Optimal Maintenance Scheduling of a Gas Engine Power Plant

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Introduction

• All industrial sites require regular maintenance to enhance equipment reliability & avoid emergency shutdowns
  – Main concern of maintenance scheduling is to minimize payment for skilled labor
  – Plants or equipments will maintain separately
• Generator maintenance one of the most significant problems in power systems operation & management
  – Tries to avoid unplanned and costly power outages
  – Affects many short- and long-term planning functions
    • Unit commitment, fuel scheduling, etc.
• Project objectives:
  – Address the maintenance scheduling problem of a power plant involving multiple shutdowns for each generator
  – Saving online hours for the season with highest electricity pricing
  – Incorporate practical, very challenging scheduling constraints
  – Approach is to generate MILP starting from GDP model

Problem statement

• Gas Engine Power Plant Project in Sasolburg (SGEPP)
  – 18 identical gas engines consuming natural gas & producing electricity
    • Generation capacity per engine \( p_w \) = 10 MW
  – Only 1 maintenance team doing shutdowns
• Shutdown period \( s\text{d}_t \) mandatory after \([p_t^L, p_t^U]\) h of online operation

<table>
<thead>
<tr>
<th>Shutdown period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_t^L ) (h)</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
<td>1500</td>
<td>1500</td>
<td>...</td>
</tr>
<tr>
<td>( p_t^U ) (h)</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>3000</td>
<td>2500</td>
<td>3000</td>
<td>...</td>
</tr>
<tr>
<td>( s\text{d}_t )</td>
<td>12</td>
<td>72</td>
<td>12</td>
<td>96</td>
<td>12</td>
<td>120</td>
<td>132</td>
<td>1432</td>
<td>12</td>
<td>...</td>
</tr>
</tbody>
</table>

• Challenging (hard) constraints
  – Minimum power output \( p_w^L = 100 \) MW
  – Maximum power output limited during 3 weeks/year, \( p_w^U = 140 \) MW
  – Maintenance team unavailable around Christmas
• Objective is to schedule maintenance shutdowns so as to maximize revenue for a given \# shutdown periods
  – While taking into account seasonal variations in electricity pricing

Mathematical formulation (MILP)

• Main features
  – Continuous-time formulation with one time grid per time engine
    • Time slots correspond to maintenance periods (see below)
    – Easy to generate linear timing constraints
    – Difficult to generate complex constraints involving binary variables
• Modeling approach
  – First formulate constraints in Generalized Disjunctive Programming (GDP) format
  – Use standard big-M and convex hull reformulations to generate complete MILP from GDP
• Minimum power output constraint not requiring GDP
  – Handled by ensuring that (first) 11 gas engines are never idle (either online or in shutdown mode)
Timing constraints

- Enforce bounds on timing variables to improve performance
  - Lower bounds are exact, upper bounds are heuristic

Unavailability of maintenance team

- Precedence variables
  - \( Z_{m,t,u} \) shutdown task \((t, m)\) ends before start of unavailable period \( u \)
- Big-M convex hull

Power output cannot exceed demand

- General precedence sequencing variables
  - Binary variables \( Y_{m,t,m'} \)
    - Shutdown in slot \( t \) of engine \( m \) starts before shutdown in slot \( t' \) of engine \( m' \)
    - Since engines are identical
      - \( Y_{m,t,m} = 1 \) \( \forall t, t', m > m \)
- Big-M more efficient than hull reformulation (same relaxation)

Single maintenance team constraint

- Low demand period \( t_d \)
  - \( X_{m,t,d} \) power output = demand
  - \( Y_{m,t,d} \) time period \( t_d \)

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Accounting for electricity pricing periods

<table>
<thead>
<tr>
<th>Period</th>
<th>tp = 1</th>
<th>tp = 2</th>
<th>tp = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location type</td>
<td>A_{1,tp} = True</td>
<td>A_{2,tp} = True</td>
<td>A_{3,tp} = True</td>
</tr>
<tr>
<td>Constant price</td>
<td>c_{tp}</td>
<td>c_{tp}</td>
<td>c_{tp}</td>
</tr>
<tr>
<td>Constant price period</td>
<td>1 to 2</td>
<td>2 to 3</td>
<td>3 to 4</td>
</tr>
</tbody>
</table>

Maximum power input

Reorganizing the disjunctions

\[
\begin{align*}
A_{1, tp} &\lor B_{2, tp} \lor C_{3, tp} \lor D_{4, tp} \\
A_{1, tp} &\lor B_{2, tp} \lor C_{3, tp} \lor D_{4, tp} \\
A_{1, tp} &\lor B_{2, tp} \lor C_{3, tp} \lor D_{4, tp} \\
A_{1, tp} &\lor B_{2, tp} \lor C_{3, tp} \lor D_{4, tp} \\
A_{1, tp} &\lor B_{2, tp} \lor C_{3, tp} \lor D_{4, tp} \\
\end{align*}
\]

• Leads to fewer & tighter constraints
  – e.g. Big-M reformulation

Computational results

• Testing of various reformulation strategies

<table>
<thead>
<tr>
<th>Model</th>
<th>Reformulation</th>
<th>BB-1</th>
<th>BB-2</th>
<th>Hybrid</th>
<th>Hull</th>
<th>Hull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single maintenance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Unavailability of maintenance</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Interaction with electricity price periods (slide 3)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

• Key results for \( M^{ON} = \{1, ..., 9\} \) (pw\(^c\)=80 MW)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>BB-1</th>
<th>BB-2</th>
<th>Hybrid</th>
<th>Hull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>83.64</td>
<td>-</td>
<td>83.64</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>127.31</td>
<td>-</td>
<td>127.31</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>183.64</td>
<td>-</td>
<td>183.64</td>
<td>-</td>
</tr>
</tbody>
</table>

Computational results (cont.)

• Problem easier to solve if flexibility in online hours is reduced
  – More constrained problem leading to slightly worse solutions
  \( p_{f}>0 \) h v t

<table>
<thead>
<tr>
<th>Reformation</th>
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<th>Hull</th>
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<tbody>
<tr>
<td>[F(^\prime)]</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Revenue (%)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CPUs (%)</td>
<td></td>
<td></td>
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<tr>
<td>Gap (%)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Total variables</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total equations</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Equations (% of I.G.)</td>
<td></td>
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• Major differences in problem size and integrality gap
  – Reorganizing the disjunctions improves both KPIs (BM-2<BM-1)

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<tbody>
<tr>
<td>[F(^\prime)]</td>
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<td></td>
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</tr>
<tr>
<td>Total variables</td>
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<tr>
<td>Total equations</td>
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<tr>
<td>Equations (% of I.G.)</td>
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Plan for 12 shutdowns (≈3 full years)

- Main results
  - $251.4 \times 10^6$
  - Max 1 engine in shutdown mode in winter
- Results for $\omega = 80$ MW
- All constraints are met
- Major bottleneck start of year 3
- Need to study benefits from 2 teams

Conclusions & future work

- Model efficiently taking into account major scheduling constraints
  - Very good computational performance
    - allows to consider 3 full years of operation
  - Clear identification of process bottlenecks
- Can be used as key element of decomposition strategy to generate 10-year plan
  - Rolling horizon approach potentially allows for a larger number of unavailability time periods
- No maintenance on Sundays
- Future work
  - Cost benefit analysis of using 2 teams instead of 1 around the 432 h shutdown periods
  - Explore hull reformulation of constraints in slide 9
  - Ways of handling terminal constraints
  - Other aspects or problems to be defined during EWO Fall meeting
    - Pittsburgh, September 4-5, 2013