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# Risk-based integrated production scheduling and electricity procurement for continuous power-intensive processes

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ABSTRACT

For optimal operation of power-intensive plants, production scheduling and electricity procurement have to be considered simultaneously. In addition, uncertainty needs to be taken into account. For this purpose, an integrated stochastic mixed-integer linear programming model is developed that considers the two most critical sources of uncertainty: spot electricity price, and product demand. Conditional value-at-risk is incorporated into the model as a measure of risk. Furthermore, scenario reduction and multicut Benders decomposition are implemented to solve large-scale real-world problems. The proposed model is applied to an illustrative example as well as an industrial air separation case. The results show the benefit from stochastic optimization and the effect of taking a risk-averse rather than a risk-neutral approach. An interesting insight from the analysis is that in risk-neutral optimization, accounting for electricity price uncertainty does not yield significant added value; however, in risk-averse optimization, modeling price uncertainty is crucial for obtaining good solutions.



## 1. Introduction

Due to high fluctuations in electricity demand and increasing penetration of intermittent renewable energy into the electricity supply mix, it is becoming increasingly difficult to match electricity demand and supply in the power grid (Hand et al., 2012). As a result, electricity prices have become extremely volatile and difficult to predict, which poses immense challenges to power-intensive industries, such as air separation, aluminum, and chlor-alkali manufacturing.

For large industrial electricity consumers, there are two ways of dealing with uncertainty in electricity price: (1) dynamically adjust the production schedule to changes in the spot price, i.e. shift the electricity load to lower-price periods, which is also referred to as demand response (Charles River Associates, 2005); (2) remove price uncertainty by signing power contracts with agreed fixed prices. Both strategies can be very effective in reducing the electricity cost, but they also have their limitations and drawbacks. A plant's capability for demand response is limited by the flexibility of the production process, which has to be carefully evaluated in order to avoid detrimental disruptions caused by sudden changes in the plant operation. Power contracts provide fixed electricity prices; however, this reduction in risk usually comes at the cost of higher expected average prices. Moreover, power contracts require the consumers to commit themselves in advance to the amount that they are going to purchase for a certain period of time. This commitment reduces the consumers' demand response opportunities since there is less room for adjustments in response to real-time price changes. Hence, there is a trade-off between purchasing power from contracts and from the spot market.

It is clear that often only a combination of the two aforementioned strategies will lead to the best result. Here, the major challenge in the decision-making is uncertainty. This uncertainty does not only occur in the electricity price; another source of uncertainty that has a possibly even greater impact on the production schedule is product demand. Major operational decisions and decisions regarding the commitment to power contracts have to be made before the actual spot electricity price and product demand are known for the time horizon of interest. There is only limited room for reactive actions as soon as these decisions are made. Therefore, it is crucial to account for these uncertainties in the decision-making process.

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**Nomenclature**

*Indices*

| | |
|---|---|
| $b, b'$ | contract blocks |
| $c$ | power contracts |
| $i$ | products |
| $j$ | vertices |
| $m, m', m''$ | operating modes |
| $p$ | time-of-use (TOU) periods |
| $s$ | general scenarios |
| $\bar{s}$ | product demand scenarios |
| $\hat{s}$ | electricity price scenarios |
| $t$ | time periods |

*Sets*

| | |
|---|---|
| $B_c$ | blocks in contract $c$ |
| $C$ | power contracts |
| $I$ | products |
| $J_m$ | vertices of polytope describing mode $m$ |
| $M$ | operating modes |
| $P_c$ | TOU periods for contract $c$ |
| $S$ | general scenarios |
| $S^D$ | product demand scenarios |
| $S^P$ | electricity price scenarios |
| $SQ$ | 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, $\overline{T} = \{1, 2, \ldots, t^{\text{fin}}\}$ |
| $\widehat{T}_{cp}$ | time periods in TOU period $p$ of contract $c$ |
| $TR$ | possible mode transitions |
| $TR_m^f$ | modes from which mode $m$ can be directly reached |
| $TR_m^t$ | modes which can be directly reached from mode $m$ |

*Parameters*

| | |
|---|---|
| $D_{its}$ | demand for product $i$ in time period $t$ in scenario $s$ (kg) |
| $\overline{EC}_{cp}^{\max}$ | maximum amount of electricity that can be purchased from contract $c$ in one time period within TOU period $p$ (kW h) |
| $\widehat{EC}_{cb}^{\max}$ | maximum amount of electricity that can be purchased from block $b$ of contract $c$ (kW h) |
| $ES_t^{\max}$ | maximum amount of electricity that can be purchased from the spot market in time period $t$ (kW h) |
| $IV_i^{\text{fin}}$ | minimum final inventory of product $i$ (kg) |
| $IV_i^{\text{ini}}$ | initial inventory of product $i$ (kg) |
| $IV_i^{\min}$ | minimum inventory of product $i$ (kg) |
| $IV_i^{\max}$ | maximum inventory of product $i$ (kg) |
| $R_s$ | total revenue in scenario $s$ (\$) |
| $v_{mji}$ | amount of product $i$ produced in one time period at vertex $j$ of mode $m$ (kg) |
| $y_m^{\text{ini}}$ | 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 |
| $\alpha$ | confidence level at which the CVaR is defined, $\alpha \in (0, 1)$ |
| $\alpha_{ct}^{EC}$ | unit electricity price for purchasing electricity from contract $c$ in time period $t$ (\$/kW h) |
| $\alpha_{ts}^{ES}$ | unit electricity price for purchasing electricity from the spot market in time period $t$ in scenario $s$ (\$/kW h) |
| $\alpha_{it}^{PC}$ | unit cost for purchasing product $i$ in time period $t$ (\$/kg) |
| $\beta_{cb}^{EC}$ | unit electricity price for purchasing electricity from block $b$ of contract $c$ (\$/kW h) |
| $\gamma_{mi}$ | unit electricity consumption corresponding to product $i$ if plant operates in mode $m$ (kW h/kg) |
| $\delta_m$ | fixed electricity consumption if plant operates in mode $m$ (kW h) |
| $\Delta t$ | length of one time period (h) |
| $\zeta$ | weight factor for total expected cost, $\zeta \in [0, 1]$ |
| $\theta_{mm'}$ | minimum stay time in mode $m'$ after switching from mode $m$ to $m'$ $[\Delta t]$ |
| $\bar{\theta}_{mm'm''}$ | fixed stay time in mode $m'$ of the predefined sequence $(m, m', m'')$ $[\Delta t]$ |
| $\theta^{\max}$ | maximum minimum or predefined stay time in a mode $[\Delta t]$ |
| $\varphi_s$ | probability of scenario $s$ |
| $\varphi_{\bar{s}}^D$ | probability of demand scenario $\bar{s}$ |
| $\varphi_{\hat{s}}^P$ | probability of price scenario $\hat{s}$ |

*Continuous variables*

| | |
|---|---|
| $BC_c$ | base cost for purchasing electricity from contract $c$ (\$) |
| $EC_{ct}$ | amount of electricity purchased from contract $c$ in time period $t$ (kW h) |
| $\overline{EC}_{cp}$ | amount of electricity purchased in each time period during TOU period $p$ of contract $c$ (kW h) |
| $\widehat{EC}_c$ | amount of electricity purchased from contract $c$ (kW h) |
| $\widetilde{EC}_{cb}$ | amount of electricity purchased from block $b$ of contract $c$ (kW h) |
| $ES_{ts}$ | amount of electricity purchased from the spot market in time period $t$ in scenario $s$ (kW h) |
| $EU_{ts}$ | amount of electricity used by the plant in time period $t$ in scenario $s$ (kW h) |
| $EW_{ts}$ | amount of electricity wasted in time period $t$ in scenario $s$ (kW h) |
| $CV$ | conditional value-at-risk (CVaR) (\$) |
| $IV_{its}$ | inventory of product $i$ at time $t$ in scenario $s$ (kg) |
| $PC_{its}$ | amount of product $i$ purchased in time period $t$ in scenario $s$ (kg) |
| $PD_{its}$ | amount of product $i$ produced in time period $t$ in scenario $s$ (kg) |
| $\overline{PD}_{mits}$ | amount of product $i$ produced in mode $m$ in time period $t$ in scenario $s$ (kg) |
| $PW_{its}$ | amount of product $i$ discarded in time period $t$ in scenario $s$ (kg) |
| $SL_{its}$ | amount of product $i$ sold in time period $t$ in scenario $s$ (kg) |
| $TC$ | total expected cost (\$) |
| $\kappa$ | auxiliary variable for modeling CVaR |
| $\lambda_{mjts}$ | coefficient for vertex $j$ in mode $m$ in time period $t$ in scenario $s$ |
| $\omega_s$ | auxiliary variable for modeling CVaR associated with scenario $s$ |

*Binary variables*

| | |
|---|---|
| $x_{cb}$ | 1 if electricity is purchased from block $b$ of contract $c$ |
| $y_{mt}$ | 1 if plant operates in mode $m$ in time period $t$ |
| $z_{mm't}$ | 1 if plant operation switched from mode $m$ to mode $m'$ at time $t$ |

*Boolean variables*

| | |
|---|---|
| $X_{cb}$ | true if electricity is purchased from block $b$ of contract $c$ |