Int. J. Production Economics 170 (2015) 551–562

Contents lists available at ScienceDirect

Int. J. Production Economics

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

Slab scheduling at parallel continuous casters

Matthias Gerhard Wichmann *, Thomas Stefan Spengler

Technische Universität Braunschweig, Institute of Automotive Management and Industrial Production, Mühlenpfordtstr. 23, 38106 Braunschweig, Germany

ARTICLE INFO

Article history:
Received 15 April 2014
Accepted 3 August 2015
Available online 12 August 2015

Keywords:
Scheduling
Steel industry
GRASP

ABSTRACT

Continuous casting is the central process of steel shaping in the steel industry. Here, liquid steel is transformed into solid cuboid shape using a continuous casting process. In most companies, there are parallel continuous casters, which need to be balanced and scheduled. The production process is order driven. Orders in terms of slabs to be casted are not assigned to a specific caster per se. As a result, production planning has to decide about the assignment of slabs to casters as well as the sequence of slabs on individual casters. Scheduling a single caster has to take four specific requirements into account. These are a material supply in batches, flexible slab specifications, a continuous adjustable casting width and different types of setup. While scheduling of a single caster has been studied recently, approaches taking the assignment of slabs to casters as well as its impact on the individual scheduling task into account are missing. In our contribution we present a planning framework for the problem. The framework consists of a MIP-model formulation and a two stage heuristic solution procedure for given problem instances. the framework is applied to a numerical case study and compared to a lower bound as well as to an industry benchmark. The numerical case study shows, that the framework is always able to obtain feasible solutions of the problem with a better quality than the discussed industry benchmark.

1. Introduction

Continuous casting is the most important process of primary shaping the steel industry. Here, liquid molten steel is processed into a solid shape using continuous casters (CC). Due to its importance, steel plants often comprise more than one CC. Nowadays, more than 92% of world steel production is based on continuous casting (cp. Stahleisen, 2010).

In a CC, liquid molten steel is transformed into solid rectangular blocks, referred to as slabs. Doing so, charges of liquid steel are cast through a tundish into a water cooled copper mold. The shape of the mold determines the profile of the resulting steel strand. In general, the mold can be resized during casting, resulting in different casting widths. In the cooled mold the liquid steel solidifies beginning from the surface and passes through the continuous caster while being continuously cooled. The casting process ends with cutting the completely solidified steel strand into slabs of individual length. Each slab is uniquely produced to a specific customer order due to specific requirements on alloy, weight and width of the final product. The production process at a CC is shown in Fig. 1.

The scheduling of slabs at continuous casters addresses two interdependent planning tasks. The first planning task is the assignment of nearly homogeneous workloads to all of the CCs, since CCs often are the bottleneck in integrated steel plants. The workload of a caster is described by the time necessary to produce all assigned slabs.

The second planning task concerns the slab sequence of a single CC. From this sequence, further important control parameters such as the casting width, the sequence of charges as well as the amount of unassigned material are derived. Several specific constraints have to be taken into consideration. These include the supply of charges of liquid material which have a much higher weight than a single slab, non-preemptive casting processes, flexible slab specifications, sequence dependent continuous adjustment of the casting width as well as setup constraints. As a result of the two interdependent decisions and the specific constraints, scheduling continuous casters requires for problem related modeling approaches.

In this paper we present a planning approach which addresses both planning tasks, the assignment of orders to CCs as well as the scheduling of orders on a single CC, simultaneously. Doing so, in Section 2 the planning problem is described and a literature review is given. In Section 3 a mathematical problem formulation is introduced. In Section 4 a solution procedure is pointed out. Further, the scheduling approach is visualized by a numerical example. In Section 5, a numerical case study is conducted to show the potential

* Corresponding author. Tel.: +49 531 391 2215.
E-mail addresses: ma.wichmann@tu-braunschweig.de (M.G. Wichmann), t.spengler@tu-braunschweig.de (T.S. Spengler).

http://dx.doi.org/10.1016/j.ijpe.2015.08.003
0925-5273/

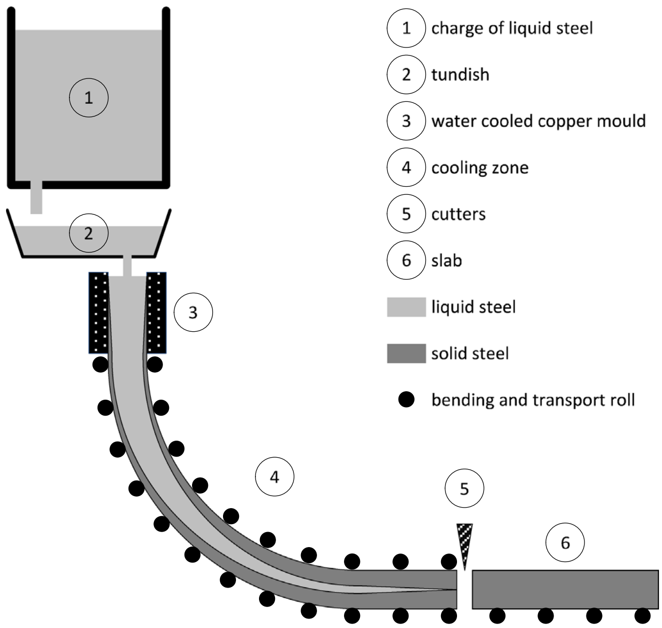

Fig. 1. Schematics of a continuous caster.

of the proposed solution approach. The paper closes with a summary and an outlook.

2. Slab scheduling at continuous casters

In this section, we introduce the planning problem of scheduling slabs at continuous casters. Doing so, the problem characteristics are described and a literature review is given.

2.1. Problem characteristics

The production of slabs at CCs comprises five special characteristics, which require for a specific scheduling approach. These include flexible production orders, material supply in batches, a continually adjustable casting width, different kinds of setups and parallel machines (cp. Degner, 2008). These characteristics are discussed in more detail in the following.

First, each slab to be produced represents a production order, referred to as job. It is related to a specific customer order. Each job is described by three parameters: the alloy, the slab weight and the casting width range. The alloy and the slab weight are fixed values and are set according to the customer order. The casting width range is related to the specifications of the final product as well. Due to the later reshaping of slabs in the downstream production processes, there is flexibility associated with the casting width. Thus, if the casting width is within a predefined range, the resulting slab can be transformed into the required final product. As a result, job specifications are flexible.

Second, material is supplied in batches, referred to as charges. Each charge consists of homogenous liquid steel of a specific alloy. The weight of a charge is much higher than the weight of a single job. As a result, multiple jobs of the same alloy have to be cast from one charge. Further, charges are special in two characteristics. On the one hand, it is possible, to cast multiple charges of the same alloy in an uninterrupted sequence. Thus, possible overhead of multiple charges can be combined in order to fulfill additional jobs. On the other hand, the casting of a begun charge cannot be disrupted. Thus, the amount of steel within a charge or charge sequence, which is not assigned to a specific job, can be regarded as scrap. For the sequencing of slabs, the accumulation of jobs to batches directly depends on the slab sequence and therefore has to be considered within a scheduling approach.

Third, the casting width results from the shape of the CC mold. A slab-producing rectangular mold is parameterized by its height and its thickness. The molds height determines the slab thickness and is typically fixed. The molds width determines the slab width and can be changed continuously. Adjusting the casting width allows for production of slabs with different width ranges out of one charge without stop of production. The casting width has to be controlled such that the casting width at the end of a job fits to the width range of the subsequent job. Besides, the casting width determines the productivity of the CC. The wider the mold's width is chosen, the more material is cast per time unit, given a fixed casting speed. If the weight of a job is constant, its production time depends on its (average) casting width. In order to incorporate the flexibility in adjusting the casting width and the associated effects on productivity it is necessary to take the casting width into account in the scheduling approach.

Fourth, the casting process is characterized by two different types of job sequence-dependent machine setups. If two consecutive jobs have the same alloy and an overlapping width range, no setup is necessary. If the width ranges between two consecutive orders of a sequence do not match, a step-wise width change as first type of machine setup becomes necessary. Here the continuous flow of material has to be stopped and all unassigned material of the preceding charge has to be cast through the caster. After cleaning and adjusting of the casting width, a new charge has to be inserted. This leads to non-productive processing times as well as high material costs for the unassigned material which is to be scrapped. If the alloys of two consecutive jobs do not match, an alloy change as second type of machine setup becomes necessary. Two types of alloy changes can be distinguished. First, if the width ranges between the last job of a charge and the first job of the subsequent charge overlap, it is possible to continue production once the processing of the first charge is completed. In this case, unassigned material of the first charge has to be scrapped. The non-productive processing times are limited to the time needed for processing the unassigned material. Second, if the width ranges do not match, a stepwise width change analog to type one becomes necessary. Both types of machine setups have to be considered when sequencing slabs at CCs.

Fifth, in general there are multiple parallel CCs within a steel plant. As CCs often are the bottleneck of production, they have to be used to their full potential. Doing so, two requirements accrue. On the one hand, the schedule on each machine has to be as efficient as possible. On the other hand, all continuous casters should be used nearly equally in order to avoid overloading on individual machines.

Based on these constraints, the objective of slab scheduling at continuous casters is to find a job sequence to minimize the total production related variable overhead costs of a given order portfolio. This requires assigning jobs to charges and determining the realized casting width. The total production related variable overhead costs result from the deviation of the realized production to the optimal utilization of production capacity. They consist of three components. First, there are material costs for scrap. Second, there are setup costs for stepwise width changes. Third, there are opportunity costs for not casting slabs at maximum productivity. These are related to the difference between the maximum and the realized average casting width of a job.

2.2. Literature review

Following reviews on planning and sequencing in the steel industry like (Tang et al., 2001) or (Lee et al., 1996), literature on slab scheduling can be divided into four streams.

The first stream focuses on the determination of overall multi-stage master plans. The objective is either to identify the optimal rate of input materials to meet the demand forecast (cp. Fabiani,