Modelling industrial flexibility from the electricity consumption and the human resources points of view

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Context

What if November 2016 becomes usual?

Steel mill consumption: ~ 50 MWh / 100 tonnes
Thus...

**electrical flexibility**

- Flexibility is about **exploiting those price fluctuations** to lower the costs

- Some possible answers?
  - Use gas instead of electricity
  - Produce less and/or later
  - Don’t produce

- Not possible with all processes...
Example of result

Use the machines when the prices are low

Price scenario

High prices: low consumption

Low prices: high consumption

Melt (EAF)

Transform (LF)

Cast (CC)
What limitations flexibility?

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

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

- InduStore
- Methodology
  - Production model
  - HR model
- Evaluation
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
  - Further split into production and HR

- Better price predictions

- More HR flexibility
How do we exploit flexibility?

• Long term: two subproblems
  • First, production: when are workers required? → HR is a cost
  • Second, HR: who works when? → Well-being-related constraints
  • Horizon: limited by electricity price prediction
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
Determine a production planning horizon?
- Long enough to have a significant order book
- Small enough to have good price predictions

What about HR considerations?
- Workers are “just” a cost
  - Roughly 1000€ for a team during one hour
- No specific constraint for well-being
Which level of details for the plant?

<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 rough model is enough
  - Except if a process is not well approximated
- The details are for the short-term optimisation
What does the model look like?

• 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?
    \[ \text{quantity}_{t,p} \geq 0, \]
    \[ \forall t \in \text{time steps}, \forall p \in \text{processes} \]
What does the model look like?

- Objective: minimise the costs

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

- Could have more precise consumption model: linear, quadratic, etc.
What does the model look like?

• 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
  \( \text{quantity}_{t,p} = \text{quantity}_p^{\text{max}} \text{processOn}_{t,p} \),
    \( \forall p \in \text{processes}, \forall t \in \text{time steps} \)
What does the model look like?

• **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

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

Assign teams to shifts

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

• Major constraint: are workers required?
  \[ \sum_{t \in \text{teams}} \text{assigned}_{s,t} = \text{required}_s, \]
  \[ \forall s \in \text{shifts} \]
### HR model

#### Assign teams to shifts

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
<th>Day 6</th>
<th>Day 7</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Day 8</td>
<td>Day 9</td>
<td>Day 10</td>
<td>Day 11</td>
<td>Day 12</td>
<td>Day 13</td>
<td>Day 14</td>
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<td></td>
</tr>
<tr>
<td>Day 15</td>
<td>Day 16</td>
<td>Day 17</td>
<td>Day 18</td>
<td>Day 19</td>
<td>Day 20</td>
<td>Day 21</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

- 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

Assign teams to shifts

- 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:
    \[
    \sum_{\delta = d}^{d+8} \text{inPair}_{\delta,t} \geq 1, \forall d \in \text{days}\setminus \{9 \text{ last days}\}, \forall t \in \text{teams}
    \]
**HR model**

Assign teams to shifts

- **Day 1**
- **Day 2**
- **Day 3**
- **Day 4**
- **Day 5**
- **Day 6**
- **Day 7**
- **Day 8**
- **Day 9**
- **Day 10**
- **Day 11**
- **Day 12**
- **Day 13**
- **Day 14**
- **Day 15**
- **Day 16**
- **Day 17**
- **Day 18**
- **Day 19**
- **Day 20**
- **Day 21**

- **Shift workers should work no more than 50 hours per week**
  - **Otherwise, overtime**

- **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

Assign teams to shifts

- On average, shift workers should work 38 hours per week
  - The average is computed on 13 weeks

- Hard to implement:
  - Production schedule for two weeks
  - Constraint for 13 weeks
HR model

Assign teams to shifts

- Legal, HR-related constraints
  - Minimum rest time between two work periods
  - Week-end equivalent for shift work
  - Maximum 50 hours per week (or overtime)
  - Average number of hours per week, computed over 13 weeks (in Belgium)

- Try to accommodate well-being:
  - Warn the workers a few days before about their schedule
  - Avoid changing too often what the workers are said
  - Avoid overtime

Hard constraints

Committed shifts

Penalisation
Budget of hours

- Why is the average number of hours a problem?

- Reach an average of hours over 13 weeks
  - Can only work on 2 weeks!
  - Production plan after one week is already not really reliable...

- Constraint absolutely needed
  - Must keep flexibility for the weeks after
  - Avoid too many days at the beginning
  - Avoid too many days unused at the end
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
Budget of hours

- Its implementation 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
Objective function

- Minimise penalisations:
  - Hours overtime
  - Hours outside budget (below and above)
  - Number of changes against previous solution

- Each one has a different weight
  - Easy to get multiple assignments
Evaluation

Three axes:
• Computation times
• Monetary gains
• Working conditions
• These problems are easy to solve
  • 13 weeks, each program with a horizon of 2 weeks
  • Mill used 85% of the time
  • 5 teams

• Production model:
  • On average: 0.2s (maximum: 29s)

• HR model:
  • On average: 0.2s (maximum: 0.3s)

• Statistics based on:
  • 6 order books
  • 18 price scenarios
Compare this “smart” approach to:

- Two usual industrial scenarios:
  - Produce during the night
  - Produce during the night or the WE

- A softened version of our approach:
  - Cannot reconsider shifts once they are decided
<table>
<thead>
<tr>
<th>Algorithm</th>
<th>HR cost</th>
<th>Electricity cost</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart</td>
<td>974,426</td>
<td>752,689</td>
<td>1,727,114</td>
</tr>
<tr>
<td>No change</td>
<td>1,023,973</td>
<td>904,324</td>
<td>1,928,297</td>
</tr>
<tr>
<td>Night</td>
<td>1,289,920</td>
<td>979,200</td>
<td>2,269,125</td>
</tr>
<tr>
<td>Night and WE</td>
<td>1,262,530</td>
<td>1,025,600</td>
<td>2,288,131</td>
</tr>
</tbody>
</table>

Monetary gains

![Bar chart demonstrating monetary gains for different algorithms.](37)
Working conditions

• Monitor several KPIs:
  • Physiological KPIs
  • Social KPIs
  • Economical KPIs

• Major problems?
  • Scarce literature for flexible shifts
  • Some important notions no more make sense
    • Cycle, rotation, mostly
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>
<td>3.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Social KPIs (14 days)

Total shifts                   | 6  | 6  | 7  | 6  | 6  |
Morning shifts                  | 1  | 3  | 0  | 3  | 2  |
WE shifts                       | 0  | 0  | 0  | 0  | 0  |

Economical KPIs (14 days)

<table>
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<td>Total shifts</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total wage</td>
<td>6000</td>
<td>6000</td>
<td>7000</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Diff. with max (%)</td>
<td>14.2857</td>
<td>14.2857</td>
<td>0</td>
<td>14.2857</td>
<td>14.2857</td>
</tr>
<tr>
<td>Hourly wage</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
</tbody>
</table>
### Physiological KPIs (14 days)

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<td>0</td>
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<td>0</td>
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<td>0</td>
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<tr>
<td>Clockwise transitions</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>(MA, AN, NM)</td>
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<tr>
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</tr>
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<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>
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<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>
</tr>
</tbody>
</table>

### Economical KPIs (14 days)

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</table>
Conclusion and future work
Conclusion

• From 19th-century planning to flexibility:
  ➢ Could save 30% in costs!

• Probably not acceptable as such:
  • Complete mentality change
  • Workers and directors not always ready

• Objective elements to foster thinking
Future work: production model

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

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

- Great troubles for HR analysis: even further away into the unknown!

- Price uncertainty not explicitly modelled
Future work: HR model

- Introduce fairness criteria when making teams
  - May have large impact on some KPIs
- Potential performance degradation (cf. attic problem)
- First tests show that the effect on runtime is limited
Questions?