Computers and Chemical Engineering 111 (2018) 55–65

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Integrated scheduling of rolling sector in steel production with consideration of energy consumption under time-of-use electricity prices

Shengnan Zhao[a,b], Ignacio E. Grossmann[c], Lixin Tang[d,e,*]

[a] Liaoning Engineering Laboratory of Operations Analytics and Optimization for Smart Industry, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China
[c] Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh 15213, PA, United States
[d] Liaoning Key Laboratory of Manufacturing System and Logistics, Northeastern University, Shenyang 110819, China
[e] Institute of Industrial and Systems Engineering, Northeastern University, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 25 August 2017
Revised 22 December 2017
Accepted 28 December 2017
Available online 29 December 2017

Keyword:
Integrated scheduling
Continuous time modeling
MINLP
GDP

ABSTRACT

Due to increasing load and penetration of renewables, the electric grid is using time-of-use pricing for industrial customers. Involving energy-intensive processes, steel companies can reduce their production cost by accounting for changes in electricity pricing. In particular, steel companies can take advantage of processing flexibility to make better use of electric power, and thus reduce the energy cost. In this paper, we address a new integrated scheduling problem of multi-stage production derived from the rolling sector of steel production, with consideration of campaign decisions and demand-side management. The problem is formulated as a continuous time mixed-integer nonlinear programming (MINLP) model with generalized disjunctive programming (GDP) constraints, which is then reformulated as a mixed-integer linear programming (MILP) model. Numerical results are presented to demonstrate that the model is computationally efficient and compact.

1. Introduction

The rolling sector is the major and most profitable sector in steel production, where semi-finished coils are further processed to various types of highly individualized finished products with high added-value. The average sale price of galvanized product (one of main products in rolling sector) during December 12-15, 2017 in China was 5409 CNY/ton, which is 19.8% higher compared to 4516 CNY/ton, the price of hot rolled product (data from China Iron & Steel Association). Therefore, cost reduction is becoming increasingly important to the steel enterprise, especially when facing supply-front reform which aims at promoting lean production. Nowadays, many steel enterprises are encountering decreasing profit margins due to the rising prices of electric power and raw material, which makes it critical to control costs to remain competitive. From the various methods to reduce production costs, optimizing production management is an effective approach, for which no additional investment is required.

Usually, a rolling sector consists of acid rolling, annealing, rewinding and a series of metal coating sections. Fig. 1 shows a simplified distribution of the rolling sector, which includes some typical sections. Each section uses its own criterion for scheduling the production and most of time they organize the production independently without coordination with other sections. Usually, this mode leads to some undesired situations such as unbalanced material flow, shortage of feedstock at downstream section and losses in production efficiency, which often yields extra production cost and decreased profit. This implies the need for proper integrated scheduling over all sections in the rolling sector to guarantee optimal production and to reduce production costs.

Another factor that represents a rather considerable part of production cost is electricity consumption. Steel production involves several energy-intensive processes, acid rolling for example. In a small to medium size steel company in China with 3.5–4 million tons of output, the monthly average electricity consumption in acid rolling sector is 7630 MWh, which consumes nearly 70% of the whole energy consumption of acid rolling. A major operation in acid rolling section is to roll the thick steel strip into a much thinner one. All the rolling mills are driven by electricity and it consumes a large amount of electricity to generate rolling pressure during production. Due to the rapid increase of power de-

* Corresponding authors: Liaoning Key Laboratory of Manufacturing System and Logistics, Northeastern University, Shenyang 110819, China.
E-mail addresses: grossmann@cmu.edu (I.E. Grossmann), qhjytlx@mail.neu.edu.cn (L. Tang).

https://doi.org/10.1016/j.compchemeng.2017.12.018
0098-1354/

Nomenclature

Indices

i, j	Coils
s, s'	Units
k	Slots
tp	Constant electricity price period

Sets and Parameters

S	Set of total units, $S = \{1, 2, ..., \lvert S \rvert\}$
AC	Set of units in acid rolling section
S'	Set of units that have downstream units
L_s	Set of units that are downstream units of s
N	Set of total coils
N_s	Set of coils that need to be processed at unit s, $N_s = \{1, 2, ..., n_s\}$, $s \in S \backslash AC$
N'_{ac}	Set of coils that need to be processed in acid rolling section, $N'_{ac} = \{1, 2, ..., ac\}$
$N_{s,s'}$	Set of coils that released from unit s to unit s'
T_s	Set of slots at unit s, $T_s = \{1, 2, ..., t_s\}$
TP	Set of electricity pricing periods, $TP = \{1, 2, \ldots, tp_{\max}\}$
τ_i^s	Processing time of coil i at unit s
m_1	Coefficient of total changeover costs in objective function
m_2	Coefficient of total costs of rolling facilities in objective function
m_3	Coefficient of total costs of electricity consumption in objective function
$F_{i,j}^s$	Changeover cost if coil i is processed followed by coil j at unit s
mc_i^s	Minimum changeover cost of coil i with adjacent coil at unit s
pwh^s	Electricity amount that unit s will consume per hour
$setup^s$	Setup time between campaigns at unit s
$nB_{\max}$	Maximum capacity of each campaign
c_{roller}	A constant cost of each rolling facility (roller) in acid rolling production
ce_{tp}^{buy}	The price of electricity during time period tp
cp_{tp}^L	Lower bound of time period tp
cp_{tp}^U	Upper bound of time period tp
UB_s	Upper bound of timing variables of unit s

Discrete variable

$nbatch_{s,k}$	Capacity of slot (campaign) k at unit s

Binary variables

$y_{s,k,i}$	If coil i is assigned to slot k at unit s
$z_{i,j,k}^s$	If coil i is assigned to slot k and coil j is assigned to slot $k+1$ at unit s
$r_{s,k}$	If slot k at unit s is selected (k is not idle)

Continuous variables

$\widehat{tb}_i^s$	Beginning time of coil i at unit s
$\widehat{tf}_i^s$	Completion time of coil i at unit s
$\overline{tb}_k^s$	Beginning time of slot k at unit s
$\overline{tf}_k^s$	Completion time of slot k at unit s
$tb_{i,k}^s$	Beginning time of coil i in slot k at unit s
$tf_{i,k}^s$	Completion time of coil i in slot k at unit s
$cd_{i,k}^s$	Processing time of coil i in slot k at unit s, $s \in S \backslash AC$
sd_k^s	Processing time of slot k at unit s, $s \in AC$
p_{tp}	Amount of electricity that is consumed during time period tp
$\Delta T_{s,k,tp}$	Time fractions of a selected slot k during a constant time period tp at unit s

mand, the power grid is now using time-of-use pricing strategy on industry customers to improve the utilization of electricity power on the demand side and keep stability of the power supply. Pricing of electricity can significantly affect the production mode and profitability of steel production. In this context, the steel enterprise can take advantage of production flexibility and pricing scheme to gain potential benefits, and reduce energy cost by organizing production on proper pricing time period.

Production scheduling has become a major optimization problem of industrial significance. Harjunkoski et al. (2014), Maravelias and Sung (2009), Méndez et al. (2006) reviewed the scope for industrial applications of scheduling models and solution methods. As for the steel industry, most of the literature focuses on the upstream process of steel production involving steel making and casting process. Harjunkoski and Grossmann (2001) addressed a decomposition approach to solve complex scheduling problem in steel making process. Tang et al. (2000) proposed a multiple traveling salesman model for hot rolling scheduling. Pacciarelli and Pranzo (2004) developed a model of steelmaking-continuous casting production based on alternative graph formulation with detailed constraints that are relevant for the scheduling problem. Tang et al. (2001) gave a comprehensive analysis of scheduling of integrated steel production. Li et al. (2012) addressed a multi-stage

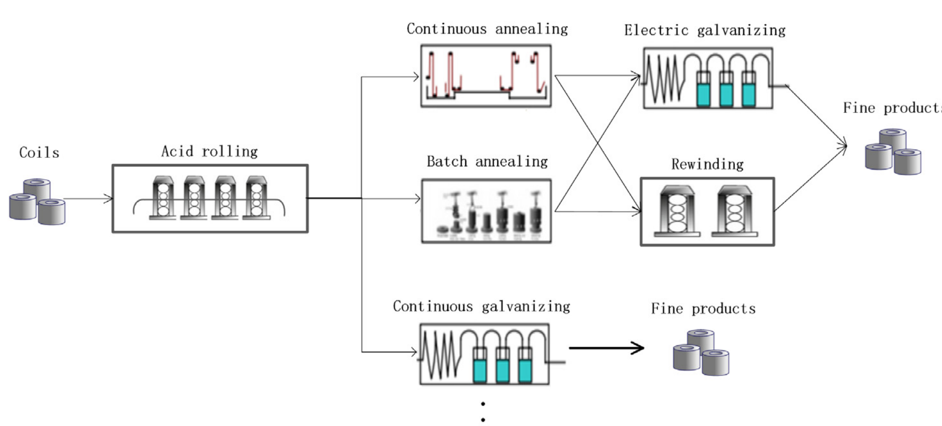

Fig. 1. Typical distribution of rolling sector.