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Simultaneous optimization of slab permutation scheduling and heat controlling for a reheating furnace

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ABSTRACT

In this report, for a reheating furnace, which is employed in one of the processes for producing steel sheets from slabs, we propose a modelling method that simultaneously optimizes both the permutation scheduling of slabs and the heat controlling of the furnace. The proposed modelling scheme is based on a hybrid model composed of a nonlinear advection equation that expresses the behavior of the slab temperature and a discrete model for feeding slabs. The model predictive control problem of this model, which will be reduced to a mixed integer programming problem, is formulated by discretizing the advection equation in time and space by means of the method of characteristics and spatially piecewise-linearizing the nonlinear term. It is shown by numerical simulations that the proposed model predictive control method is very effective from the viewpoint of the control performance and the computational burden.

1. Introduction

In the steel industry, thin steel sheets are produced by a process called a hot strip mill (see Fig. 1), where slabs are heated to approximately 1200 °C by a continuous reheating furnace consisting of three or four heating zones, and then milled by rollers. Recently, the efficient production of various types of steel sheets has become necessary to meet the market demand. In the case of small lot production, because the frequently changing specifications of factory lines hamper productivity, it is important to formulate a suitable production plan. In particular in the reheating process, both improvements in productivity and reduction in cost are required, which involves an issue on achieving high control performance. Slabs, in general, have different initial/target temperatures, and the feed schedule of such slabs (i.e., the order and timing of feeding slabs into the reheating furnace) has been determined by engineers' intuition so far. On the other hand, controllers for burners are designed independently of the feed schedule so that the slabs are heated along a temperature rising curve. In fact, there are many studies in the literature focusing on the control of burners, e.g., [2,12,20,21]. However, to achieve control performance superior to that of the conventional methods, it is important that feed scheduling and temperature controlling are designed together. To the best of our knowledge, there are few works treating both these aspects [7,17]. Thus, this paper considers simultaneous optimization problems for the feed schedule and the control of the burners in the reheating furnace. Some of the time-varying decision variables are the following:

(a) the temperatures of the slabs and the furnace, fuel inputs to the burners, and
(b) the order of the slabs fed to the furnace.

The former variables take continuous values, whereas the latter variables take discrete values.

Although it is in general difficult to treat systems in which continuous-valued and discrete-valued variables coexist, studies on control theory for hybrid systems have been developing for a decade [5,6,8,9,14,15]: In particular, schedule and/or control problems for

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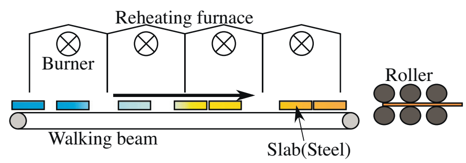

Fig. 1. Sketch of a hot strip mill.

flowshop-type systems, which include continuous-value dynamics of jobs and machines, have been considered important. A method in which a mixed logical dynamical (MLD) model is used and an optimization problem is reduced to its mixed integer programming (MIP) problem is well known as one of the model predictive control (MPC) schemes for hybrid systems (e.g., [3,7,17]). In this MIP problem, however, the computational cost for solving it in a worst-case scenario exponentially increases with respect to the number of discrete-valued variables. To reduce the computational cost, it is necessary to formalize the problem so that the solutions are more easily found.

Fujii et al. [7] formulated the schedule and control problem for the reheating furnace as a hybrid flowshop problem that is different from conventional problems, and succeeded in significantly reducing the computational burden in solving the MIP problem. In [7], the process, from the feeding to the extraction in the furnace, was modeled in three stages. However, because there always exist 20–30 slabs and it takes 30–90 min to heat each slab in practical furnaces, the control interval is 10–30 min for the three-stage-model. Although a higher-resolution model is required to achieve more efficient and practical furnace control, the method in [7] has the drawback that the number of binary decision variables proportionally increases as the number of stages increases, thereby increasing the computational cost. Furthermore, the temperature behavior of slabs is described by linear systems in [7], although the temperature increases owing to the radiant heat from the combustion gas and the furnace walls are expressed by the nonlinearity of approximately quartic functions in practice [19,20].

To overcome the above two problems, this paper proposes a novel modelling method for controlling a reheating furnace so that the feed schedule of slabs into the furnace and the temperature control of burners are simultaneously optimized. First, a hybrid model consisting of a continuous-time nonlinear distributed parameter system, i.e., a nonlinear advection equation, and a discrete model for feeding slabs is introduced, where a set of slab temperatures is regarded as one distribution (see Fig. 2). Then, by discretizing this equation both in time and space by the method of characteristics, a high-resolution model with fewer binary decision variables is derived. Next, through a spatially linear approximation of nonlinear terms, a spatial piecewise affine model is presented, which allows us to transform the system into a linear MLD model. Consequently, our optimization problem is reduced to an MIP problem. The solution of this MIP problem can be used as an optimal feedforward control law for the operation of the furnace. We show that the optimal solutions obtained for the proposed model are superior to those obtained for a model based on linear equations in the sense of realization of target temperatures for slabs, and also, the calculation time for solving the MIP problem is reduced to a practical duration. This low calculation cost allows us to employ the MPC, where the processes calculating and applying optimal solutions are successively repeated. In the last part of this paper, we show application examples of the MPC, and confirm that the realization of target temperatures for slabs is better than in the feedforward control case. The preliminary versions of this paper were our two conference papers [17,18]: This paper includes the details on the method in [18], which is an extension of [17], and also, provide new simulation results.

The rest of the paper is organized as follows: In Section 2, a nonlinear advection equation is introduced as a fundamental model, and then, it is transformed to hybrid difference equations by discretization and addition of constraints. Next, after the above model is appropriately approximated, an MLD model is derived, and our optimization problem is reduced to an MIP problem in Section 3. Finally, simulation results based on optimal solutions, which are used as feedforward control or MPC, are presented in Section 4.

2. Modelling of a reheating furnace

We first introduce a dynamical model for the temperatures of slabs in the reheating furnace. In a general modelling framework for a reheating furnace, one considers a single slab resting in the furnace and the dynamics of the slab temperature [11,12]. On the other hand, since our purpose is the optimization for feed scheduling of stored slabs and heat controlling of the entire inside of the furnace, a model that takes into account multiple slabs inclusively is needed. To derive such a model, we regard the temperatures of slabs arrayed in a line in the furnace at each time t as a distribution on an interval $[0, h]$, and represent the distribution using a piecewise-smooth function $y(\cdot, t) : [0, h] \to \mathbb{R}$, as seen in [19,20]. If there is a sub-interval on which no slab exists, we consider that there exists a virtual slab having a much lower temperature than other real slabs (see Fig. 2).

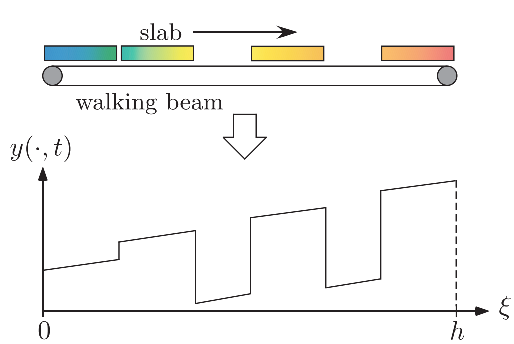

Fig. 2. Temperature distribution of slabs in the furnace: A snapshot view.