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An adjustable robust optimization approach to scheduling of continuous industrial processes providing interruptible load

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ABSTRACT

To ensure the stability of the power grid, backup capacities are called upon when electricity supply does not meet demand due to unexpected changes in the grid. As part of the demand response efforts in recent years, large electricity consumers are encouraged by financial incentives to provide such operating reserve in the form of load reduction capacities (interruptible load). However, a major challenge lies in the uncertainty that one does not know in advance when load reduction will be requested. In this work, we develop a scheduling model for continuous industrial processes providing interruptible load. An adjustable robust optimization approach, which incorporates recourse decisions using linear decision rules, is applied to model the uncertainty. The proposed model is applied to an illustrative example as well as a real-world air separation case. The results show the benefits from selling interruptible load and the value of considering recourse in the decision-making.

1. Introduction

With rising electricity demand, deregulated electricity markets, and increasing penetration of intermittent renewable energy into the power supply mix, the level of uncertainty in the power grid has increased tremendously. As a result, the stable and reliable operation of the power grid has become increasingly challenging. In recent years, the notion of a *smart grid* has been evolving, which represents the idea of effectively coordinating the major grid operations—electricity generation, transmission, distribution, and consumption—through improved communication, holistic optimization, and market design.

One main element of the smart grid concept is the utilization of the flexibility for load adjustment on the electricity consumers' side, which is also referred to as demand response (DR). In DR, one distinguishes between dispatchable and nondispatchable DR (FERC, 2010). Dispatchable DR refers to load adjustment capacities that consumers provide to the grid operator such that these capacities can be dispatched to maintain grid stability or in times of emergency. The grid operator has control over dispatchable DR resources by either direct load control or by sending load adjustment requests to the consumers. In nondispatchable DR, consumers are not obliged to meet any load change requests by the grid operator, but rather choose to adjust their power consumption profiles based on price signals from the electricity market.

Only recently, researchers and practitioners have acknowledged the high potential benefits of demand side management (DSM), which involves energy efficiency and DR measures, for the chemical processing industry (Paulus and Borggrefe, 2011; Samad and Kiliccote, 2012; Merkert et al., 2014). In particular, the scheduling of power-intensive industrial processes has evolved into a major research field. In this context, processes such as steelmaking (Ashok, 2006; Castro et al., 2013), electrolysis (Babu and Ashok, 2008), cement production (Castro et al., 2011), and air separation (Ierapetritou et al., 2002; Karwan and Keblis, 2007; Mitra et al., 2012; Zhang et al., 2016) have been considered. In their recent review, Zhang and Grossmann (2015) present a comprehensive overview of the advances made in planning and scheduling for industrial DSM, and highlight future challenges in this area. One of the conclusions of the review is that most existing works only

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Nomenclature

Indices

f	supporting hyperplanes
i	products
j	vertices
m, m', m''	operating modes
r	operating subregions
t	time periods

Sets

F_{mr}	supporting hyperplanes associated with subregion r of mode m
I	products
J_{mr}	vertices of polytope describing subregion r of mode m
M	operating modes
$\overline{M}$	flexible operating modes, $\overline{M} \subseteq M$
$\widehat{M}$	inflexible operating modes, $\widehat{M} \subseteq M$
R_m	subregions of mode m
SQ	predefined sequences of mode transitions
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, $\overline{T} = \{1, 2, \ldots, t^{\text{fin}}\}$
TR	possible mode transitions
$\overline{TR}_m$	modes from which mode m can be directly reached
$\widehat{TR}_m$	modes which can be directly reached from mode m

Deterministic parameters

a_{mrfi}	coefficient related to product i used in the equation representing the supporting hyperplane f of subregion r of mode m
b_{mrf}	coefficient used in the equation representing the supporting hyperplane f of subregion r of mode m [kg]
D_{it}	demand for product i in time period t [kg]
$IL_t^{\min}$	minimum amount to provide if interruptible load is provided in time period t [kWh]
$IL_t^{\max}$	maximum amount to provide if interruptible load is provided in time period t [kWh]
IV_i^{ini}	initial inventory of product i [kg]
$IV_{it}^{\min}$	minimum inventory of product i at time point t [kg]
$IV_{it}^{\max}$	maximum inventory of product i at time point t [kg]
$PD_{mri}^{\max}$	maximum amount of product i that can be produced in subregion r of mode m [kg]
v_{mrji}	amount of product i produced in one time period at vertex j of subregion r of mode m [kg]
y_m^{ini}	1 if plant was operating in mode m in the time period before the start of the scheduling horizon
$z_{mm't}^{\text{ini}}$	1 if operation switched from mode m to mode m' at time t before the start of the scheduling horizon
α_t^{EC}	unit electricity price in time period t [$/kWh]
α_t^{IL}	unit price for provided interruptible load in time period t [$/kWh]
α_{it}^{PC}	unit cost for purchasing product i in time period t [$/kg]
α_{mri}^{RP}	unit cost for recourse associated with the p-variables [$/kg]
α_i^{RQ}	unit cost for recourse associated with the q-variables [$/kg]
δ_{mr}	fixed electricity consumption if plant operates in subregion r of mode m [kWh]
$\Delta EC_{mr}^{\max}$	the maximum load change that can be achieved in subregion r of mode m [kWh]
Δt	length of one time period [h]
γ_{mri}	unit electricity consumption corresponding to product i if plant operates in subregion r of mode m [kWh/kg]
Γ_t	budget parameter for time period t
ζ_t	number of preceding time periods of which the uncertain parameters are considered in the decision rule for recourse in time period t, $\zeta_t \in [0, t-1]$
$\overline{\zeta}$	$\max_{t \in \overline{T}} \zeta_t$, $\overline{\zeta} \in [0, t^{\text{fin}}]$
$\theta_{mm'}$	minimum stay time in mode m' after switching from mode m to m' [Δt]
$\overline{\theta}_{mm'm''}$	fixed stay time in mode m' of the predefined sequence (m, m', m'') [Δt]
$\theta^{\max}$	maximum minimum or predefined stay time in a mode [Δt]
Ω	big-M parameter [kWh]

Uncertain parameters

LR_t	amount of load reduction requested in time period t
w_t	normalized load reduction request in time period t

Continuous variables

EC_t	amount of electricity consumed in time period t [kWh]
IL_t	amount of interruptible load provided in time period t [kWh]
IV_{it}	inventory of product i at time t [kg]
p_{mritk}	coefficient for recourse decision rule related to the change in the amount of product i produced in subregion r of mode m in time period t in response to uncertainty realized in time period k [kg]
PC_{it}	amount of product i purchased in time period t [kg]
$\widehat{PC}_{it}$	target amount of product i purchased in time period t [kg]
$\widetilde{PC}_{it}$	response change in amount of product i purchased in time period t [kg]
PD_{it}	amount of product i produced in time period t [kg]
q_{itk}	coefficient for recourse decision rule related to the change in the amount of product i purchased in time period t in response to uncertainty realized in time period k [kg]
$\overline{PD}_{mrit}$	amount of product i produced in subregion r of mode m in time period t [kg]
$\widehat{PD}_{mrit}$	target amount of product i produced in subregion r of mode m in time period t [kg]
$\widetilde{PD}_{mrit}$	response change in amount of product i produced in subregion r of mode m in time period t [kg]
SL_{it}	amount of product i sold in time period t [kg]
TC	total net operating cost [$]
λ_{mrjt}	coefficient for vertex j in subregion r of mode m in time period t

Binary variables

x_t	1 if interruptible load is provided in time period t
y_{mt}	1 if plant operates in mode m in time period t (can also be defined as a continuous variable)
$\overline{y}_{mrt}$	1 if plant operates in subregion r of mode m in time period t
$z_{mm't}$	1 if plant operation switched from mode m to mode m' at time t