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Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes

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ABSTRACT

Power-intensive processes can lower operating expenses when adjusting production planning according to time-dependent electricity pricing schemes. In this paper, we describe a discrete-time, deterministic MILP model that allows optimal production planning for continuous power-intensive processes. We emphasize the systematic modeling of operational transitions, that result from switching the operating modes of the plant equipment, with logic constraints. We prove properties on the tightness of several logic constraints. For the time horizon of 1 week and hourly changing electricity prices, we solve an industrial case study on air separation plants, where transitional modes help us capture ramping behavior. We also solve problem instances on cement plants where we show that the appropriate choice of operating modes allows us to obtain practical schedules, while limiting the number of changeovers. Despite the large size of the MILPs, the required solution times are small due to the explicit modeling of transitions.

1. Introduction

The profitability of industrial power-intensive processes is affected by the availability and pricing of electricity supply. Nowadays, two major trends increase the complexity of managing power-intensive processes. First, deregulation in the 1990s introduced hourly as well as seasonal variations. Second, the environmental pressure to reduce CO_2 emissions and diminishing natural resources lead to an increasing share of renewable energies, which intensifies the aforementioned problem. These trends have added a considerable amount of uncertainty and variability in the daily operating expenses of power-intensive industries, which in turn affect their competitiveness.

One important component of the current and future power system is the concept of Demand Side Management (DSM), consisting of Energy Efficiency (EE) and Demand Response (DR). A report released by The World Bank (Charles River Associates, 2005) defines DSM as the "systematic utility and government activities designed to change the amount and/or timing of the customer's use of electricity for the collective benefit of the society, the utility and its customers." While EE aims for permanently reducing demand for energy, DR focuses on the operational level (Voytas et al., 2007). The official classification of DR by the North American Electric Reliability Corporation (NERC) distinguishes between dispatchable and non-dispatchable programs (see Fig. 1).

Dispatchable DR programs include any kind of demand response that is according to instructions from a grid operator's control center. They are divided into capacity services, such as load control and interruptible demand, and ancillary services, such as spinning and nonspinning reserves as well as regulation. The control actions, which balance the electricity supply and demand, differ on the time scale and usually range from a few seconds to one hour. Hence, participation in one of these dispatchable DR programs requires the process to be highly flexible, while process feasibility and safety have to be maintained. Nowadays, chemical companies, which operate flexible processes like chlor-alkali synthesis, market already a few percent of their total load as operative capacity reserve (e.g. in Germany; Paulus & Borggrefe, 2011). The potential of ancillary services for aluminum production was recently evaluated in a case study by ALCOA (Todd et al., 2009). However, both processes, chlor-alkali synthesis and aluminum production, are examples of capital-intensive processes that are operated at a high level of capacity utilization. Thus, these processes usually only shift production on a minute level around a predefined setpoint.

In contrast to dispatchable DR programs, non-dispatchable DR programs do not involve instructions from a control center. Instead, the electricity consumption of industrial customers is influenced by the market price of electricity. Typical examples of time-sensitive electricity prices are time-of-use (TOU) rates and real-time prices (RTP). While TOU rates are usually specified in terms of on-peak,

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Nomenclature

Sets

P (index p) the set of plants or production lines
$M(p)$ (index m), abbreviated as M the set of modes, depending on plant p
$I(p, m)$ (index i), abbreviated as I the set of extreme points that relate to mode m of plant p
G (index g) the set of products. For air separation plants it is $\{LO2, LN2, LAr, GO2, GN2\}$.
$Storable \subseteq G$ the subset of products that are storable. For air separation plants it is $\{LO2, LN2, LAr\}$
$Nonstorable \subseteq G$ the subset of products that are not storable. For air separation plants it is $\{GO2, GN2\}$
ST the set of shared storage tanks
H (index h) the set of hours of a week in the operational model
$H_x \subseteq H$ subset of hours, where x can stand for, e.g. a certain day
$MinStay(m, m')$ a placeholder for the sets UT, DT and TT
$UT(p)$, abbreviated as UT the set of hours that a plant p has to stay online, once it was started
$DT(p)$, abbreviated as DT the set of hours that a plant p has to stay offline, once it was shut down
$TT(p)$, abbreviated as TT the set of hours that a plant p has to stay in a transitional mode
$Trans(p, m, m', m'')$ the set of possible transitions for plant p from mode m to a production mode m'' with the transitional mode m' in between
$AL(p, m, m')$ the set of allowed transitions for plant p from mode m to another mode m'
$DAL(p, m, m')$ the set of disallowed transitions from mode m to mode m' of plant p

Binary variables

$X^h_{st,g}$ indicates which product g is stored in storage st at hour h (for shared storage)
$y^h_{p,m}$ determines whether plant p operates in mode m in hour h
$Z^h_{p,m,m'}$ indicates whether there is a transition from mode m to mode m' at plant p from hour $h-1$ to h

Continuous variables

$\overline{Pr}^h_{p,m,g}$ production amount of product g in mode m at plant p in hour h
$Pr^h_{p,g}$ total production of product g at plant p in hour h
$\lambda^h_{p,m,i}$ variable for the convex combination of slates i to describe the feasible region of the plant p of mode m in hour h
$INV^h_{p,g}$ inventory level of product g at plant p in hour h
$S^h_{p,g}$ sales of product g from plant p in hour h
$Store^h_{p,st,g}$ keeps track how much of product g is transferred from production line p to storage tank st in hour h (for shared storage)
OBJ objective function variable

Parameters

$\hat{\alpha}_{LN2}, \hat{\alpha}_{LO2}, \hat{\alpha}_{LAR}$ conversion parameters for equivalent liquid rate
$\alpha_{p,m}, \beta_{p,m}, \gamma_{p,m}$ fitting parameters for mode m of plant p in [power/volume]
$\delta_{p,g}$ cost coefficient for inventory of product g at plant p in [\$/volume]
$\zeta_{p,m,m'}$ cost coefficient for transitions from mode m to m' at plant p in [\$]
e^h_p electricity prices for plant p in hour h
$x_{p,m,i,g}$ extreme points i of the convex hull of mode m of plant p in terms of the products g
$\bar{M}_{p,m,g}$ BigM constant for bounds on production for plant p (i.e. max. production of product g in mode m)
$K^{min}_{m,m'}$ number of hours the plant has to stay in mode m' after a transition from mode m
$K^{max}_{m,m'}$ number of hours the plant can stay at most in mode m' after a transition from mode m
$r_{p,m,g}$ maximum rate of change for product g at plant p in mode m
$d^{daily}_{p,g}, d^{weekly}_{p,g}$ daily/weekly demand for the products g of plant p. For air separation plants, it is the demand for the liquid products.
$d^{h,hourly}_{p,g}$ hourly demand for the products g of plant p in hour h. For air separation plants, it is the demand for the gaseous or the liquid products.
$INV^U_{p,st,g}$ tank capacity of tank st for product g at plant p
PW^h_{max} maximum power consumption at hour h (under restricted power availability)

mid-peak and off-peak hours, real-time prices vary every hour and are quoted either on a day-ahead or hourly basis. Other pricing models exist but strongly depend on the characteristics of the regional market (NERC study; (Voytas et al., 2007)).

Non-dispatchable DR programs allow industrial customers to perform production planning based on predefined hourly prices. At first glance it may seem that production planning due to price fluctuations is only attractive for processes that are operated significantly below the process capacity, and therefore have operational flexibility. However, major demand drops due to economic changes, such as the 2008 recession, can lead to over-capacities, which in turn make a systematic production planning more attractive. Promising examples can be found in the industrial gases sector (cryogenic air separation plants) and in the cement industry.

The purpose of this paper is to describe a general model that helps decision-makers for power-intensive production processes to optimize their production schedules with respect to operating costs that are due to fluctuations in electricity prices, which are in turn caused by non-dispatchable DR programs.

2. Literature review

The economic potential for DSM of industrial processes in developed countries has been recognized by numerous institutions and authors (World Bank report: (Charles River Associates, 2005); NERC study (Voytas et al., 2007); Klobasa, 2007; Gutschi & Stigler, 2008; Paulus & Borggrefe, 2011). In these publications, we can find a list of various chemical processes where the consumption of electricity is due to different unit operations: grinding (cement, paper pulp production), compression (air separation), electrolysis (chlor-alkali, aluminum) and drying (paper production). Fig. 1 illustrates possible DR applications for these processes. In chemical engineering, two different lines of research address optimizing operations of these processes according to time-sensitive pricing.

The first line of research proposes a control approach. For the economic optimization of air separation plants, Zhu, Legg, and Laird (2011) developed a model based on heat and mass balances,