A bi-level heuristic for steel plant scheduling under complex time-sensitive price structures
Challenges of Present and Future Grid
Interest in Active Load Management

- Renewables Expansion
  - Smart grid
  - Solar
  - Wind
  - Grid stability and reliability

- Demand & Supply
  - Need for peak load (1)
  - Environmental policies and investment costs

- Market Liberalization
  - Variable electricity prices (2)
  - 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


Electric Arc Furnace (EAF)
Argon Oxygen Decarburization (AOD)
Ladle Furnace (LF)
Continuous Casting (CC)

scrap metal load → $m_1$ → heat $p$ → $m_2$ → heat $p$ → $m_3$ → heat $p$ → $m_4$ → heat $p$ → $m_5$ → heat $p$ → $m_6$ → heat $p$ → $m_7$ → heat $p$ → $m_8$ → steel slab

power $[MW]$ vs. time $[min]$
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 $t_{m}^{\text{setup}}$ and transportation times $t_{m,m'}^{\text{min}}$
- Max hold-up times $t_{p,st}^{\text{max}}$ 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

\[
\min \left( \text{weight} \cdot \text{makespan} \right) + \text{net consumption cost} + \text{deviation penalties}
\]
Each arc is defined by parameters and flow volume variable

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

\[ \sum_{i \in \text{Sources}} \text{flow}_{i,j} = \sum_{k \in \text{Sinks}} \text{flow}_{j,k} \quad \forall j \in \text{Balance} \]
Energy Purchase Optimization
Electricity Flow Network

- Base load contract
  - Node i1

- Time-of-use contract
  - Node i2

- Day-ahead spot market
  - Node i3

- Onsite generation
  - Node i4

- Source of electricity

- Balancing area
  - Node i5

- Sink of electricity
  - Node i6
  - Node i7

- Sales to grid

Process demand – to be always satisfied
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
Bi-level heuristic
General approach

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

Upper level $UL$

$add\ cuts$

- Eliminate evaluated solutions, reduce the search space

Lower level $LL$

Stopping criteria met?

Fix decisions
Bi-level heuristic

Algorithm flow

start

Upper level $UL1$
(EAF-CC)
Find rough schedule

If $gap_{iter}^{LL1} > \beta$
cut previous solution;
else
cut previous solution
and
the range of time slots for
event start;

update assignment on EAF

no

CPUs limit reached?

Upper level $UL2$
(all stages)
Find better EAF assignment

fix assignment on AODs, LFs
fix all sequences (based on global sequence)
fix event start to particular time slot

yes

stop

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

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

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

**Heuristic vs Monolithic (GAMS/CPLEX v23.7)**

<table>
<thead>
<tr>
<th>Instance</th>
<th>Model type</th>
<th>Model statistics</th>
<th>Min objective 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>4 065</td>
<td>25 443</td>
<td>102 335</td>
<td>247 838</td>
</tr>
<tr>
<td></td>
<td>Heuristic 1</td>
<td>UL2: 1 458</td>
<td>UL2: 28 050</td>
<td>UL2: 102 335</td>
<td>193 845</td>
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<tr>
<td>24 h, 20 products, low prices spot</td>
<td>Monolithic 2</td>
<td>4 065</td>
<td>25 443</td>
<td>102 335</td>
<td>200 038</td>
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<tr>
<td></td>
<td>Heuristic 2</td>
<td>UL2: 1 458</td>
<td>UL2: 28 050</td>
<td>UL2: 102 335</td>
<td>165 196</td>
</tr>
<tr>
<td>24 h, 16 products, high prices spot</td>
<td>Monolithic 3</td>
<td>3 229</td>
<td>20 199</td>
<td>80 528</td>
<td>155 226</td>
</tr>
<tr>
<td></td>
<td>Heuristic 3</td>
<td>UL2: 1 276</td>
<td>UL2: 22 152</td>
<td>UL2: 80 528</td>
<td>134 588</td>
</tr>
</tbody>
</table>

- What if the plant over-commits expected electricity consumption?

| 24 h, 16 products, high prices spot, agreed load as for 20 products | Monolithic 4 | 3 229 | 20 199 | 80 528 | 204 173 | 22,50% | - |
| Heuristic 4 | UL2: 1 276 | UL2: 22 152 | UL2: 80 528 | 176 006 | 8,71% | 4(3) |
Model Results

Gantt Chart example

**Makespan – driven schedule**

**Electricity price**

**Electricity cost – driven schedule**
Summary Discussion
Conclusions and Further Work

- Benefits and limitations
  - Cost reduction realized by energy-aware scheduling
  - Very large instances still intractable, even with heuristic
  - No lower bound from upper level problem results in no convergence behavior

- Further work
  - One-sided Mean Value Cross-decomposition on monolithic formulation to functionally separate energy purchase from production scheduling
  - Application to pulp and paper industry

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