Optimal Multi-scale Capacity Planning under Hourly Varying Electricity Prices

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Motivation of this work

- **Deregulation** of the electricity markets caused electricity prices to be highly volatile.

- Under the assumption that our decisions do not affect the prices: Can we make strategic investment decisions (**long-term**) to take advantage of the market situation (**short-term**), i.e. reduce costs? (**retrofit**)

- **Challenge**: Multi-scale nature of the problem!
  - Hourly varying electricity prices vs. **10-15 years** investment horizon
  - But: There are **patterns/similarities**
Problem Statement for an Air Separation Plant

**Due to compressors!**

- Electricity costs

**Price forecast**

**Operational Decisions**
- When to produce and amounts?
- Inventory levels?

**Strategic Decisions**
- Additional equipment?
- Additional tanks?
- Equipment upgrade?

Investment Costs

Demand forecast

**Caribbean Mellon**

### Air Separation Plant

<table>
<thead>
<tr>
<th>Gaseous Product</th>
<th>Liquid Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAN Nitrogen</td>
<td>LN</td>
</tr>
<tr>
<td>GAN Argon</td>
<td>LAR</td>
</tr>
<tr>
<td>GOX Oxygen</td>
<td>LOX</td>
</tr>
<tr>
<td>CO2 Carbon Dioxide</td>
<td>HDO</td>
</tr>
<tr>
<td>HC Impurities</td>
<td>-</td>
</tr>
</tbody>
</table>

**Liquid Oxygen**

**Liquid Nitrogen**

**Liquid Argon**

**Gaseous Oxygen**

**Gaseous Nitrogen**
Literature Review

- **Multi-period capacity planning**
  (e.g. Sahinidis et al. (1989), Liu and Sahinidis (1996), van den Heever and Grossmann (1999))
  → Divide planning horizon into time periods
  → Assume constant operating conditions over the time periods

- We need to **incorporate a scheduling representation** that can deal with hourly changing electricity prices.
  (e.g. Castro et al. (2009) for batch scheduling, Ierapetritou et al. (2002), Karwan et al. (2007) and Zhu and Laird (2010) for air separation plants)

- **Multi-period capacity planning = large-scale problems**
  → We need an efficient solution algorithm
  → Bi-level decomposition (Iyer and Grossmann (1998), You et al. (2010))
Overview: Methodology

- **deterministic**
- **stochastic**

**Step 1**
Obtain an efficient model for the short-term scheduling

**Step 2a**
Model the investment decisions: additional equipment, upgrade equipment, add. storage tanks; (retrofit, multi-period)

**Step 2b**
Develop a suitable algorithm to solve the large-scale optimization problem

**Step 3**
Model the uncertainty in electricity prices

- **Single plant**
- **Multiple plants**

operational  
strategic

modeling  
solution method
Operational Representation

- **Feasible region**: projection in product space (here: plant data)
- **Modes**: different ways of operating a plant
- **Transitions**: between modes to enforce e.g. min. uptime/downtime
- **Energy consumption**: requires correlation with production levels
- **Demand constraints**: differences for products with and without inventory

Feasible regions for different modes

State diagrams for transitions (air separation plant)
Year 1, spring: Investment decisions
Year 1, summer: Investment decisions
Year 1, fall: Investment decisions
Year 1, winter: Investment decisions
Year 2, spring: Investment decisions

- Horizon: 5-15 years, each year has 4 periods (spring, summer, fall, winter)
- Each period is represented by one week on an hourly basis
  Varying inputs: electricity prices, demand data, configuration slates
- Each representative week is repeated in a cyclic manner
- Connection between periods: Only through investment decisions
- Investments are modeled by discrete choices
<table>
<thead>
<tr>
<th>Operational</th>
<th>Strategic</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disjunction over the modes that describe the feasible region</td>
<td>Additional storage</td>
<td>Operational</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Logic constraints for transitions (e.g. minimum uptime/downtime)</td>
</tr>
<tr>
<td></td>
<td>Equipment replacement</td>
<td>Mass balances for inventory, constraints related to demand</td>
</tr>
<tr>
<td></td>
<td>Idea: additional modes for which all variables are controlled by the corresponding binary investment variable</td>
<td>Terms for the objective function</td>
</tr>
</tbody>
</table>
Bi-level decomposition algorithm

Solve aggregated problem (AP) (relax transitional constraints) to get a lower bound and investment decisions (VU, VN, VS)

Feasible?

No

Stop

Yes

With fixed investment decisions:
Solve detailed operational problems (DP) for every time period and obtain upper bound

Feasible?

No

Add integer cut that excludes the previously obtained investment decision

Yes

Update the upper bound
If \(||(UB-LB)/UB|| < \text{tolerance: Stop} \)

Idea: Remove most of the transitional constraints and variables

Add design cut, superset cuts and subset cuts

Idea: Infer information on total and operating costs
Strategic Model: Case Study

Superstructure

- Existing equipment
  - Option A
  - Option B (upgrade)
- Additional Equipment

Air Separation Plant

- LN2 1. Tank
- LN2 2. Tank?
- LO2 1. Tank
- LO2 2. Tank?
- LAR 1. Tank
- LAR 2. Tank?

Liquid Oxygen
Liquid Nitrogen
Liquid Argon
Gaseous Oxygen
Gaseous Nitrogen

Time

Spring - Investment decisions: (yes/no)
- Option B for existing equipment?
- Additional equipment?
- Additional Tanks?

Fall - Investment decisions: (yes/no)
- Option B for existing equipment?
- Additional equipment?
- Additional Tanks?
Solution:
- **Buy the new equipment** in the first time period
- Do not upgrade the existing equipment
- Do not buy further storage tanks

Take-away message on the operational level for this case:
Switch off the new equipment when prices are high.

- Bi-level decomposition requires 1.3 hrs. of CPU time (vs. full-space approach: > 5 hrs.)
Conclusion

• We developed a new model for **multi-scale capacity planning** under **varying electricity prices**

• A **computationally efficient operational subproblem** is an important ingredient and was developed as well

• The gap in the **bi-level decomposition** can be closed within one iteration due to a strong relaxation

Outlook

• Description of feasible regions for general models (nonconvex, disjoint)

• **Parallelization** for operational subproblems

• **Uncertainty:**
  - Reduce uncertain parameters
  - Robust Optimization for operational subproblems?
  - Stochastic Programming (recourse)?

• Different types of plants: utility plants, cement plants