Optimising workforce and energy costs by exploiting production flexibility

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Context

What if November 2016 becomes usual?

Steel mill consumption: ~ 50 MWh / 100 tonnes

Cost: 35,900€ for 100 tonnes
Thus...

electrical flexibility

• Flexibility is about exploiting those price fluctuations to lower the costs

• Some possible answers?
  • **Load shifting**: produce later
  • **Load shedding**: avoid producing
  • **Fuel switching**: gas instead of electricity, e.g.
What we want

Use the machines when the prices are low
What limits flexibility?

- **Price prediction**: highly dependent on weather
  - Good predictions for a few days
  - Useless after a week

- **Processes are not always flexible**
  - Some cannot be switched on and off on demand, e.g.

- What about the **workers**? They need:
  - Schedule predictability
  - Schedules that barely impact health
Overview of this talk

- InduStore
- Methodology
  - Production model
  - HR model
- Evaluation
- Conclusions and future work
InduStore

Two goals: *quantify* and *exploit* electrical flexibility

http://www.industore-project.be/
InduStore highlights energy flexibility in industrial sites

- How sizeable is flexibility?
- How to reconcile flexibility and workers well-being?
- How to exploit this flexibility by optimal production planning?
- How to bring flexibility on the energy market?
Our methodology

How to exploit electrical flexibility in industrial sites?
Three different time scales

• Hence, decompose in three steps:
  • Long term: workers shifts, approximate production plan
  • Medium term: production plan
  • Short term: adapt production plan

• Focus on long-term planning

More HR flexibility

Better price predictions
How do we exploit flexibility?

• Long term: two optimisation models

  • First, **production**: when are workers required?
    → Workers are modelled as a cost

  • Second, **HR**: who works when?
    → Well-being-related constraints
How do we deal with the long-term planning?
Production model

Goals:
• Estimate a production planning
• Determine when workers are needed
Production model

Determine a production planning

- Orders
- Processes
- Electricity prices

Approximate plant model

- Workers shifts
- Production planning
Which level of details for the plant?

- A rough model is enough
  - Except if a process is not well approximated
- The details are for shorter-term optimisation

<table>
<thead>
<tr>
<th>Rough model</th>
<th>Fine model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any process lasts 1 h</td>
<td>Some processes take 30 min, others 45 min</td>
</tr>
<tr>
<td>Consumption is constant with production, fixed batch size</td>
<td>Consumption is linear, quadratic...</td>
</tr>
<tr>
<td>Some stages are ignored</td>
<td>All stations are included</td>
</tr>
<tr>
<td>No wait time between processes</td>
<td>Wait time can be optimised</td>
</tr>
</tbody>
</table>
A glimpse of the MILP formulation

- **Decision variables:**
  - Are workers required? \( \text{shiftOn}_s \in \{0,1\}, \forall s \)
  - Is the process on? \( \text{processOn}_{t,p} \in \{0,1\}, \forall t, \forall p \)
  - What quantity is being processed? \( \text{quantity}_{t,p} \geq 0, \forall t, \forall p \)

- **Objective:** minimise costs
  \[
  \min \sum_s \text{cost}_s \text{shiftOn}_s + \sum_t \text{price}_t \sum_p \text{processOn}_{t,p}
  \]

- **Constraints:**
  - Process started only if workers are present
  - Process succession
  - Fixed batch size
  - Order book
HR model

Goal: assign shift to worker teams
Respect legal and well-being constraints
HR model

Assign teams to shifts

Shift workers must have some rest between two shifts
HR model

Assign teams to shifts

Shift workers also need a WE, i.e. a pair of days off every so often
HR model

Assign teams to shifts

Shift workers should work no more than 50 hours per week

- Otherwise, overtime
• Decision variable:
  • Is a team assigned to a shift? \( \text{assigned}_{s,t} \in \{0,1\}, \forall s, \forall t \)

• Constraints:
  • Assign workers when they are needed
  • Rest between shifts: if working shift \( s \), cannot work any shift within the set of forbidden shifts \( \text{FS}(s) \)
  • \( \text{WE} \): detect pairs of days off; at least one pair for each period of nine consecutive days
  • 50 hours per week: less than 50 hours per week... plus slack (for overtime)
Objective function

- Maximise well being, i.e. minimise:
  - Hours overtime
  - Number of changes against previous solution
  - Unfairness in the number of shifts for each team
Evaluation

Axes:

• Computation times
• Monetary gains
• These problems are easy to solve
  • Mixed-integer programs with a horizon of 2 weeks
  • Mill used 50-85% of the time, staffed with 5 teams

Production model: 90% below 0.1s, 100% below 30s
HR model: 90% below 0.5s, 100% below 5 minutes

Statistics based on 6 order books, 18 price scenarios, 4 penalisation weights
Monetary gains

Compare this “smart” approach to:

• A usual industrial scenario
  • Independent of price scenario
  • No flexibility

• A softened version of our approach:
  • Cannot reconsider shifts once they are decided
  • Weaker flexibility
### Monetary gains

<table>
<thead>
<tr>
<th>Approaches</th>
<th>HR cost</th>
<th>Electricity cost</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>High flexibility</td>
<td>974,426</td>
<td>752,689</td>
<td>1,727,114</td>
</tr>
<tr>
<td>Low flexibility</td>
<td>1,023,973</td>
<td>+ 5.1%</td>
<td>1,928,297</td>
</tr>
<tr>
<td>Current situation</td>
<td>1,289,920</td>
<td>+ 32.4%</td>
<td>2,269,125</td>
</tr>
</tbody>
</table>

#### Graph

- **High flexibility**
- **Low flexibility**
- **Current situation**
Conclusions and future work
Conclusion

• From 20th-century planning to full flexibility:
  ➢ Could **save 30%** in costs!

• **Implementation must be discussed:**
  • Complete mentality change
  • Workers and directors not always ready

• **Objective** elements to foster thinking

• **Try it for yourself!**
Future work

- Some HR flexibility not yet exploited:
  - What about \textit{variable} shift lengths?
  - E.g., if 4 consecutive hours are very cheap

- For now: fixed to 8 hours, distinction between morning/afternoon/night shifts

- Price uncertainty not explicitly modelled
Thank you for your attention!

Questions?
Back up
• Main decision variables:
  • Are workers required?
    \[ \text{shiftOn}_s \in \{0,1\}, \forall s \in \text{shifts} \]
  • Is the process on?
    \[ \text{processOn}_{t,p} \in \{0,1\}, \forall t \in \text{time steps}, \forall p \in \text{processes} \]
  • What quantity is being processed?
    \[ \text{quantity}_{t,p} \geq 0, \forall t \in \text{time steps}, \forall p \in \text{processes} \]
• Objective: minimise the costs

\[ \min \sum_{s \in \text{shifts}} \text{cost}_s \text{shiftOn}_s \]
\[ + \sum_{t \in \text{time steps}} \text{price}_t \sum_{p \in \text{processes}} \text{processOn}_{t,p} \]

• Could have more precise consumption model: linear, quadratic, etc.
• Constraints:
  • A process can be on only if workers are present
    \[ \text{processOn}_{t,p} \leq \text{shiftOn}_s, \]
    \[ \forall p \in \text{processes}, \forall s \in \text{shifts}, \forall t \in s \]
  • A process can be used only if it is on; the batch size is fixed
    \[ \text{quantity}_{t,p} = \text{quantity}_{p}^{\text{max}} \text{processOn}_{t,p}, \]
    \[ \forall p \in \text{processes}, \forall t \in \text{time steps} \]
Production model 4/4

- Constraints:
  - The processes follow each other and last one time step
    \[
    \text{quantity}_{t,\text{lf}} = \alpha \text{quantity}_{t-1,\text{eaf}}, \\
    \text{quantity}_{t,\text{cc}} = \text{quantity}_{t-1,\text{lf}}, \\
    \text{quantity}_{t,\text{out}} = \text{quantity}_{t-1,\text{cc}}, \\
    \forall t \in \text{time steps}
    \]
  - Transformation factor between EAF and LF: some losses between the input raw material and the molten steel
  - The order book must be respected
    \[
    \sum_{\tau \leq t} \text{quantity}_{\tau,\text{out}} \geq \text{totalOrderedQuantityUpTo}_{t}, \\
    \forall t \in \text{time steps}
    \]
HR model (1/6)

- Decision variable:
  - Is a team assigned to a shift?
    \[ \text{assigned}_{s,t} \in \{0, 1\}, \quad \forall s \in \text{shifts}, \forall t \in \text{teams} \]

- Major constraint: are workers required?
  \[ \sum_{t \in \text{teams}} \text{assigned}_{s,t} = \text{required}_s, \quad \forall s \in \text{shifts} \]
Shift workers must have some rest between two shifts

Notion of “forbidden shifts”

- If working shift $s$, cannot work any shift within FS

$$\sum_{u \in \text{FS}(s)} \text{assigned}_{t,u} \leq 1 - \text{assigned}_{t,s},$$

$\forall s \in \text{shifts}$
HR model

(3/6)

- Shift workers also need a "WE, i.e. a pair of days off every so often"
  - Detect pairs of days off
    - New variable: does the team work in the given pair of days?
      \( \text{inPair}_{d,t} \in \{0,1\}, \forall d \in \text{days}\setminus \{\text{last day}\}, \forall t \in \text{teams} \)
    - Detect those pairs with shifts (6 shifts for 2 days off):
      \( \text{inPair}_{d,t} \leq 1 - \frac{\sum_{s \in d} \text{assigned}_{t,s}}{6}, \forall d \in \text{days}\setminus \{\text{last day}\}, \forall t \in \text{teams} \)
    - For each period of nine days, at least one pair:
      \( \sum_{\delta = \delta_0}^{d+8} \text{inPair}_{\delta,t} \geq 1, \forall d \in \text{days}\setminus \{9 \text{ last days}\}, \forall t \in \text{teams} \)
Shift workers should work no more than 50 hours per week
  
Overtime is still allowed, though!
  
- New variable: amount of overtime
  \[ \text{overtime}_{t,w} \geq 0, \forall w \in \text{weeks}, \forall t \in \text{teams} \]
  
- One shift lasts 8 hours
  \[
  \sum_{s \in w} 8 \text{ assigned}_{t,s} \leq 50 + \text{overtime}_{t,w},
  \]
  \[ \forall w \in \text{weeks}, \forall t \in \text{teams} \]
HR model (5/6)

- On average, shift workers should work 38 hours per week
  - The average is computed on 13 weeks
  - Hard to implement! Need for a trick!
Budget of hours

- Use a *heuristic* 2-week budget
  - Try to have *at least X* hours, *at most Y* hours
  - Minimise budget violation

- Leaves some freedom for the current 2 weeks
- Keep margin for the weeks to come
• The implementation of the budget of hours is straightforward:

\[
\min \leq \sum_{s \in \text{shifts}} 8 \text{ assigned}_{t,s} \leq \max
\]

• In practice: with slacks to avoid too quick infeasibility
Working conditions

Monitor several KPIs:
- Physiological KPIs
- Social KPIs
- Economical KPIs

Summarised in a complete visualisation
### Physiological KPIs (14 days)

<table>
<thead>
<tr>
<th>Team</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence night–rest</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sequence rest–night</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clockwise transitions (MA, AN, NM)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Counterclockwise transitions (AM, MN, NA)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No transition (MM, AA, NN)</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Night shifts</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Average hours per day</td>
<td>3.4</td>
<td>3.4</td>
<td>4.0</td>
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<tr>
<td>Total shifts</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Diff. with max (%)</td>
<td>14.2857</td>
<td>14.2857</td>
<td>0.0000</td>
<td>14.2857</td>
<td>14.2857</td>
</tr>
<tr>
<td>Total wage</td>
<td>6000.00</td>
<td>6000.00</td>
<td>7000.00</td>
<td>6000.00</td>
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<tr>
<td>Hourly wage</td>
<td>125.00</td>
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</tr>
</thead>
<tbody>
<tr>
<td>Morning shifts</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>WE shifts</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

### Economical KPIs (14 days)

<table>
<thead>
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<th>Team</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total shifts</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Diff. with max (%)</td>
<td>14.2857</td>
<td>14.2857</td>
<td>0.</td>
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<td>0.</td>
<td>14.2857</td>
<td>14.2857</td>
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<tr>
<td>Hourly wage</td>
<td>125.</td>
<td>125.</td>
<td>125.</td>
<td>125.</td>
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</tbody>
</table>