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A discrete-time scheduling model for continuous power-intensive process networks with various power contracts

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ABSTRACT

Increased volatility in electricity prices and new emerging demand side management opportunities call for efficient tools for the optimal operation of power-intensive processes. In this work, a general discrete-time model is proposed for the scheduling of power-intensive process networks with various power contracts. The proposed model consists of a network of processes represented by Convex Region Surrogate models that are incorporated in a mode-based scheduling formulation, for which a block contract model is considered that allows the modeling of a large variety of commonly used power contracts. The resulting mixed-integer linear programming model is applied to an illustrative example as well as to a real-world industrial test case. The results demonstrate the model's capability in representing the operational flexibility in a process network and different electricity pricing structures. Moreover, because of its computational efficiency, the model holds much promise for its use in a real industrial setting.

1. Introduction

With deregulated electricity markets and increasing penetration of intermittent renewable energy into the electricity supply mix, the level of uncertainty in the power grid has increased tremendously. This has led to highly volatile electricity prices, which pose immense challenges to power-intensive industries, such as air separation, aluminum, and chlor-alkali manufacturing. Demand side management (DSM), which refers to electric energy management on the consumers' side, has the potential of both significantly reducing the electricity cost for the consumer as well as improving the efficiency and reliability of the power grid.

Only in recent years, the high potential benefits of DSM for the chemical processing industry have been acknowledged by researchers and practitioners (Paulus and Borggrefe, 2011; Samad and Kiliccote, 2012; Merkert et al., 2014). One main concept of industrial DSM is to use the operational flexibility of the plant, which consumes a large amount of power, to take advantage of time-sensitive electricity prices (Charles River Associates, 2005; Albadi and El-Saadany, 2008). This can be achieved, for example, by shifting the production to low-price hours; however, load shifting has to be well-considered since one still has to satisfy process constraints and meet product demand. The critical time component in DSM calls for effective scheduling tools that consider the constraints on the production process as well as the price structures and purchasing limitations for different power sources.

Production scheduling has been an active area of research in process systems engineering (PSE) since the late 1970s. Since then, much progress has been made in the modeling of both batch and continuous scheduling problems as well as in the development of efficient methods for solving these models. Numerous general scheduling models have been proposed, many of which are based on the concepts of state-task network (STN) (Kondili et al., 1993; Shah et al., 1993) or resource-task network (RTN) (Pantelides, 1994). In this work, we focus on the specific case of continuous power-intensive production processes. Hence, for recent general reviews on the broad area of production scheduling in PSE, we refer to Méndez et al. (2006), Maravelias (2012), and Harjunkoski et al. (2014).

In recent years, scheduling frameworks for DSM have been proposed for various industrial power-intensive processes such as steelmaking (Ashok, 2006; Castro et al., 2013), electrolysis (Babu and Ashok, 2008), cement production (Vujanic et al., 2012), and air separation (Ierapetritou et al., 2002; Karwan and Keblis, 2007; Zhang et al., 2015a). In their comprehensive review, Zhang and Grossmann (2015) present an overview of the advances made in planning and scheduling for industrial DSM, and highlight future challenges in this area. One of the main research opportunities

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Nomenclature

Indices

b, b' contract blocks
c power contracts
i processes
j materials
l vertices
m, m', m'' operating modes
r (convex) operating subregions
t time periods

Sets

B_c contract blocks for block contract c
C power contracts
$\overline{C}$ block contracts, i.e. discount and penalty contracts, $\overline{C} \subseteq C$
I processes
$\bar{I}_j$ processes receiving material j
$\hat{I}_j$ processes producing material j
J_i materials associated with process i, $J_i = \bar{J}_i \cup \hat{J}_i$
$\bar{J}_i$ materials that are inputs to process i
$\hat{J}_i$ materials that are outputs of process i
L_{imr} vertices of subregion r in mode m of process i
M_i modes for process i
R_{im} subregions in mode m of process i
SQ_i predefined sequences of mode transitions in process i
T time periods, $T = \{-\theta^{\max}+1, -\theta^{\max}+2, \ldots, 0, 1, \ldots, t^{\text{fin}}\}$
$\overline{T}$ time periods in the scheduling horizon, $\overline{T} = \{1, 2, \ldots, t^{\text{fin}}\}$
$\widehat{T}_c$ cumulative electricity consumption meter reading times for contract c
TR_i possible mode transitions in process i
TR_{im}^{f} modes of process i from which mode m can be directly reached
TR_{im}^{t} modes of process i which can be directly reached from mode m

Parameters

D_{jt} demand for material j in time period t (kg)
$E_{ct}^{\min}$ minimum amount of electricity that has to be purchased from contract c in time period t (kW h)
$E_{ct}^{\max}$ maximum amount of electricity that can be purchased from contract c in time period t (kW h)
$H_{cb}^{\max}$ maximum cumulative electricity purchase in block b of contract c (kW h)
Q_j^{fin} minimum final inventory level for material j (kg)
Q_j^{ini} initial inventory level for material j (kg)
$Q_j^{\min}$ minimum inventory level for material j (kg)
$Q_j^{\max}$ maximum inventory level for material j (kg)
t^{fin} index of the last time period of the scheduling horizon $\overline{T}$
$W_j^{\max}$ maximum purchasing amount for material j (kg)
y_{im}^{ini} 1 if process i was operating in mode m in time period 0
$z_{imm't}^{\text{ini}}$ 1 if operation of process i switched from mode m to mode m' at time t before time 0
α_{ct} base unit price for electricity purchased from contract c in time period t (\$/kW h)
β_{cbt} additional unit price for cumulative electricity purchased from block b of contract c at time t (\$/kW h)
γ_{imrj} unit electricity consumption corresponding to material j if process i operates in subregion r of mode m (kW h/kg)
δ_{imr} fixed electricity consumption if process i operates in subregion r of mode m (kW h)
$\Delta_{imj}^{\max}$ maximum rate of change in the amount of material j consumed or produced in mode m of process i (kg)
Δt length of one time period (h)
ζ_{ct}^{o} unit overconsumption penalty cost for contract c at time t (\$/kW h)
ζ_{ct}^{u} unit underconsumption penalty cost for contract c at time t (\$/kW h)
$\theta_{imm'}$ minimum stay time in mode m' after switching from mode m to mode m' in process i [Δt]
$\theta^{\max}$ largest minimum stay time [Δt]
$\overline{\theta}_{imm'm''}$ fixed stay time in mode m' in the predefined sequence (m, m', m'') in process i [Δt]
ϕ_{imrlj} amount of material j associated with vertex l of subregion r in mode m of process i (kg)

Continuous variables

E_{ct} electricity purchased from contract c in time period t (kW h)
F_{ct} cumulative electricity purchased from contract c at time t (kW h)
G_{ct} cumulative electricity purchased from contract c at meter reading time t (kW h)
H_{cbt} cumulative electricity purchased in block c of contract c at meter reading time t (kW h)
$\overline{H}_{cbb't}$ diaggregated variable for H_{cbt} corresponding to block/disjunct b' (kW h)
P_{ijt} amount of material j consumed or produced by process i in time period t (kg)
$\overline{P}_{imrjt}$ amount of material j consumed or produced in subregion r of mode m of process i in time period t (kg)
Q_{jt} inventory level for material j at time t (kg)
TC total electricity cost (\$)
U_{it} electricity consumed by process i in time period t (kW h)
W_{jt} amount of material j purchased in time period t (kg)
λ_{imrlt} coefficient for vertex l of subregion r in mode m of process i in time period t

Binary variables

x_{cbt} 1 if block b is the highest block reached for contract c at time t
y_{imt} 1 if process i operates in mode m in time period t
$\overline{y}_{imrt}$ 1 if process i operates in subregion r of mode m in time period t
$z_{imm't}$ 1 if process i switches from mode m to mode m' at time t

Boolean variables

X_{cbt} true if block b is the highest block reached for contract c at time t
Y_{imt} true if process i operates in mode m in time period t
$\overline{Y}_{imrt}$ true if process i operates in subregion r of mode m in time period t