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Optimal multi-scale capacity planning for power-intensive continuous processes under time-sensitive electricity prices and demand uncertainty. Part I: Modeling

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ABSTRACT

Time-sensitive electricity prices (as part of so-called demand-side management in the smart grid) offer economical incentives for large industrial customers. In part I of this paper, we propose an MILP formulation that integrates the operational and strategic decision-making for continuous power-intensive processes under time-sensitive electricity prices. We demonstrate the trade-off between capital and operating expenditures with an industrial case study for an air separation plant. Furthermore, we compare the insights obtained from a model that assumes deterministic demand with those obtained from a stochastic demand model. The value of the stochastic solution (VSS) is discussed, which can be significant in cases with an unclear setup, such as medium baseline product demand and growth rate, large variance or skewed demand distributions. While the resulting optimization models are large-scale, they can be solved within three days of computational time. A decomposition algorithm for speeding-up the solution time is described in part II.

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1. Background

1.1. Motivation

The manufacturing base in the U.S. has been eroding over the last two decades in the face of fierce international competition. However, recent developments such as the gas production from very large deposits of shale gas (Chang, 2010, March), as well as trends in onshoring due to rising labor cost in emerging countries (Sirkin, Zinser, & Hohner, 2011), provide hope in the revitalization of U.S. manufacturing. While the economic recovery deserves further observation in the aftermath of the recession of 2008 and the current unemployment and financial market volatility, future competitiveness of industrial companies requires them to optimally design and retrofit their production facilities in anticipation of price and demand growth forecasts.

A group of chemical processes for which the design and capacity planning is very challenging is the group of power-intensive processes, such as air separation plants (compression), cement production (grinding), chlor-alkali synthesis, steel and aluminum production (electrolysis) and thermo-mechanical paper pulp production (grinding). These industries in fact consume roughly 15% of the total industrial electric power in the United States (EIA, 2013).

At the same time, the power grid is in transition to the so-called smart grid with the ambition to improve reliability, energy security, economics and greenhouse gas emissions (Samad & Kiliccote, 2012). A growing share of intermittent renewable energies, such as wind and solar, increases the challenge that grid operators face every day and every minute: balancing supply and demand of electricity on a real-time basis. A set of measures, such as co-generation, micro-grids, future storage technologies and demand-side management (DSM), is expected to play an important role in helping today's power grid, mastering the transition to the smart grid.

The societal benefit of DSM in the US is estimated to be $59 Billion by 2019, of which 40% is attributed to large commercial and industrial consumers (McKinsey study by Davito, Tai, & Uhlaner, 2010). Hence, from an industrial consumer's perspective, demand-side management (DSM), consisting of Energy Efficiency (EE) and Demand Response (DR), deserves special attention. The idea of DSM is to influence the "amount and/or timing of the customers use of electricity for the collective benefit of the society, the utility and its customers" (Charles River Associates, 2005). While EE aims for permanently reducing demand for energy, DR focuses on the operational level (Voytas et al., 2007). As a consequence, variability in time-sensitive electricity prices can be observed on various time

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Nomenclature

Sets

$DAL(m, m')$ the set of disallowed transitions from mode m to m'

G (index g) the set of products. For air separation plants it is $\{LO2, LN2, LAr, GO2, GN2\}$

H (index h) the set of weekly hours in the operational representation

$I(m, o)$ (index i), abbreviated as I the set of extreme points that relate to option o of mode m

M (index m) the set of operating modes

$MS(m, m')$ characterizes all minimum stay relationships that hold once a transition from mode m to mode m' occurs. Examples include minimum uptimes, minimum downtimes and minimum transition times.

N the set of available new equipment to be added to the plant

$NewEq(m, n)$, abbreviated as NewEq the set captures the links between the addition of equipment n with modes m that would be introduced to the state graph

$O(m)$ (index o), abbreviated as O the set of options for mode m depending on how the plant is modified

S (index s) the set of demand scenarios

ST the set of available storage tanks

T (index t) the set of time periods related to seasons (four per year); each one's operation is represented by a cyclic scheduling problem

$T_{invest} \subset T$ the subset of investment time periods

$Trans(m, m', m'')$ the set of possible transitions from mode m to a production mode m'' with the transitional mode m' in between

U the set of equipment upgrades available

$Upgrade(m, o, u)$, abbreviated as Upgrade the set captures the links between the equipment upgrade u and the options o of mode m that would be changed in their polyhedral representation

Binary investment variables

VU_u^t indicates whether upgrade u is performed in time period t

VN_n^t describes whether new equipment n is added in time period t

$VS_{st,g}^t$ indicates whether storage tank st for product g is purchased in time period t

Binary operational variables

$y_m^{t,s,h}$ determines whether the plant operates in mode m in hour h (of time period t and scenario s)

$\tilde{y}_{m,o}^{t,s,h}$ determines whether the plant operates in option o for mode m in hour h (of time period t and scenario s)

$z_{m,m'}^{t,s,h}$ indicates whether there is a transition from mode m to mode m' from hour $h-1$ to h (of time period t and scenario s)

Continuous (operational) variables

$\overline{Pr}_{m,o,g}^{t,s,h}$ production amount of product g in option o of mode m in hour h (of time period t and scenario s)

$Pr_g^{t,s,h}$ total production of product g in hour h (of time period t and scenario s)

$\lambda_{m,o,i}^{t,s,h}$ convex combination of slates i to describe the feasible region of option o of mode m in hour h (of time period t and scenario s)

$INV_g^{t,s,h}$ inventory level of product g in hour h (of time period t and scenario s)

$S_g^{t,s,h}$ sales of product g in hour h (of time period t and scenario s)

$B_g^{t,s,h}$ external product purchases in hour h (of time period t and scenario s)

$CAPEX^t$ capital spent due to investments in time period t

$OPEX^{t,s}$ operating expenses in scenario s of time period t

TC objective function variable that represents total cost

Parameters

$e^{t,s,h}$ electricity price in hour h in time period t and scenario s

$\Phi_{m,o,g}$ coefficient that correlates production level of product g for option o of mode m with power consumption, in [power/volume]

$\rho_g^{t,s}$ cost for product g shipped from another plant or procured from a competitor in time period t and scenario s, in [$/volume]

δ_g cost coefficient for inventory of product g, in [$/volume]

$\zeta_{m,m'}$ cost coefficient for transitions from mode m to m', in [$]

$\tau^{t,s}$ probability of scenario s in time period t

$x_{m,o,i,g}$ extreme points of the convex hull of the feasible regions

$K_{m,m'}$ number of hours the plant has to stay in mode m' after a transition from mode m

$r_{m,o,g}$ maximum rate of change for product g in option o of mode m

$d_g^{t,s,h}$ hourly demand for the products g in hour h (in time period t and scenario s).

INV_g^U current tank capacity for product g

$Tank_{st,g}$ tank size for new storage tank st for product g

$Cs_{st,g}^t$ cost for buying storage tank st for product g in time period t

Cn_n^t cost for investing in new equipment n in time period t

Cu_u^t cost for investing in the equipment upgrade u in time period t

Other symbols

D^t random variable for the overall product demand in time period t

μ^t the expected demand in time period t, i.e. $\mu^t = \mathbb{E}(D^t)$

σ^t the standard deviation for the demand in time period t

a annual growth rate for product demand

b_{low}, b_{high} scaling factors

scales, including hourly variations for so-called day-ahead (DA) prices that industrial consumers are exposed to in many electricity markets around the globe. However, economic benefits can be realized if the industrial consumer has the flexibility to adjust consumption (Mitra, Grossmann, Pinto, & Arora, 2012).

With pressure on both sides, the revenue side (uncertainty in product demand) and the cost side (variability in electricity prices), new designs and plant retrofits can be viable options for power-intensive processes in the context of DSM. Retrofitting includes replacing existing equipment with more energy-efficient alternatives, improving design flexibility (with respect to DR incentives), adding further production equipment and installing additional storage tanks. All these design decisions, which could potentially lead to lower operating costs, are part of strategic capacity

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