Modelling industrial flexibility

from the electricity consumption and the human resources points of view

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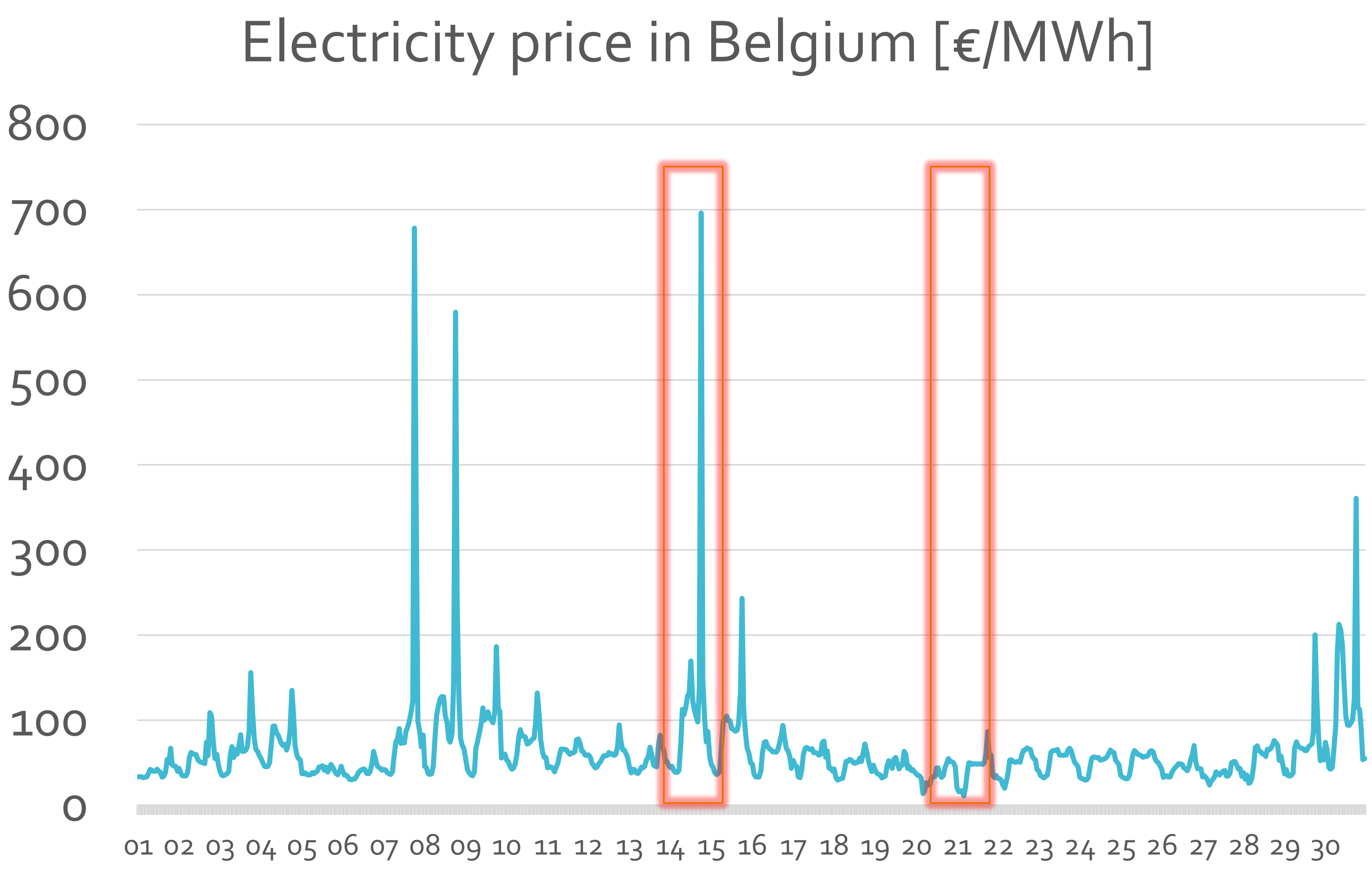
Context

What if November 2016 becomes usual?



Steel mill consumption: ~ 50 MWh / 100 tonnes

Thus…

electrical flexibility

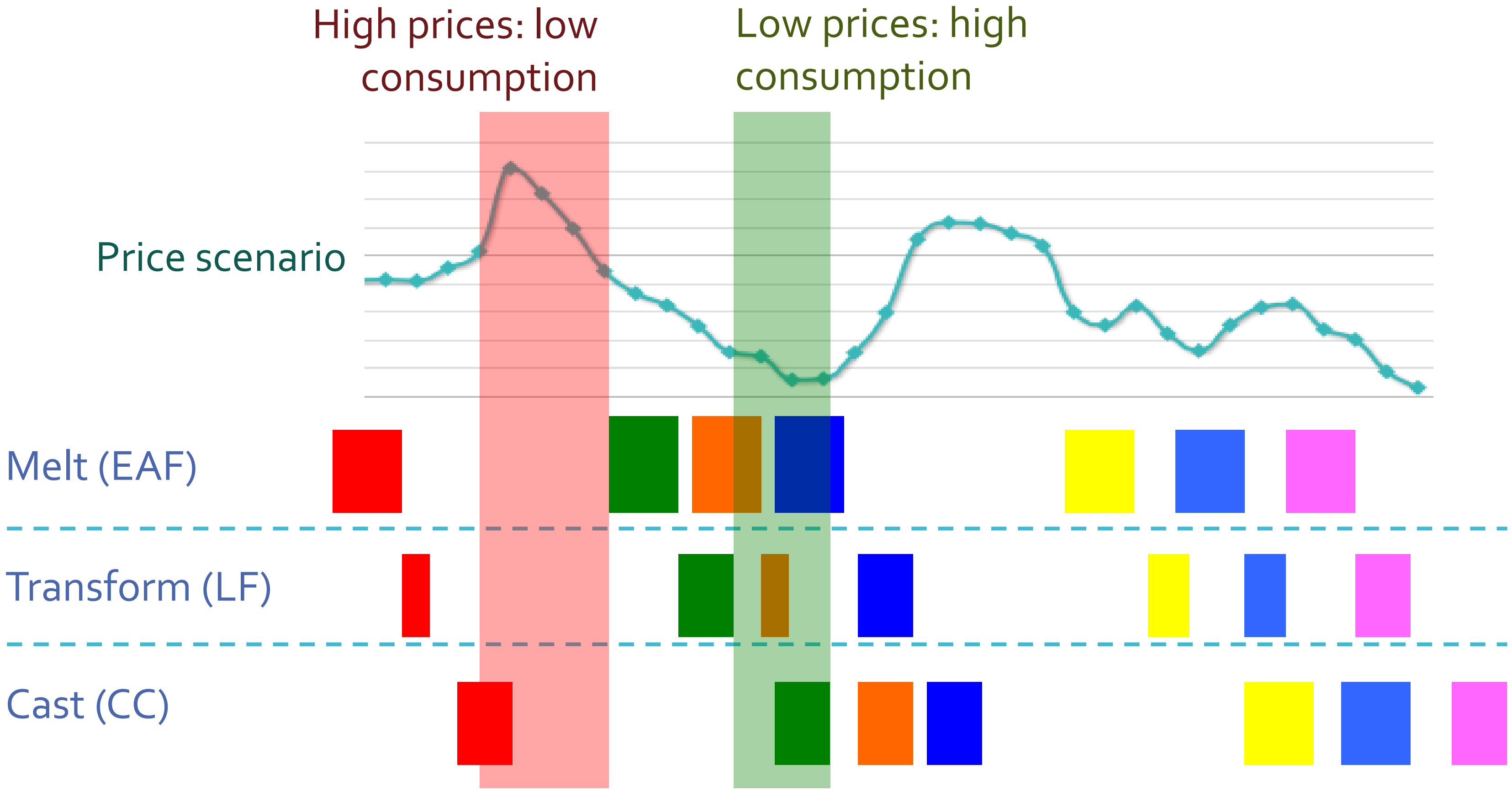
- Flexibility is about **exploiting those price fluctuations** to lower the costs

- 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



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

Partenariat N-SIDE UCL Université catholique de Louvain Université de Liège ULg ICEDD ASBL avec le soutien de Wallonie SPW Service public de Wallonie DGO 4 DGO 6

http://www.industore-project.be/

InduStore highlights energy flexibility in industrial sites

How sizeable is flexibility?

How to exploit this flexibility by optimal production planning?

InduStore

How to reconcile flexibility and workers well-being?

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:

More HR flexibility

  - Long-term: workers shifts, approximate production plan
  - Medium-term: production plan
  - Short-term: adapt production plan

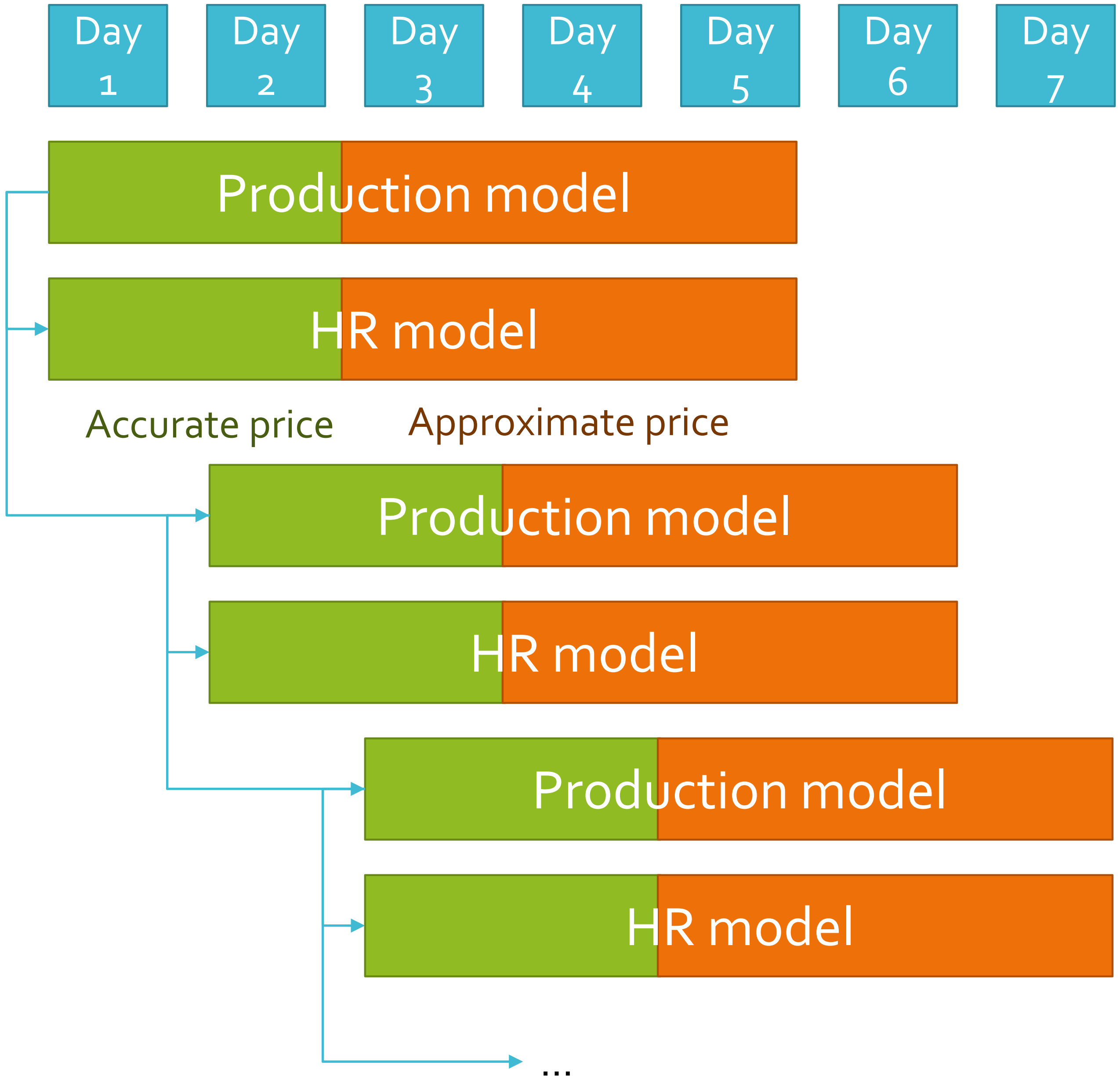
Better price predictions

- Focus on long-term planning
  - Further split into production and HR

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?



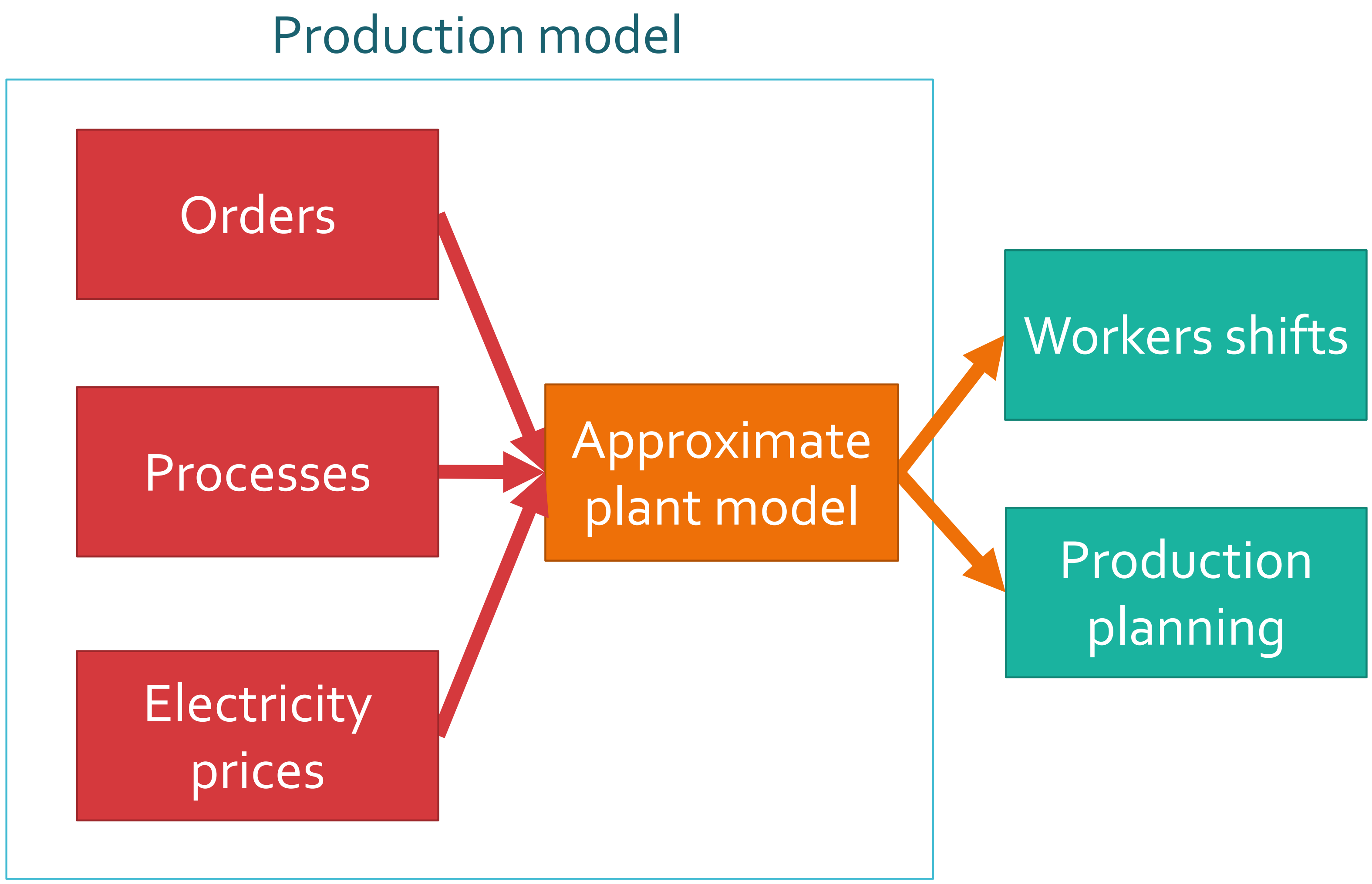
Production model

Goals:

- Estimate a production planning
- Determine when workers are needed

Production model

Determine a production planning



Production model

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?

Rough model	Fine model
Any process lasts 1 h	Some processes take 30 min, others 45 min
Consumption is constant with production, fixed batch size	Consumption is linear, quadratic…
Some stages are ignored	All stations are included
No wait time between processes	Wait time can be optimised

- 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?

$$\mathrm{shiftOn}_s \in \{0,1\}, \forall s \in \mathrm{shifts}$$

  - Is the process on?

$$\mathrm{processOn}_{\mathrm{t,p}} \in \{0,1\},$$
$$\forall t \in \mathrm{time\ steps}, \forall p \in \mathrm{processes}$$

  - What quantity is being processed?

$$\mathrm{quantity}_{\mathrm{t,p}} \geq 0,$$
$$\forall t \in \mathrm{time\ steps}, \forall p \in \mathrm{processes}$$

What does the model look like?

- Objective: minimise the costs

$$\min \sum_{s \in \text{shifts}} cost_s \, \text{shiftOn}_s$$
$$+ \sum_{t \in \text{time steps}} \text{price}_\text{t} \sum_{p \in \text{processes}} \text{processOn}_{t,\text{p}}$$

  - 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
    $$\text{quantity}_{\text{t,p}} = \text{quantity}_p^{\max}\text{processOn}_{t,p},$$
    $$\forall p \in \text{processes}, \forall t \in \text{time steps}$$

What does the model look like?

- Constraints:
  - The processes follow each other and last one time step

$$\text{quantity}_{\text{t,lf}} = \alpha \, \text{quantity}_{\text{t}-1,\text{eaf}},$$
$$\text{quantity}_{\text{t,cc}} = \text{quantity}_{\text{t}-1,\text{lf}},$$
$$\text{quantity}_{\text{t,out}} = \text{quantity}_{\text{t}-1,\text{cc}},$$
$$\forall t \in \text{time steps}$$

    - Transformation factor between EAF and LF: some losses between the input raw material and the molten steel

  - The order book must be respected

$$\sum_{\tau \leq t} \text{quantity}_{\tau,\text{out}} \geq \text{totalOrderedQuantityUpTo}_{\text{t}},$$
$$\forall t \in \text{time steps}$$

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?

$$\text{assigned}_{\text{s,t}} \in \{0,1\},$$
$$\forall s \in \text{shifts}, \forall t \in \text{teams}$$

- Major constraint: are workers required?

$$\sum_{t \in \text{teams}} \text{assigned}_{\text{s,t}} = \text{required}_{\text{s}},$$
$$\forall s \in \text{shifts}$$

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 must have some rest between two shifts
- Notion of "forbidden shifts"
  - If working shift s, cannot work any shift within FS

$$\sum_{u \in \mathrm{FS}(s)} \mathrm{assigned}_{\mathrm{t,u}} \leq 1 - \mathrm{assigned}_{\mathrm{t},s}, \quad \forall s \in \mathrm{shifts}$$

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 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?

    $$\text{inPair}_{\text{d,t}} \in \{0,1\}, \forall d \in \text{days} \setminus \{\text{last day}\}, \forall t \in \text{teams}$$

  - Detect those pairs with shifts (6 shifts for 2 days off):

    $$\text{inPair}_{\text{d,t}} \leq 1 - \frac{\sum_{s \in d} \text{assigned}_{\text{t},s}}{6}, \forall d \in \text{days} \setminus \{\text{last day}\}, \forall t \in \text{teams}$$

  - For each period of nine days, at least one pair:

    $$\sum_{\delta=d}^{d+8} \text{inPair}_{\delta,\text{t}} \geq 1, \forall d \in \text{days} \setminus \{9 \text{ last days}\}, \forall t \in \text{teams}$$

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

$$\text{overtime}_{\text{t,w}} \geq 0, \forall w \in \text{weeks}, \forall t \in \text{teams}$$

  - One shift lasts 8 hours

$$\sum_{s \in w} 8\ \text{assigned}_{\text{t,s}} \leq 50 + \text{overtime}_{\text{t,w}},$$

$$\forall w \in \text{weeks}, \forall t \in \text{teams}$$

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

- 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

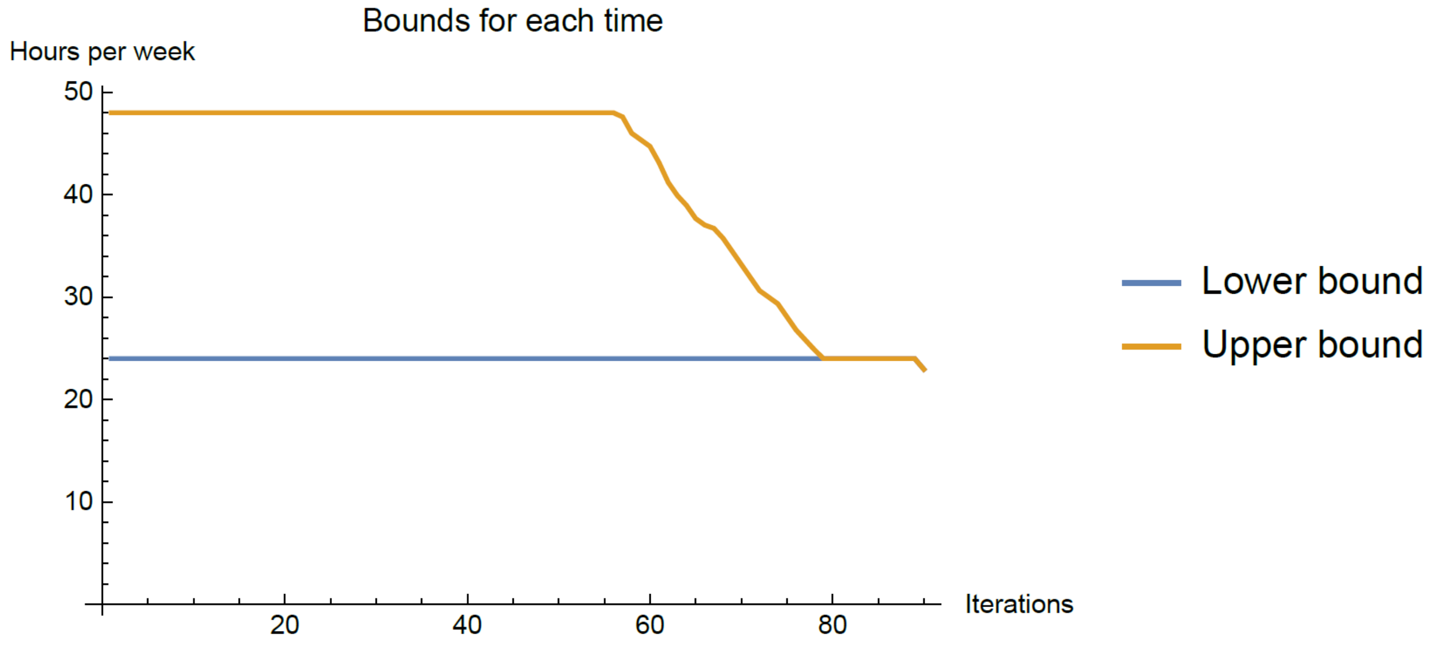
Budget of hours

- 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

Computation times

- 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

Monetary gains

Compare this “smart” approach to:

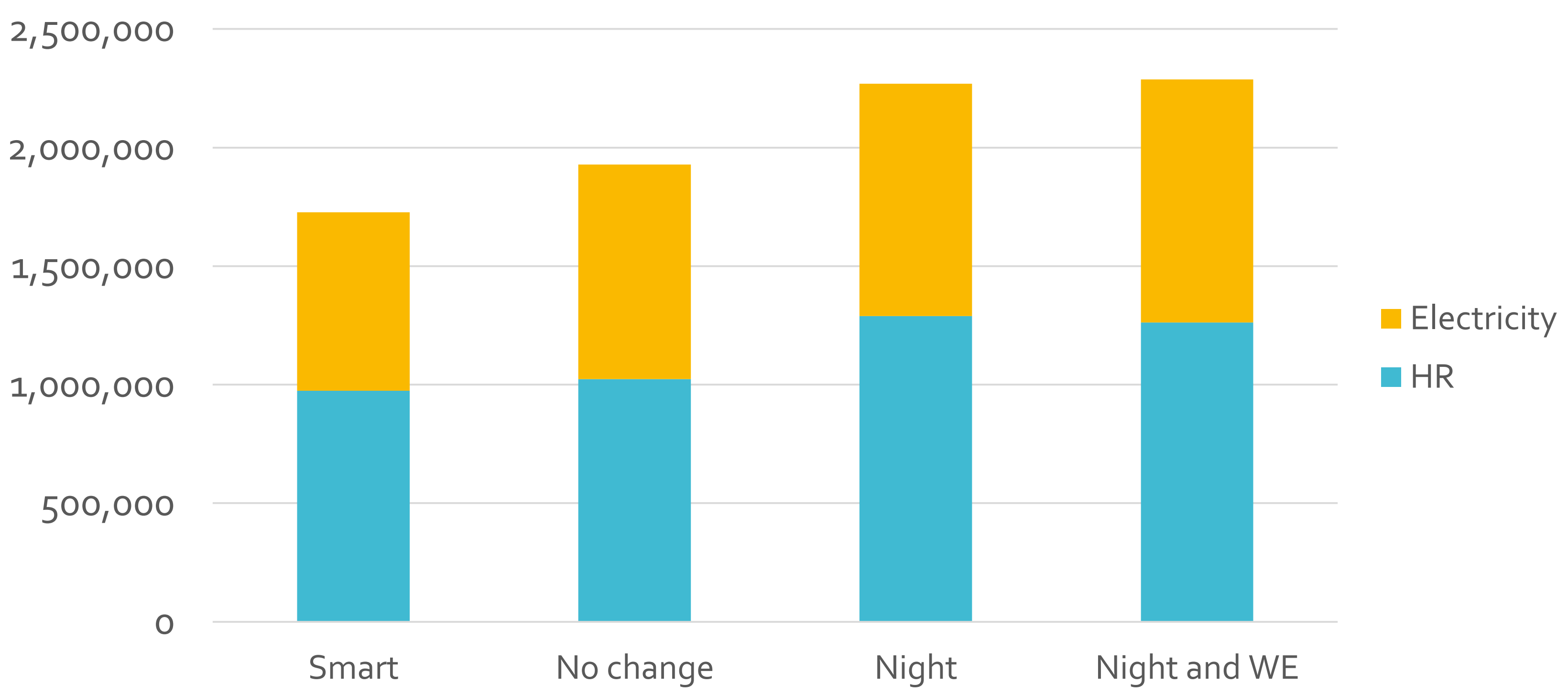
- Two usual industrial scenarios:
  - Produce during the night
  - Produce during the night or the WE

Irrespective of price scenario!

- A softened version of our approach:
  - Cannot reconsider shifts once they are decided

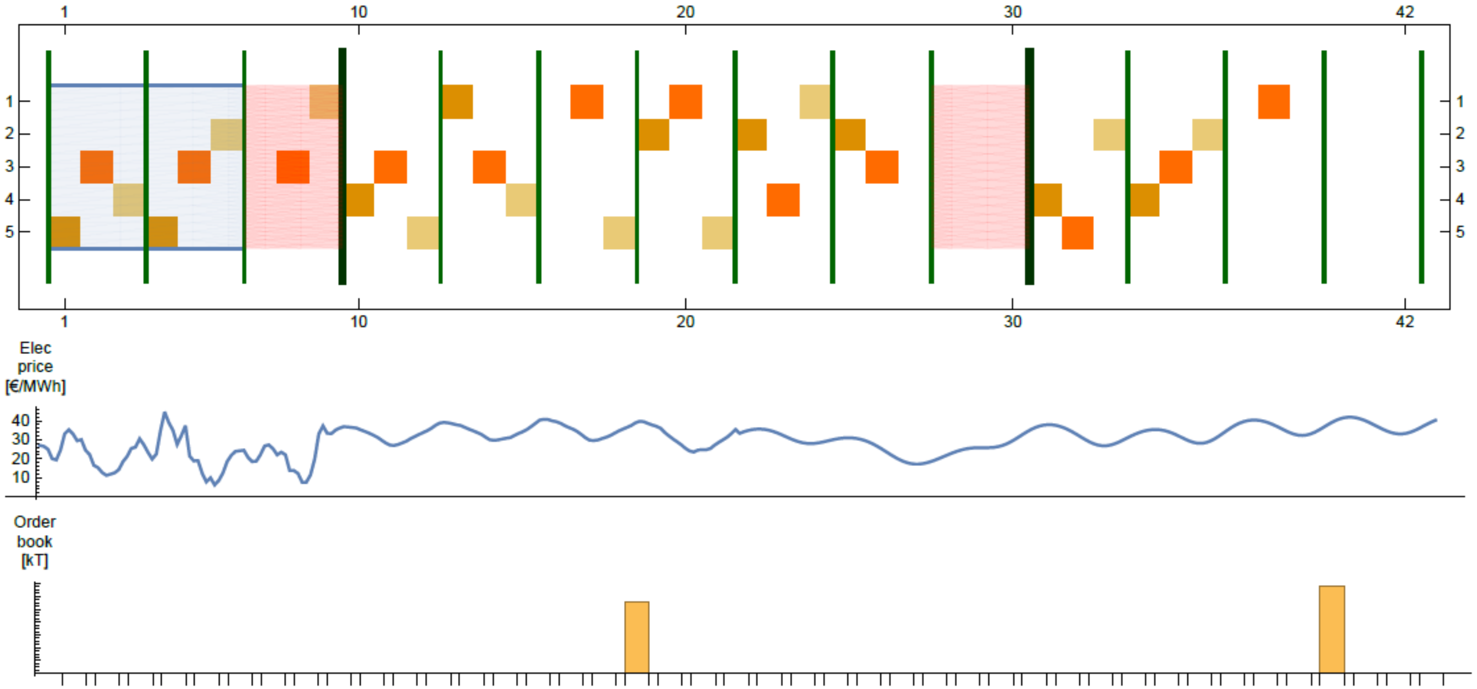
Monetary gains

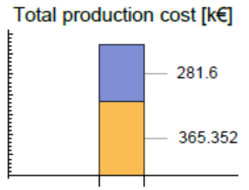
Algorithm	HR cost		Electricity cost		Total cost	
Smart	974,426		752,689		1,727,114	
No change	1,023,973	**+ 5.1%**	904,324	**+ 16.8%**	1,928,297	**+ 11.6%**
Night	1,289,920	**+ 24.5%**	979,200	**+ 23.1%**	2,269,125	**+ 31.4%**
Night and WE	1,262,530	**+ 29.6%**	1,025,600	**+ 26.6%**	2,288,131	**+ 32.5%**

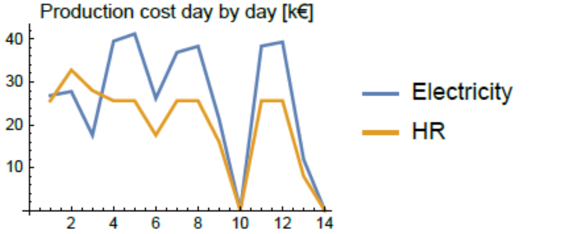


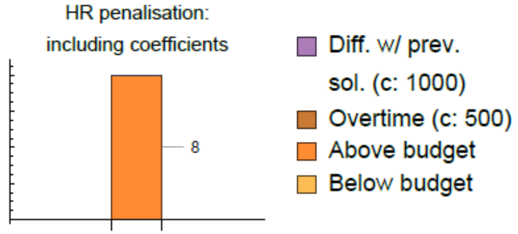
Working conditions

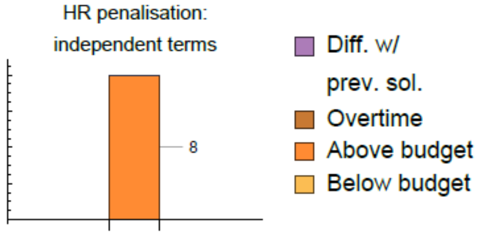
- Monitor several KPIs:
  - Physiological KPIs
  - Social KPIs
  - Economical KPIs
- Major problems?
  - Scarce literature for flexible shifts
  - Some important notions no more make sense
    - Cycle, rotation, mostly











Physiological KPIs (14 days)

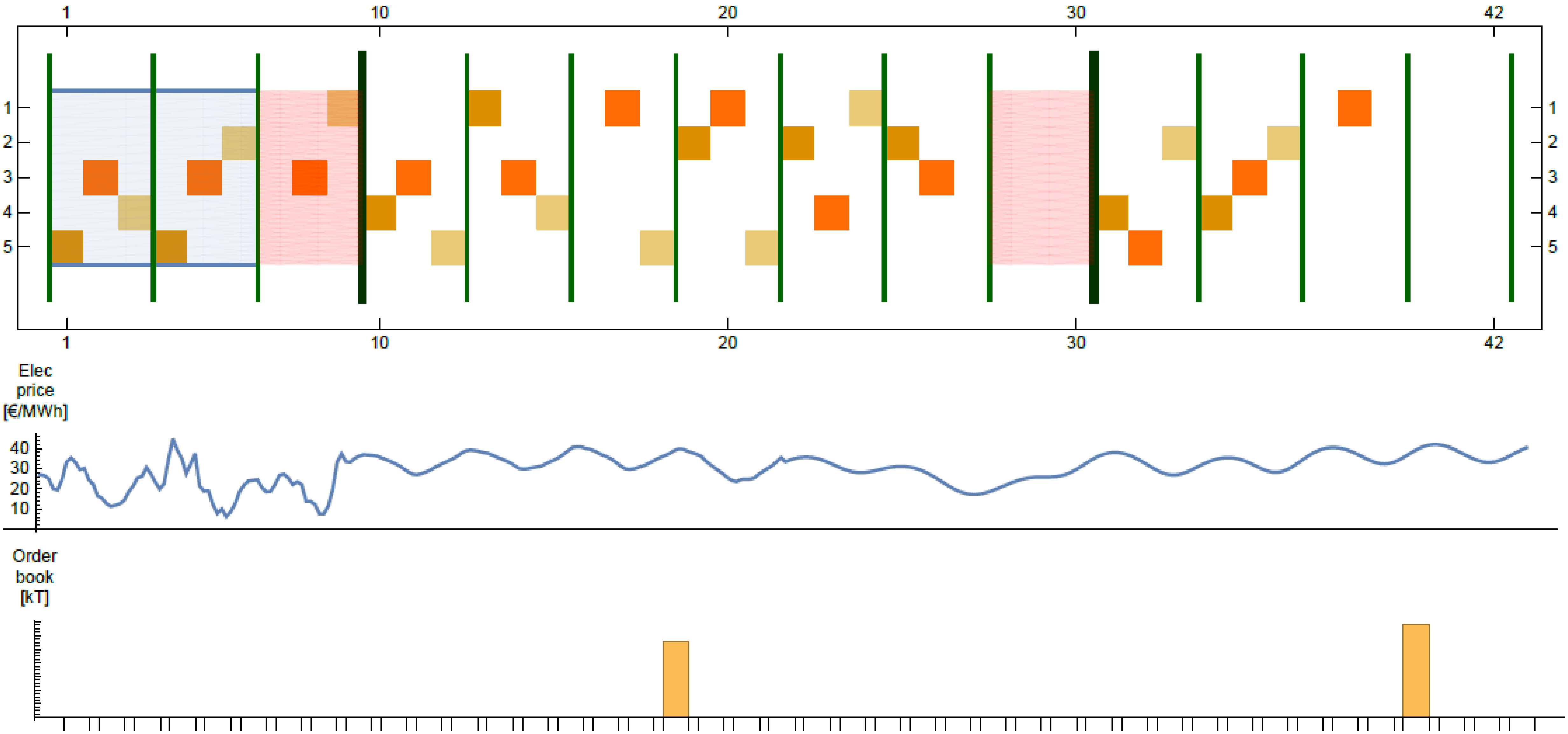
Team	#1	#2	#3	#4	#5
Sequence night–rest	0	0	0	0	0
Sequence rest–night	0	0	0	0	0
Clockwise transitions (MA, AN, NM)	0	0	0	0	0
Counterclockwise transitions (AM, MN, NA)	0	0	0	0	0
No transition (MM, AA, NN)	1	3	4	1	2
Night shifts	2	3	0	2	3
Average hours per day	3.4	3.4	4.0	3.4	3.4

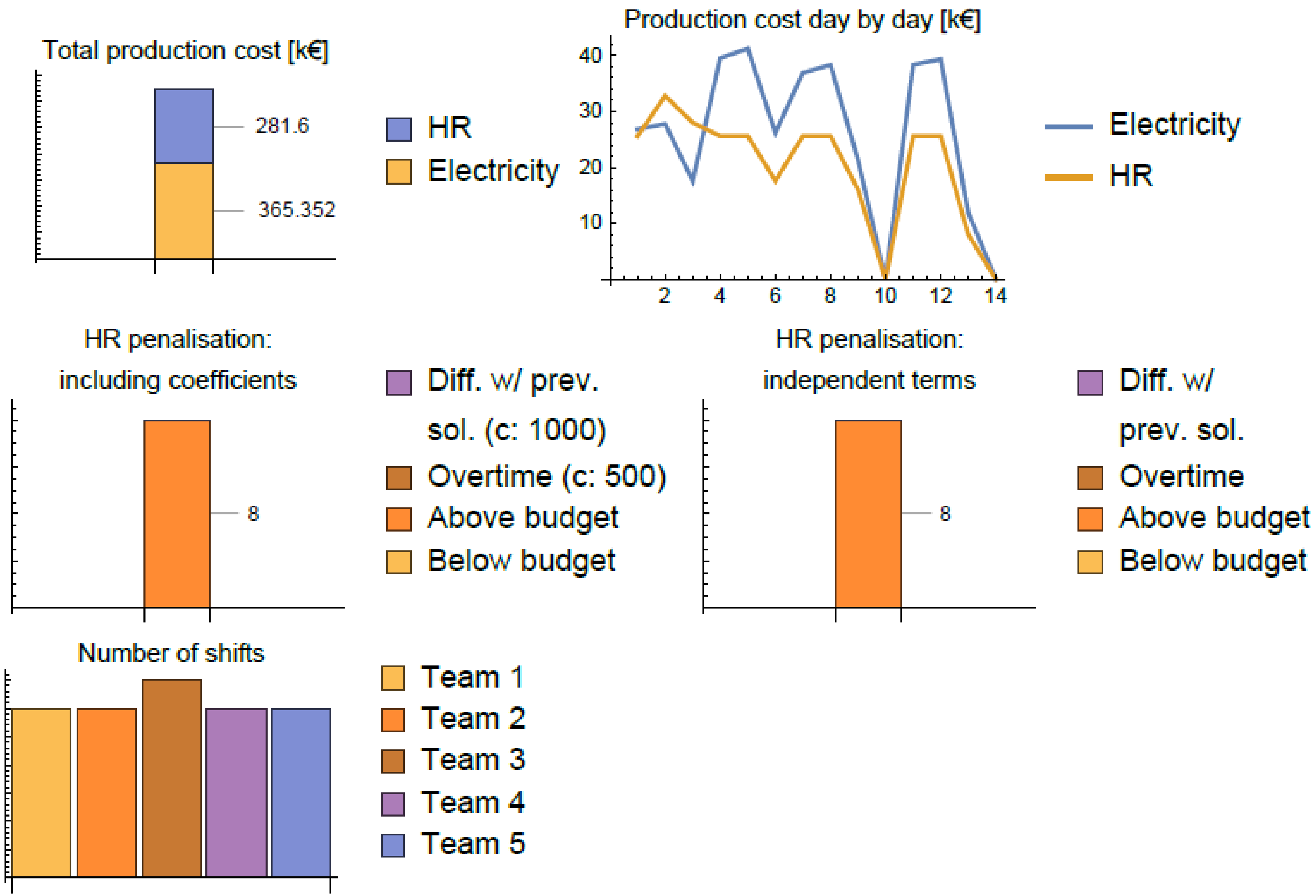
Social KPIs (14 days)

Team	#1	#2	#3	#4	#5
Morning shifts	1	3	0	3	2
WE shifts	0	0	0	0	0

Economical KPIs (14 days)

Team	#1	#2	#3	#4	#5
Total shifts	6	6	7	6	6
Diff. with max (%)	14.2857	14.2857	0.	14.2857	14.2857
Total wage	6000.	6000.	7000.	6000.	6000.
Diff. with max (%)	14.2857	14.2857	0.	14.2857	14.2857
Hourly wage	125.	125.	125.	125.	125.


1
10
20
30
42
1
2
3
4
5
Elec
price
[€/MWh]
40
30
20
10
Order
book
[kT]


Total production cost [k€]
281.6
365.352
HR
Electricity
Production cost day by day [k€]
40
30
20
10
2
4
6
8
10
12
14
Electricity
HR
HR penalisation:
including coefficients
8
Diff. w/ prev.
sol. (c: 1000)
Overtime (c: 500)
Above budget
Below budget
HR penalisation:
independent terms
8
Diff. w/
prev. sol.
Overtime
Above budget
Below budget
Number of shifts
Team 1
Team 2
Team 3
Team 4
Team 5

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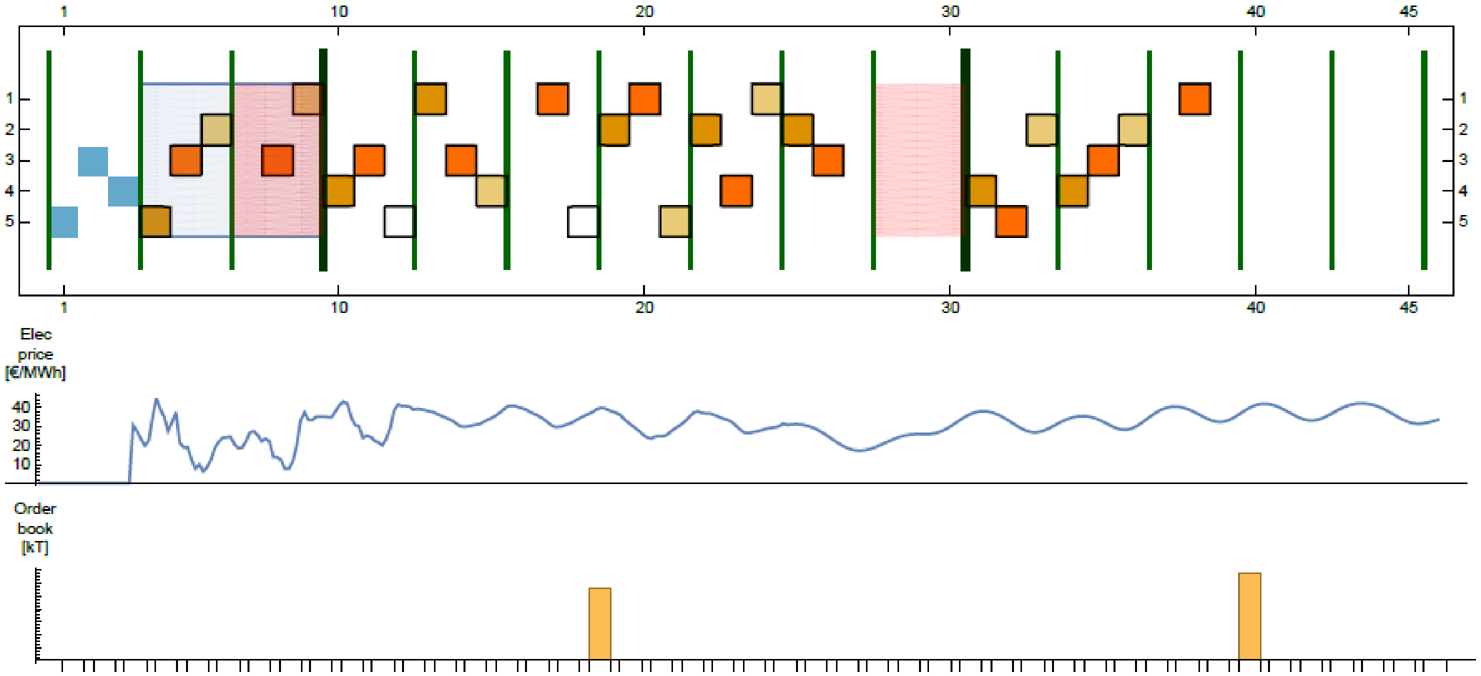

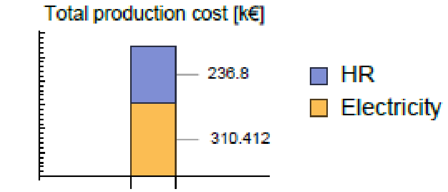

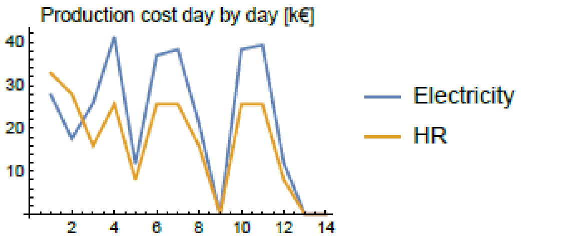

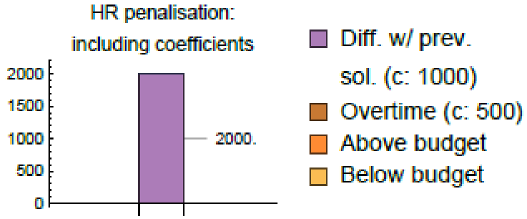

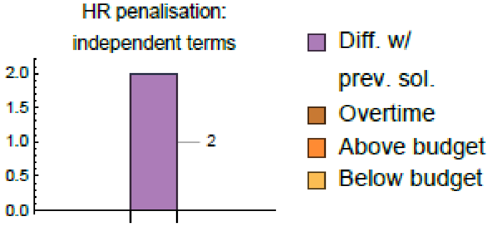

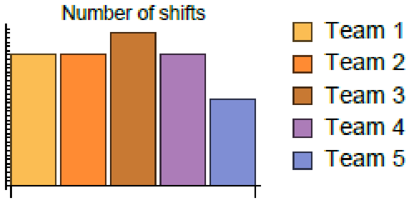

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Counterclockwise transitions (AM, MN, NA)	0	0	0	0	0
No transition (MM, AA, NN)	1	3	3	1	0
Night shifts	2	3	0	1	1
Average hours per day	3.4	3.4	3.4	2.9	1.7

Social KPIs (14 days)

Team	#1	#2	#3	#4	#5
Morning shifts	1	3	0	3	1
WE shifts	0	0	0	0	0
Shift estimate changes: come (at most 7 days before)	0	0	0	0	0
Shift estimate changes: do not come (at most 7 days before)	0	0	0	0	2

Economical KPIs (14 days)

Team	#1	#2	#3	#4	#5
Total shifts	6	6	6	5	3
Diff. with max (%)	0.	0.	0.	16.6667	50.
Total wage	6000.	6000.	6000.	5000.	3000.
Diff. with max (%)	0.	0.	0.	16.6667	50.
Hourly wage	125.	125.	125.	125.	125.

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?