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Bi-level Heuristic for Steel Production Scheduling with Electricity Costs Optimization
Challenges of Present and Future Grid
Interest in Active Load Management

Renewables Expansion

Demand & Supply

Market Liberalization

GRID STABILITY AND RELIABILITY

ENVIRONMENTAL POLICIES AND INVESTMENT COSTS

NEW MARKETS

Demand-Side Management

Sources:
(1) Pina et. Al, 2012
(2) EPEX SPOT France, 2012
Scheduling of Energy-Intensive Processes
Melt Shop of Stainless Steel Plant

- Batch process with semi-continuous stage $st_4$ (CC)
- Parallel, non-identical equipment $m$
- Equipment specific setup $t_{m}^{setup}$ and transportation times $t_{m,m'}^{min}$
- Max hold up times $t_{m,m'}^{max}$ between stages

Scheduling of Energy-Intensive Processes

Energy Management Aspects

Multiple contracts – time dependent price levels

- Pre-agreed load curve – penalties for deviation

- Demand from production process

- On-site generation – with special constraints

- Selling back to grid
Problem statement

Questions to be answered

- Problem complexity
  - Approach 1: Energy-aware scheduling with fixed assignment and sequencing
  - Approach 2: Scheduling decisions are also optimized

- Modeling challenges
  - Extending the continuous-time formulation with energy-awareness
  - Embedding the energy purchase optimization into the problem
  - Decomposing the problem for large scale instances

Note: time_slots due to electricity cost accounting
Solution Approach
Monolithic Model Structure

Production scheduling
  – general precedence model

Electricity consumption accounting
  – event binaries

Electricity purchase optimization
  – min cost flow network

Load deviation response
  – committed load problem

Obj. function

\[
\min \left( \text{weight} \cdot \text{makespan} + \text{net consumption cost} + \text{deviation penalties} \right)
\]
Model the relation between tasks and time slots through a discrete time-grid (*MILP*)

- Task contribution to electricity consumption [min] of a time slot
- Event binaries denoting start or finish of a task

Production task

Time spent within a time slot

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Each arc is defined by parameters and flow volume variable

\[ \text{[TimeSlot, MinFlow, MaxFlow, Cost, Flow]} \]

\[ \sum_{i \in \text{Sources}} \text{flow}_{i,j} = k \epsilon \]

\forall j \in \text{Balance}
Energy Purchase Optimization
Electricity Flow Network

Node i1: Base load contract
Node i2: Time-of-use contract
Node i3: Day-ahead spot market
Node i4: Onsite generation
Node i5: Balance node
Node i6: Sales to grid
Node i7: Process demand – to be always satisfied

Source of electricity
Balancing area
Sink of electricity
Approach 1: All Scheduling Binaries Fixed – Industrial Case Study
24h horizon and 20 products

- Good quality solutions (gap<2%) obtained always in few seconds
  - \(~109k\) equ, \(~29k\) var, \(~5k\) binaries, solving to optimality: 2~700s
- Computational problems when product sequence not known

<table>
<thead>
<tr>
<th>TOU [MWh]</th>
<th>Day-ahead [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net cost [k€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

- 1. High prices of spot
- 2. Low prices of spot
- 3. No base load
- 4. Sales as high spot
- 5. Flow minimal schedule
Bi-level heuristic
General approach

- Approximation of the original monolithic problem
- Full problem with fixed difficult binary decisions
Bi-level heuristic
General approach

Elaborate evaluated solutions, reduce the search space

- Approximation of the original monolithic problem
- Full problem with fixed difficult binary decisions

Stopping criteria met?

Upper level $UL$

- Full problem with fixed difficult binary decisions

$stop$

- Approximation of the original monolithic problem

$impose$ $cuts$

no

fix $decisions$

Lower level $LL$
Bi-level heuristic
Algorithm flow

Upper level $UL$
(EAF-CC)
Find rough schedule

- update assignment on EAF
- If $g_{\text{iter}}^{LL1} > \beta$
- cut previous solution;
- else
- cut previous solution and the range of time slots for event start;

Lower level $LL1$
(all stages)
Find full schedule

- fix assignment on EAFs
- fix sequence on CCs
- constrain event start to occur within a range of time slots

Lower level $LL2$
(all stages)
Find better EAF assignment

- fix assignment on AODs, LFs, CCs
- fix all sequences
- fix event start to particular time slot

stop
CPUs limit reached?

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## Approach 2: Scheduling Decisions to be Optimized – Industrial Case Study

### Heuristic vs Monolithic

<table>
<thead>
<tr>
<th>Instance</th>
<th>Model type</th>
<th>Binary vars</th>
<th>Total vars</th>
<th>Equations</th>
<th>MIP solution 600s</th>
<th>Relative gap 600s</th>
<th>Heuristic Iterations (Best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 h, 20 products, high prices spot</td>
<td>Monolithic 1</td>
<td>3 921</td>
<td>29 508</td>
<td>102 335</td>
<td>239 195</td>
<td>26%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Heuristic 1</td>
<td>LL2: 1 458</td>
<td>LL2: 29 508</td>
<td>LL2: 102 335</td>
<td>193 852</td>
<td>9.3%</td>
<td>5(4)</td>
</tr>
<tr>
<td>24 h, 20 products, low prices spot</td>
<td>Monolithic 2</td>
<td>3 921</td>
<td>29 508</td>
<td>102 335</td>
<td>193 626</td>
<td>21%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Heuristic 2</td>
<td>LL2: 1 458</td>
<td>LL2: 29 508</td>
<td>LL2: 102 335</td>
<td>165 198</td>
<td>7.2%</td>
<td>5(3)</td>
</tr>
<tr>
<td>24 h, 16 products, high prices spot</td>
<td>Monolithic 3</td>
<td>3 205</td>
<td>23 428</td>
<td>80 528</td>
<td>182 065</td>
<td>13%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Heuristic 3</td>
<td>LL2: 1 276</td>
<td>LL2: 23 428</td>
<td>LL2: 80 528</td>
<td>174 249</td>
<td>8.5%</td>
<td>3(1)</td>
</tr>
<tr>
<td>18 h, 12 products, high prices spot</td>
<td>Monolithic 4</td>
<td>2 055</td>
<td>13 348</td>
<td>45 509</td>
<td>201 961</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Heuristic 4</td>
<td>LL2: 856</td>
<td>LL2: 13 348</td>
<td>LL2: 45 509</td>
<td>195 160</td>
<td>4.2%</td>
<td>4(1)</td>
</tr>
</tbody>
</table>

- Objective function value always better than monolithic
- Gap always better than monolithic
Model Results

Gantt Chart example

- Fixed sequence and assignment
Benefits and limitations

- Continuous-time is challenging but benefits from exactness
- Cost reduction realized by energy-aware scheduling
- Very large instances still intractable, even with heuristic

Further work

- One-sided Mean Value Cross-decomposition on monolithic formulation to functionally separate energy purchase from production scheduling
- Application to other industrial cases

Acknowledgment

- We would like to acknowledge the Marie Curie FP7-ITN project "Energy savings from smart operation of electrical, process and mechanical equipment– ENERGY-SMARTOPS", Contract No: PITN-GA-2010-264940 for financial support
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