding the need for expressing the highly complex rules as explicit constraints. Tan, Huang, and Liu (2013) investigate a steelmaking process scheduling problem with variable electricity price (SMSPVEP), and present a decomposition approach. Tang, Liu, Rong, and Yang (2000) present a mathematical model for solving SCC production scheduling problem. The model is developed as a non-linear model based on actual production situations, considering both punctual delivery and production operation continuity. It is then converted into a linear programming model which can be solved using standard software packages. Tang, Guan, and Hu (2010) develop two different models to describe the practical SCC scheduling problems with converters and transporters, and propose a heuristic algorithm and a taboo search algorithm to solve the models, respectively. Atighehchian et al. (2009) propose a hybrid scheduling algorithm for the SCC problem, which is based on combination of ant colony optimization (ACO) and non-linear optimization methods. Xuan and Tang (2007) formulate the SCC scheduling problem as a hybrid flow shop (HFS) with batch production at the last stage, and then establish an integer programming model as well as a batch decoupling based Lagrangian relaxation algorithm for this problem. Mao, Pan, Pang, and Chai (2014) formulate the SCC scheduling problem as an MIP model, and propose a novel Lagrangian relaxation approach for solving SCC static scheduling problem, which outperforms traditional Lagrangian approach in terms of solution quality and running time.

Also, some researchers have proposed dynamic scheduling methods for the SCC process which are used to generate a new schedule when some unexpected events happen. Tang et al. (2014) study a dynamic scheduling problem in SCC production where the assignment, sequencing, and timetable of a set of existing and new jobs (charges) among various production stages are re-optimized for the new environment when unforeseen changes occur in the production system. They propose an improved differential evolution (DE) algorithm to solve it. Yu and Pan (2012) study the SCC rescheduling problem in response to the case of operation time delay, and propose a novel multi-objective nonlinear programming model and a three-stage rescheduling method including the batches splitting (BS), forward scheduling method (FSM) and backward scheduling method (BSM). Ouelhadj, Petrovica, Cowling, and Meiselsc (2004) solve the SCC scheduling problem by a multi-agent based approach, where a negotiation protocol is proposed for inter-agent cooperation. The purpose of this protocol is to allow the agents to cooperate and coordinate their local schedules in order to find globally near-optimal robust schedules, while minimizing the disruption caused by the occurrence of unexpected real-time events.

Dispatching rules are frequently used for real-time scheduling in practice (Metan, Sabuncuogl, & Pierreval, 2010). However, conventional dispatching rules in literature, such as SPT (shortest processing time), EDD (earliest duedate), CR (critical ratio), are difficult to be applied to the SCC real-time scheduling problem due to the strong constraints of continuous casting of charges in a cast. Also, dispatching rules tend to be myopic as most of them only incorporate job-related and machine-related local production information