Risk-based Integrated Production Scheduling and Electricity Procurement

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To mitigate the impact of electricity price uncertainty, the two common strategies have to be considered simultaneously.

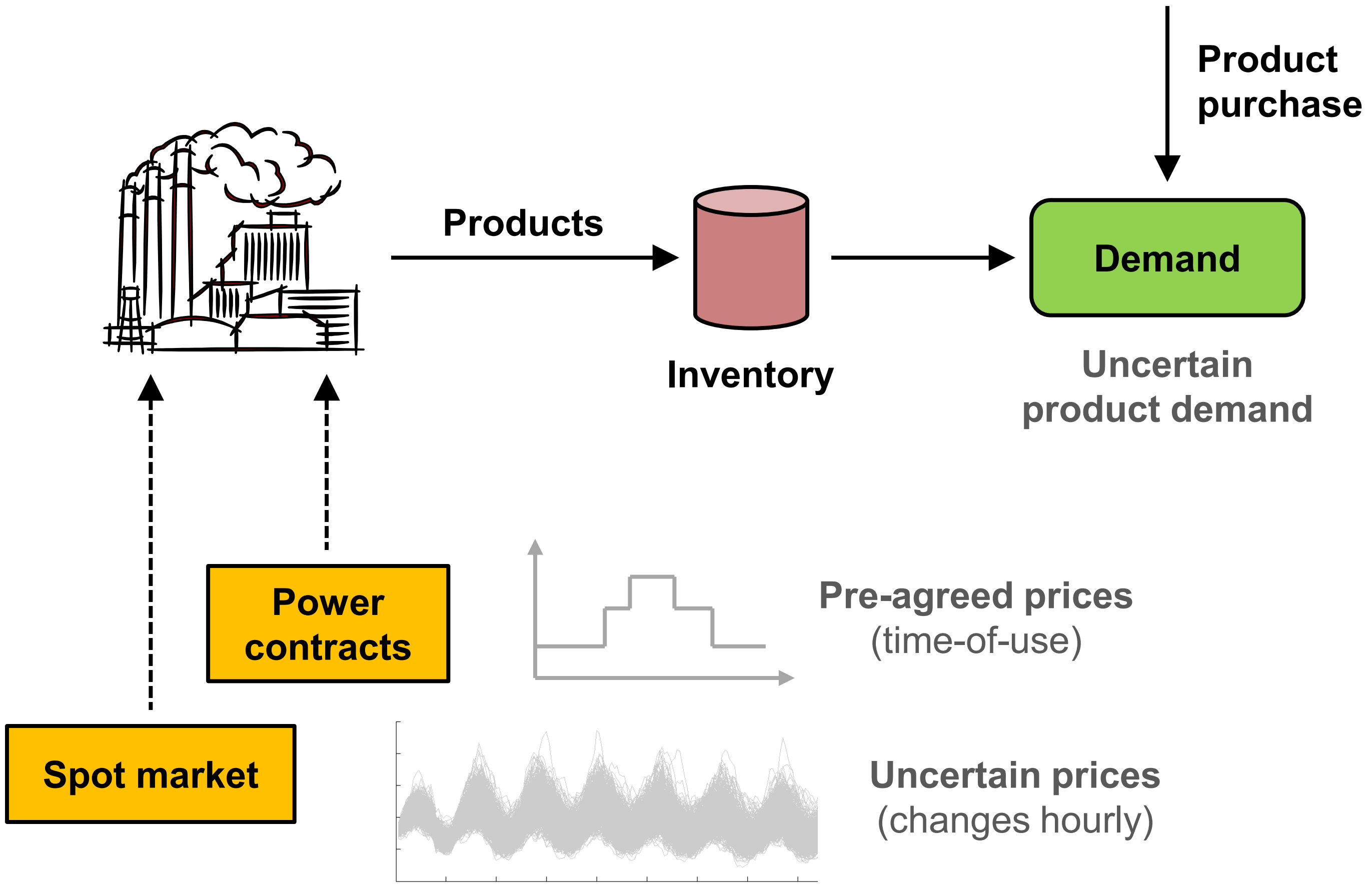
requires detailed production scheduling

	Electricity Purchase	Scheduling Flexibility	Price Uncertainty	Price Discount
Demand Response	spot market	↑	↑	↓
Bilateral Contracting	power contracts	↓	↓	↑

has to be considered in electricity procurement

Trade-off → need to simultaneously optimize both types of operations while considering uncertainty

General Problem Setup



In the particular industrial case study, we consider an air separation plant.

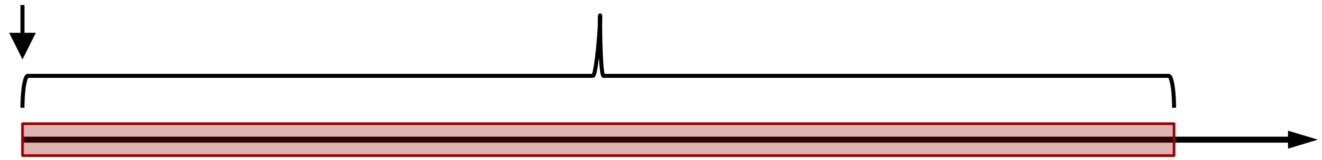
We apply two-stage stochastic programming and incorporate conditional value-at-risk to model the uncertainty/risk.

First-stage decisions

- Selection of operating modes
- Electricity purchase from contracts

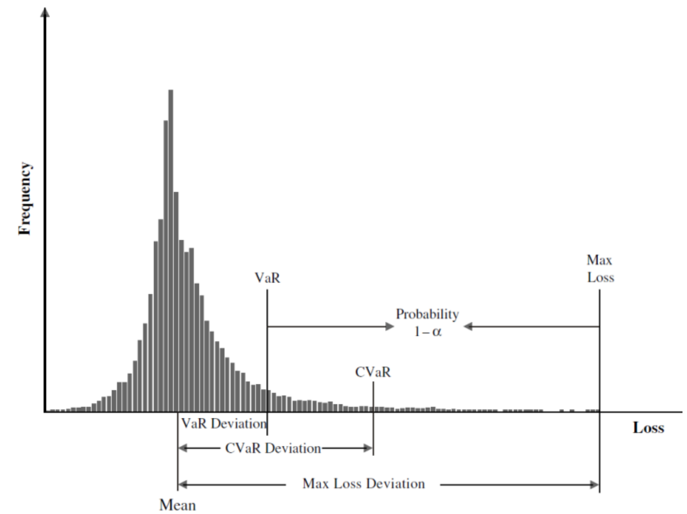
Second-stage decisions

- Production rates
- Electricity purchase from spot market



Scheduling horizon

- Conditional value-at-risk[1] (CVaR) used as risk measure
- α-CVaR is defined as the expected value of the cost greater than the α-quantile of the cost distribution
- Risk-neutral optimization = minimizing total expected cost
- Risk-averse optimization = minimizing weighted sum of total expected cost and CVaR



1. Rockafellar, Uryasev (2000). *Journal of risk*.

Source: Saryakalin et al. (2008)

In risk-neutral optimization with only price uncertainty, deterministic and stochastic models lead to the same results.

Value of Stochastic Solution (VSS):

$$VSS = \text{objective value with 1st–stage decisions from deterministic problem} - \text{objective value with 1st–stage decisions from stochastic problem}$$

$\lvert S^D \rvert$	$\lvert S^P \rvert$	$\lvert \tilde{S}^P \rvert$	Var^P	TC^{det}	TC^{sto}	$\widetilde{VSS}$ [%]
1	1,000	50	low	1.315	1.315	0.0
1	1,000	50	medium	1.314	1.314	0.0
1	1,000	50	high	1.311	1.309	0.1

no demand uncertainty, thus number of demand scenarios is 1

number of price scenarios obtained from scenario reduction

level of price uncertainty

value of considering price uncertainty is practically zero

With demand uncertainty, VSS exists, but considering price uncertainty still does not improve the solution.

$\lvert S^D \rvert$	Var^D	$\lvert S^P \rvert$	$\lvert \tilde{S}^P \rvert$	Var^P	TC^{det}	TC^{sto}	$\widetilde{VSS}$ [%]
5	low	1,000	1	medium	1.342	1.347	0.4
5	low	1,000	50	medium	1.342	1.334	0.6
5	medium	1,000	1	medium	1.404	1.379	1.8
5	medium	1,000	50	medium	1.404	1.378	1.8
5	high	1,000	1	medium	1.596	1.528	4.3
5	high	1,000	50	medium	1.596	1.527	4.3

$\widetilde{VSS}$ for $\lvert \tilde{S}^P \rvert = 1$ and $\lvert \tilde{S}^P \rvert = 50$ are practically the same

In expected cost minimization, explicitly accounting for electricity price uncertainty does not add any additional value.

- **By considering price uncertainty, VSS does not improve**
- Explanation: prices only appear in the objective function, not in the constraints
  → equivalent objective function if power consumption Q_{tdp} is the same for all price scenarios p associated with the same demand scenario d

$$\sum_t \sum_d \varphi_d \sum_p \psi_p \alpha_{tp} Q_{tdp} \approx \sum_t \sum_d \varphi_d \left(\sum_p \psi_p \alpha_{tp} \right) \bar{Q}_{td} = \sum_t \sum_d \varphi_d \, \mathbb{E}(\alpha_t) \bar{Q}_{td}$$

  - For fixed demand and fixed first-stage decisions, $\sum_t Q_{tdp} \approx \text{const.} \; \forall \, p$
  - Price trend remains the same despite uncertainty

Does this mean that accounting for price uncertainty is unnecessary?

- Not if we also consider risk!

In risk-averse optimization, accounting for price uncertainty leads to improved solutions.

Minimizing equally weighted sum of total expected cost and CVaR with $\alpha = 0.8$

$\lvert S^D \rvert$	$\lvert S^P \rvert$	$\lvert \tilde{S}^P \rvert$	Var^P	TC^{det}	CV^{det}	TC^{sto}	CV^{sto}	$\widetilde{VSS}$ [%]
1	1,000	50	low	1.315	1.347	1.316	1.336	0.4
1	1,000	50	medium	1.314	1.389	1.318	1.358	1.0
1	1,000	50	high	1.311	1.482	1.314	1.399	2.9

Now we observe significant value from accounting for price uncertainty

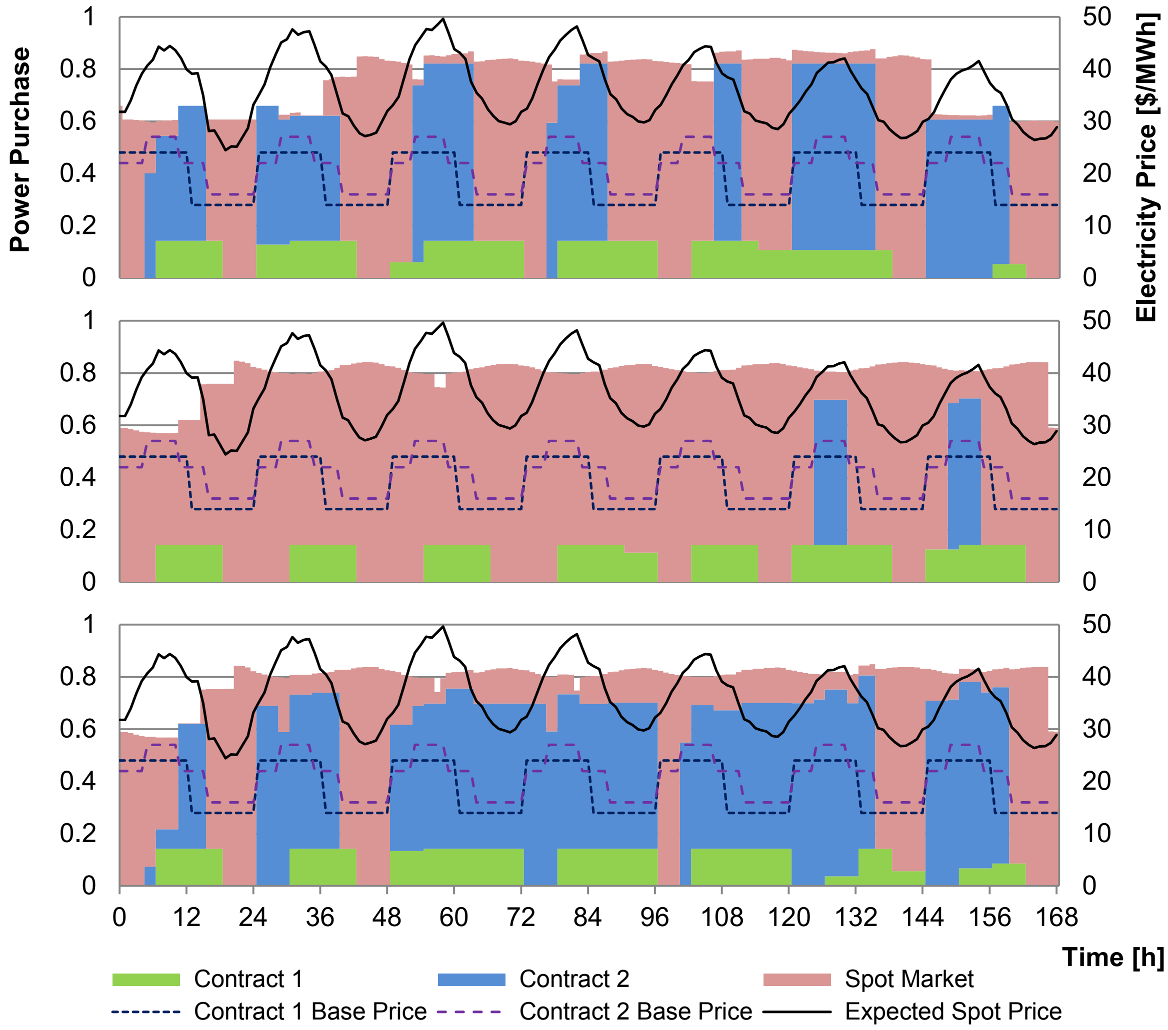
Similar results when considering both price and demand uncertainty

Results from risk-neutral and risk-averse optimization can differ significantly.

Deterministic:
mainly affected by price

Risk-neutral:
purchase from spot market to retain flexibility

Risk-averse:
purchase from contracts to hedge against risk



Novelty and Readiness for Industrial Applications

- **Novelty of the work:**
  - simultaneous optimization of production scheduling and electricity procurement (although not entirely new anymore)
  - accounting for both types of uncertainty (price and demand)
  - detailed analysis of the value of stochastic optimization, in particular the value of risk-averse optimization

- **Readiness for industrial implementation:**
  - framework ready to be deployed after incorporating the appropriate contract model
  - as demonstrated, industrial-size problems can be solved; however, computational time is still significant for large number of scenarios