Optimising workforce and energy costs
by exploiting production flexibility

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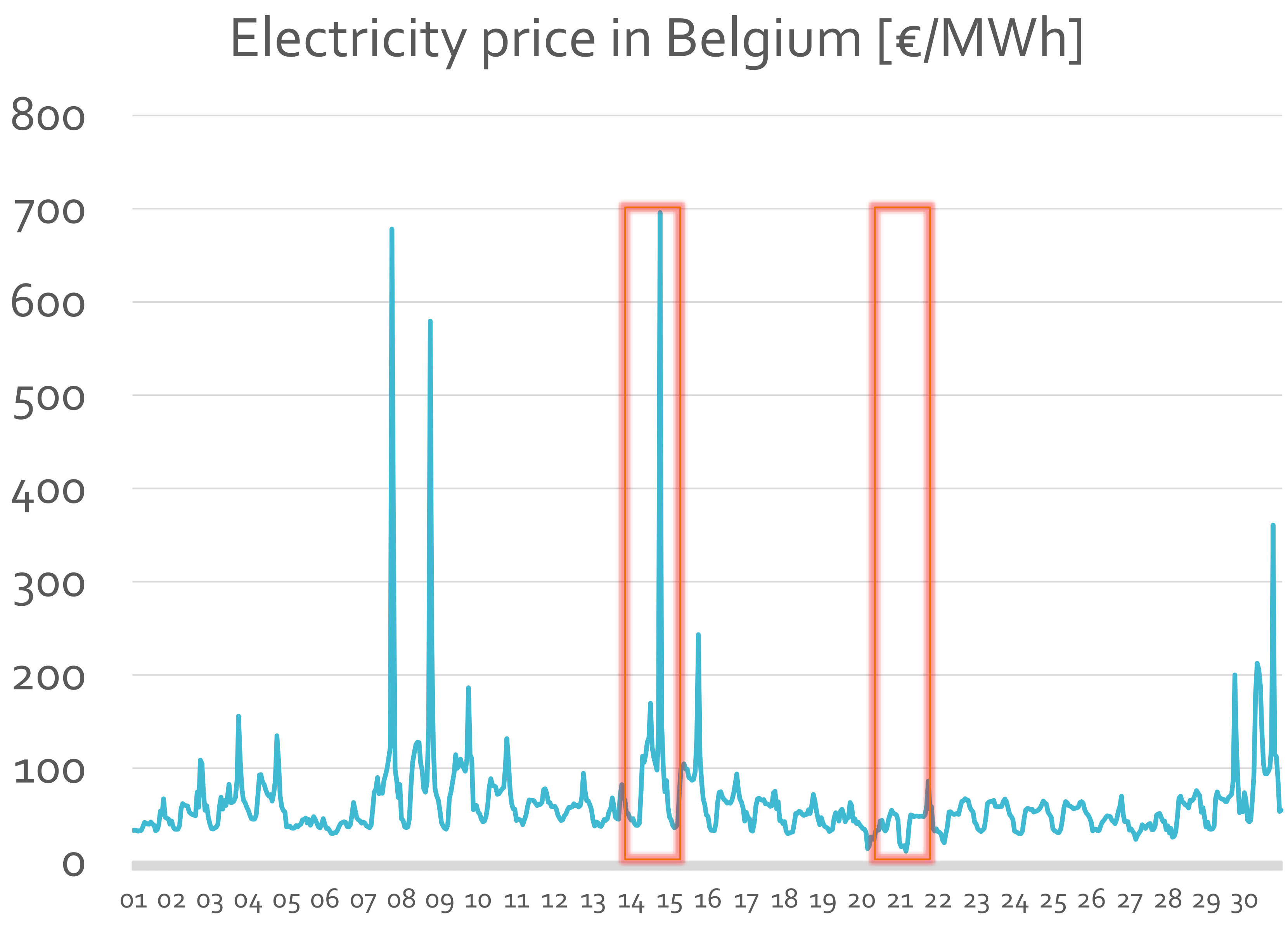
Context

What if November 2016 becomes usual?



Steel mill consumption: ~ 50 MWh / 100 tonnes

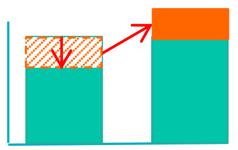
Cost: 35,900€ for 100 tonnes

Thus…

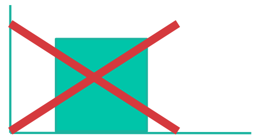
electrical flexibility

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

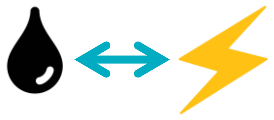
- Some possible answers?
  - **Load shifting**: produce later
  - **Load shedding**: avoid producing
  - **Fuel switching**: gas instead of electricity, e.g.



Load shifting



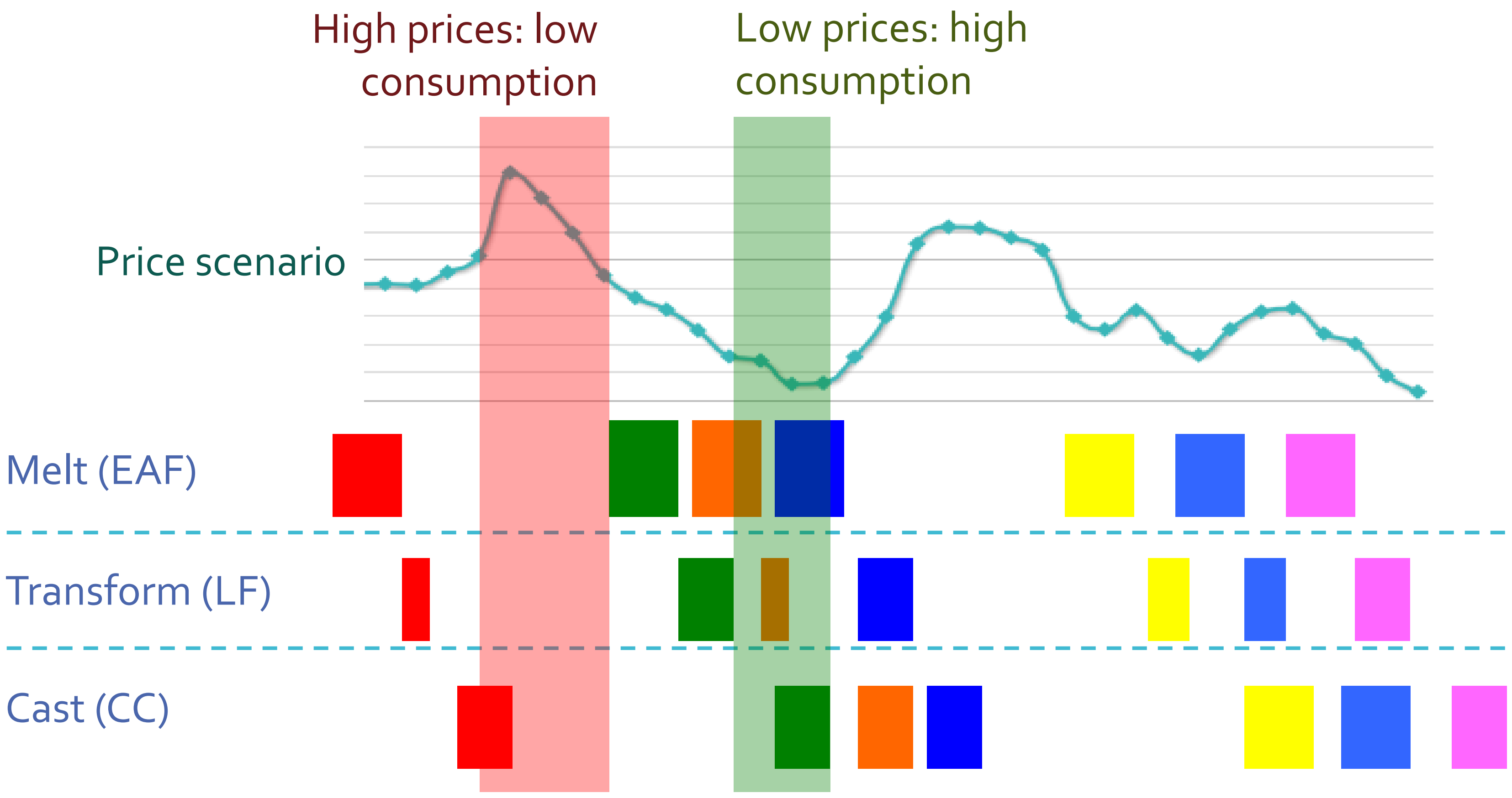
Load shedding



Fuel switching

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

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

InduStore

How sizeable is flexibility?

How to exploit this flexibility by optimal production planning?

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

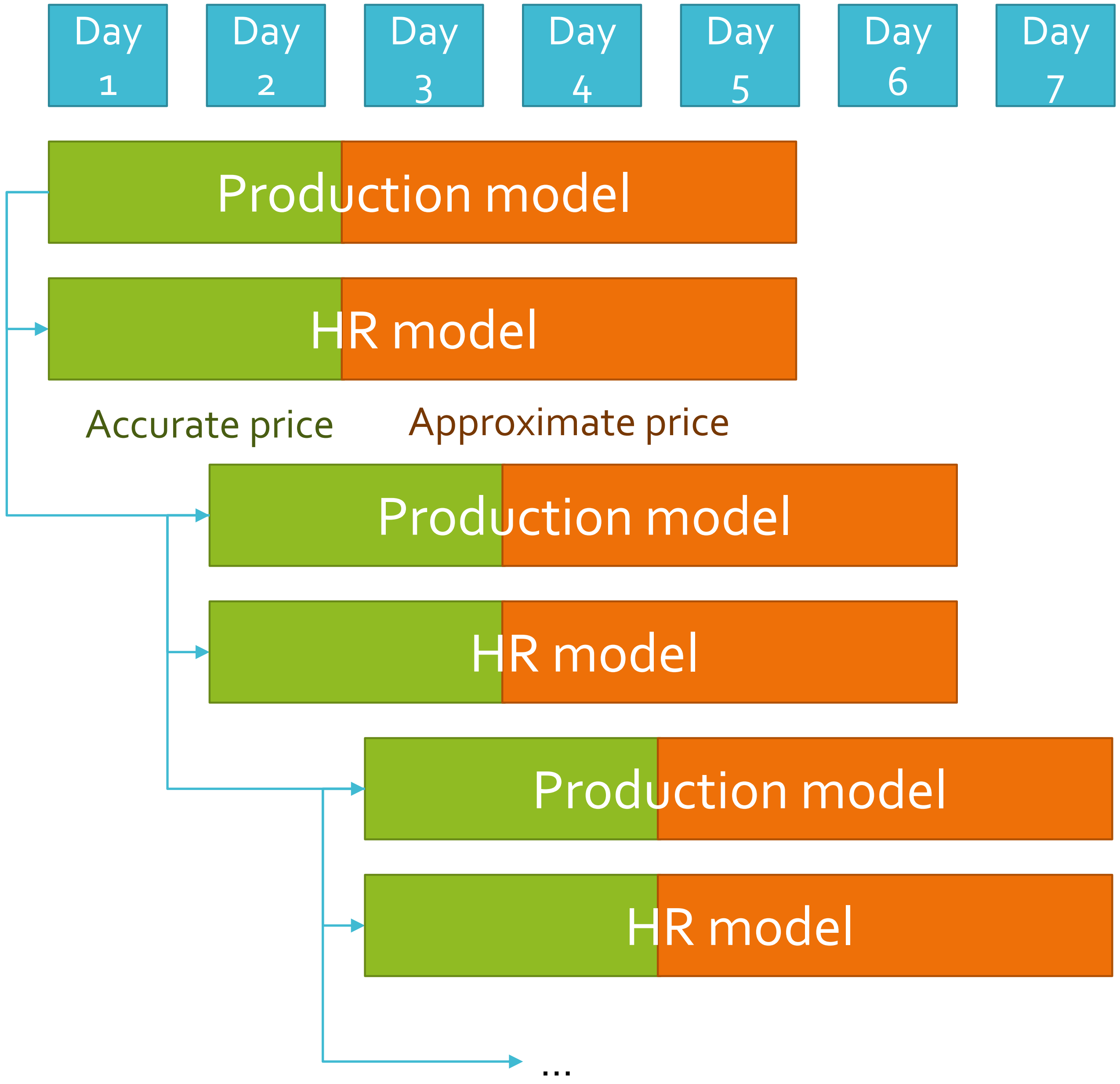
Better price predictions

- Focus on long-term planning

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?



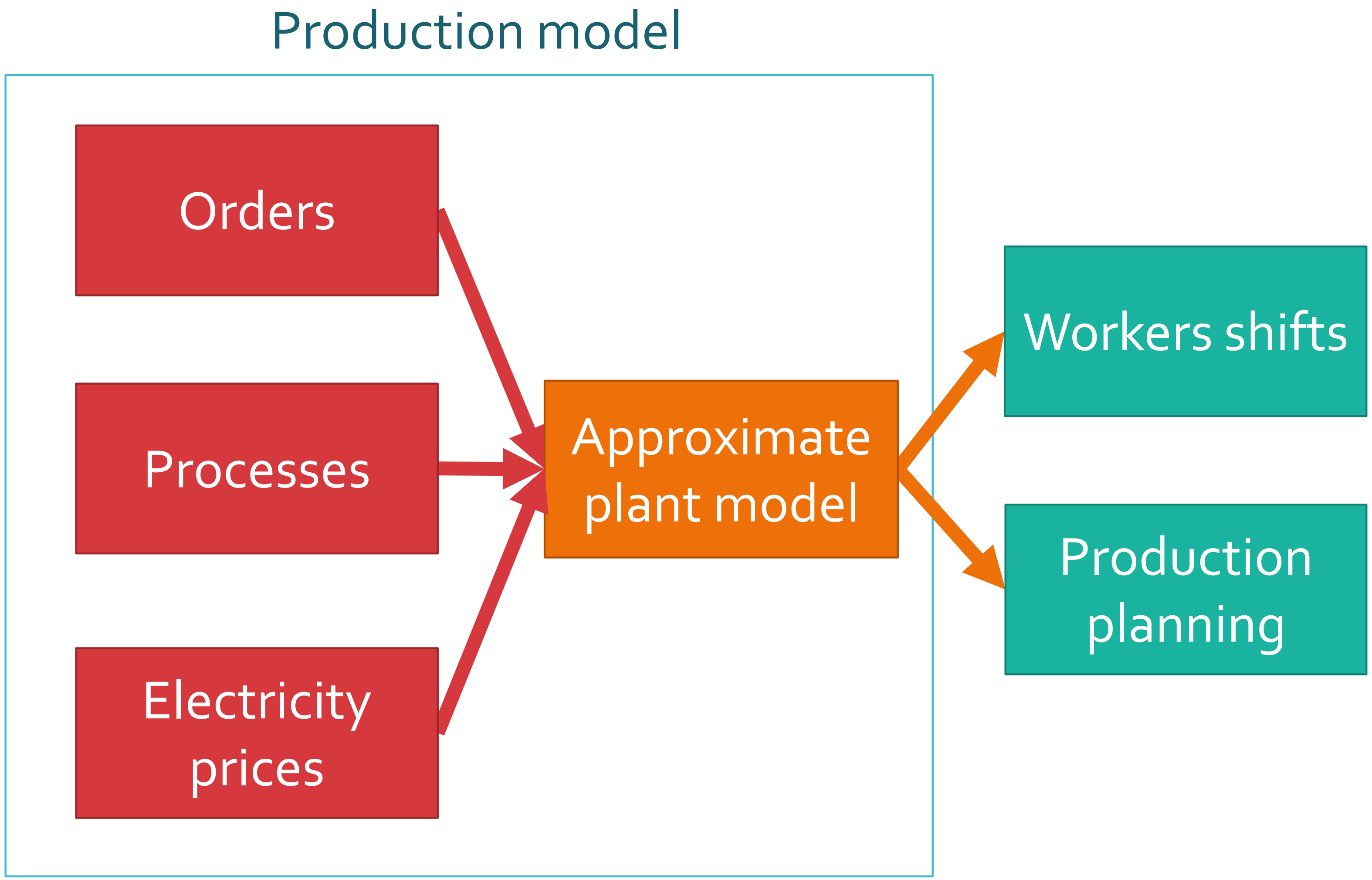
Production model

Goals:

- Estimate a production planning
- Determine when workers are needed

Production model

Determine a production planning



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 shorter-term optimisation

A glimpse of the MILP formulation

- Decision variables:
  - Are workers required? $\mathrm{shiftOn_s} \in \{0,1\}, \forall s$
  - Is the process on? $\mathrm{processOn_{t,p}} \in \{0,1\}, \forall t, \forall p$
  - What quantity is being processed? $\mathrm{quantity_{t,p}} \geq 0, \forall t, \forall p$
- Objective: minimise costs

$$\min \sum_{s} cost_{\mathrm{s}}\, \mathrm{shiftOn_s} + \sum_{t} \mathrm{price_t} \sum_{p} \mathrm{processOn}_{t,\mathrm{p}}$$

- 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

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

HR model

Assign teams to shifts

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
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Shift workers also need a WE,
i.e. a pair of days off every so often

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Shift workers should work no more than 50 hours per week

- Otherwise, overtime

MILP model so far

- 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 FS(s)
  - 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

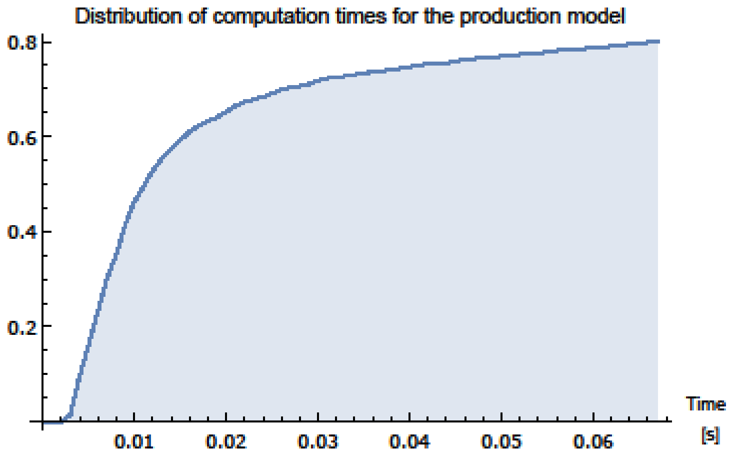
Evaluation

Axes:

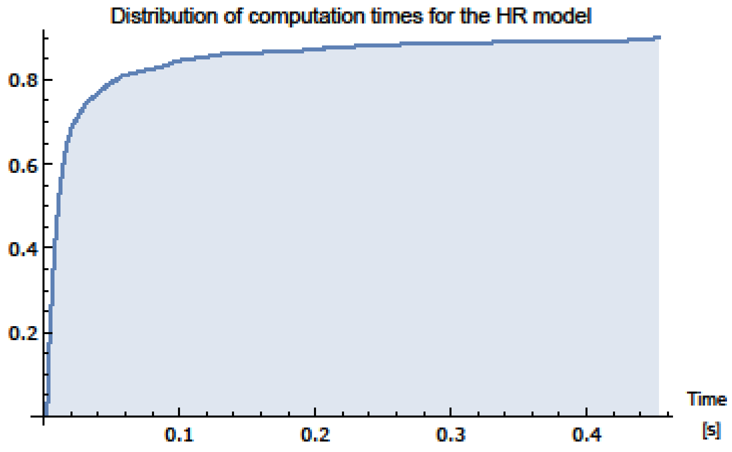
- Computation times
- Monetary gains

Computation times

- 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

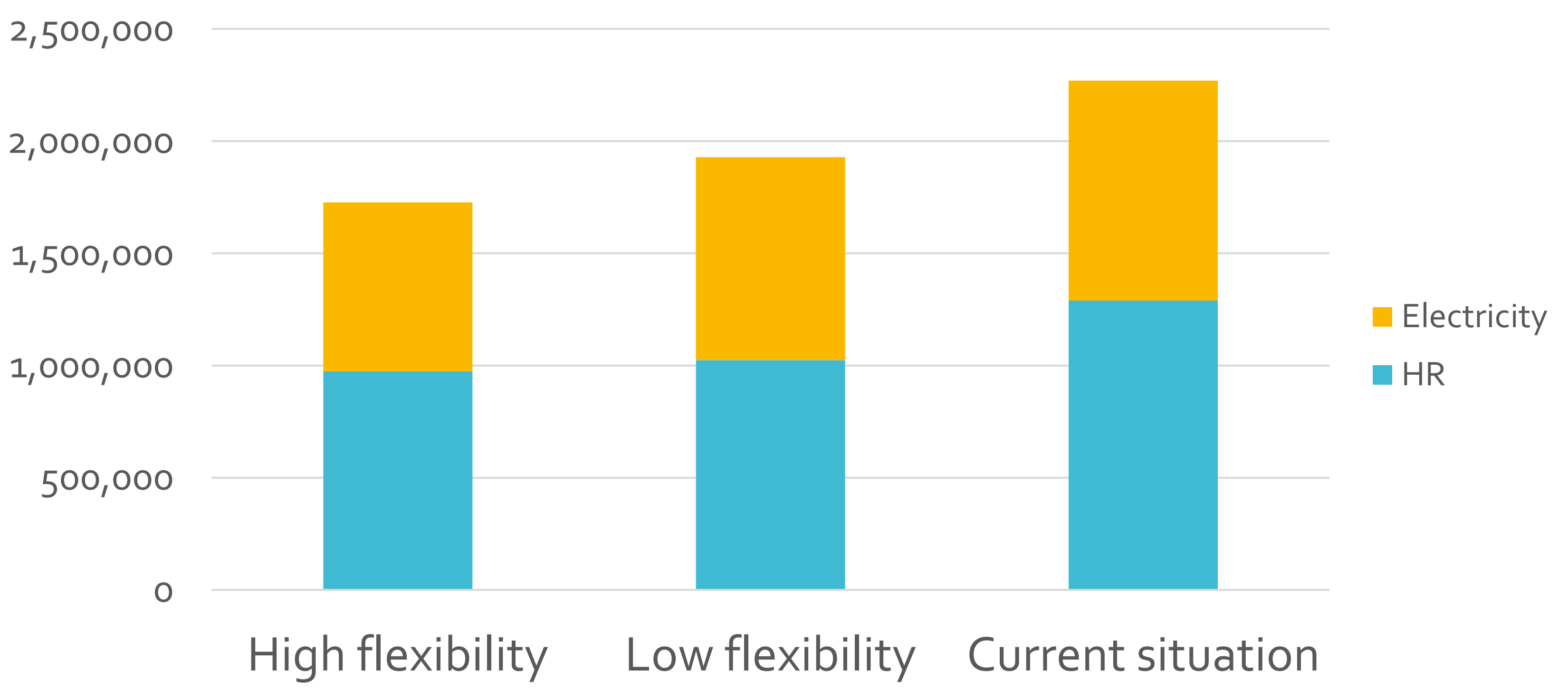
Monetary gains

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

Approaches	HR cost		Electricity cost		Total cost	
High flexibility	974,426		752,689		1,727,114	
Low flexibility	1,023,973	**+ 5.1%**	904,324	**+ 20.1%**	1,928,297	**+ 11.6%**
Current situation	1,289,920	**+ 32.4%**	979,200	**+ 30.0%**	2,269,125	**+ 31.4%**



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!
  https://github.com/douroucо5/IndustrialProcessFlexibilisation.jl

Future work

- 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
- Price uncertainty not explicitly modelled

Thank you for your attention!

Questions?

Back up

Production model 1/4

- Main decision variables:
  - Are workers required?

$$\text{shiftOn}_{\text{s}} \in \{0,1\}, \forall s \in \text{shifts}$$

  - Is the process on?

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

  - What quantity is being processed?

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

Production model 2/4

- 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.

Production model 3/4

- Constraints:
  - A process can be on only if workers are present
    $$\text{processOn}_{t,p} \le \text{shiftOn}_s,$$
    $$\forall p \in \text{processes}, \forall s \in \text{shifts}, \forall t \in s$$
  - A process can be used only if it is on;
    the batch size is fixed
    $$\text{quantity}_{\text{t,p}} = \text{quantity}_p^{\text{max}} \text{processOn}_{t,p},$$
    $$\forall p \in \text{processes}, \forall t \in \text{time steps}$$

Production model 4/4

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

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

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

  - The order book must be respected

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

HR model (1/6)

- 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 (2/6)

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 (3/6)

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?
    $$\mathrm{inPair}_{\mathrm{d,t}} \in \{0,1\}, \forall d \in \mathrm{days} \setminus \{\mathrm{last\ day}\}, \forall t \in \mathrm{teams}$$
  - Detect those pairs with shifts (6 shifts for 2 days off):
    $$\mathrm{inPair}_{\mathrm{d,t}} \leq 1 - \frac{\sum_{s \in d} \mathrm{assigned}_{\mathrm{t},s}}{6}, \forall d \in \mathrm{days} \setminus \{\mathrm{last\ day}\}, \forall t \in \mathrm{teams}$$
  - For each period of nine days, at least one pair:
    $$\sum_{\delta=d}^{d+8} \mathrm{inPair}_{\delta,\mathrm{t}} \geq 1, \forall d \in \mathrm{days} \setminus \{9\ \mathrm{last\ days}\}, \forall t \in \mathrm{teams}$$

HR model (4/6)

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 (5/6)

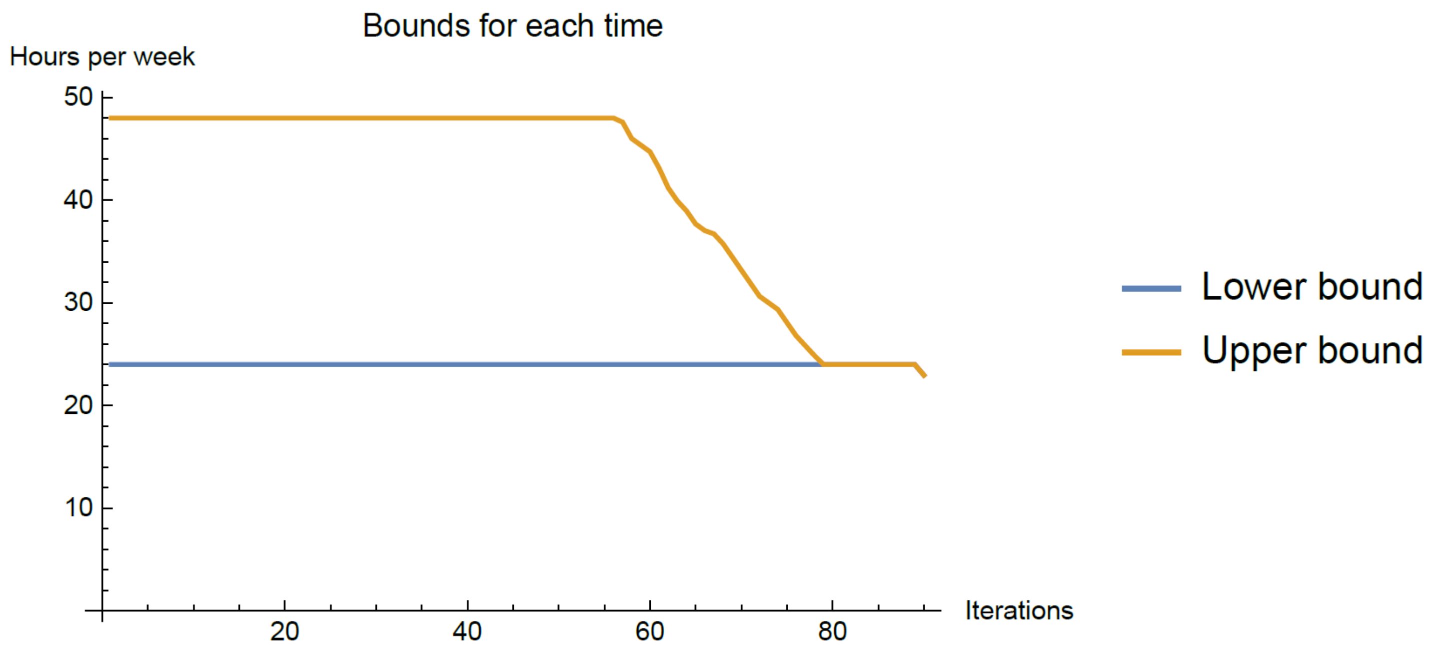
Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
Day 15	Day 16	Day 17	Day 18	Day 19	Day 20	Day 21

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



HR model (6/6)

- The implementation of the budget of hours is straightforward:

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

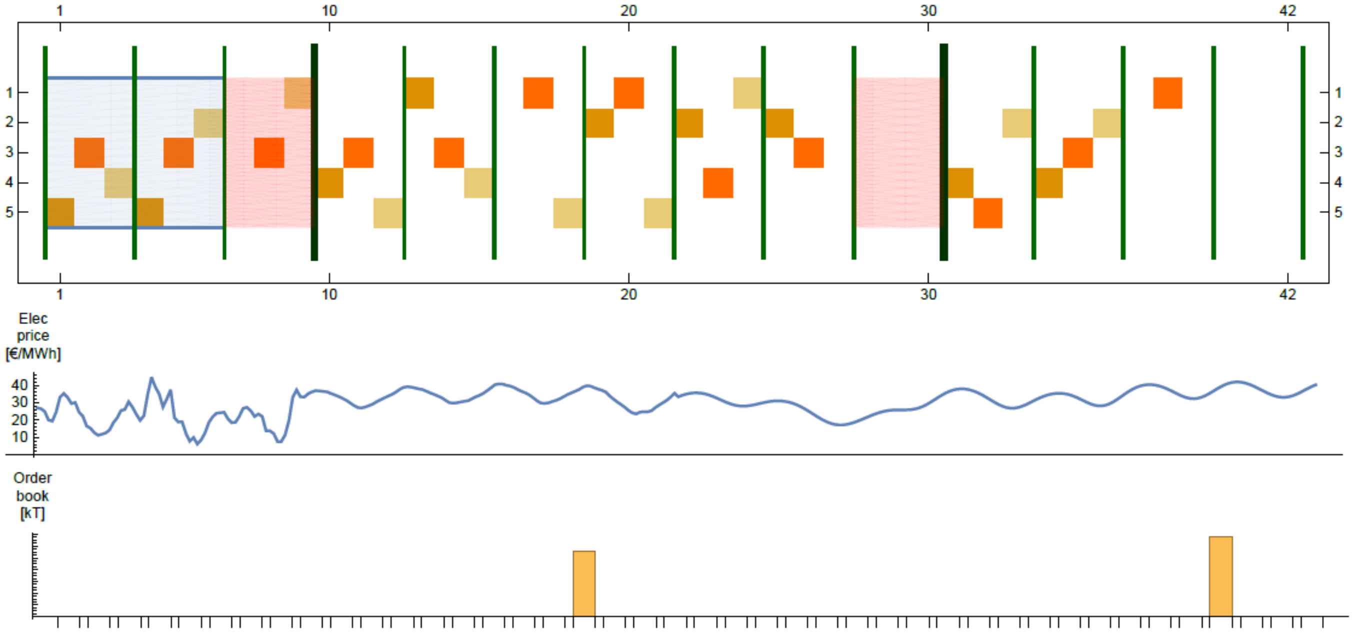
  - In practice: with slacks to avoid too quick infeasibility

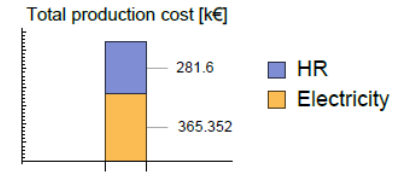
Working conditions

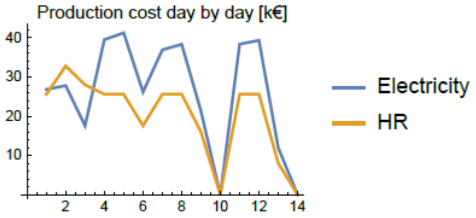
Monitor several KPIs:

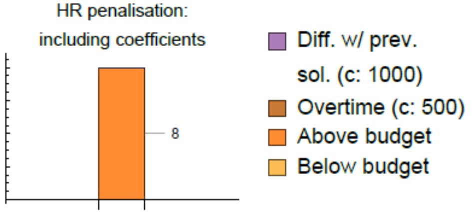
- Physiological KPIs
- Social KPIs
- Economical KPIs

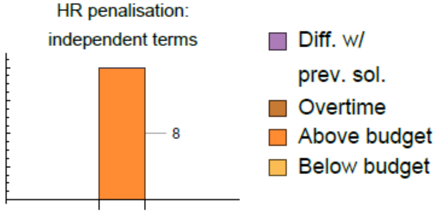
Summarised in a complete visualisation











Physiological KPIs (14 days)

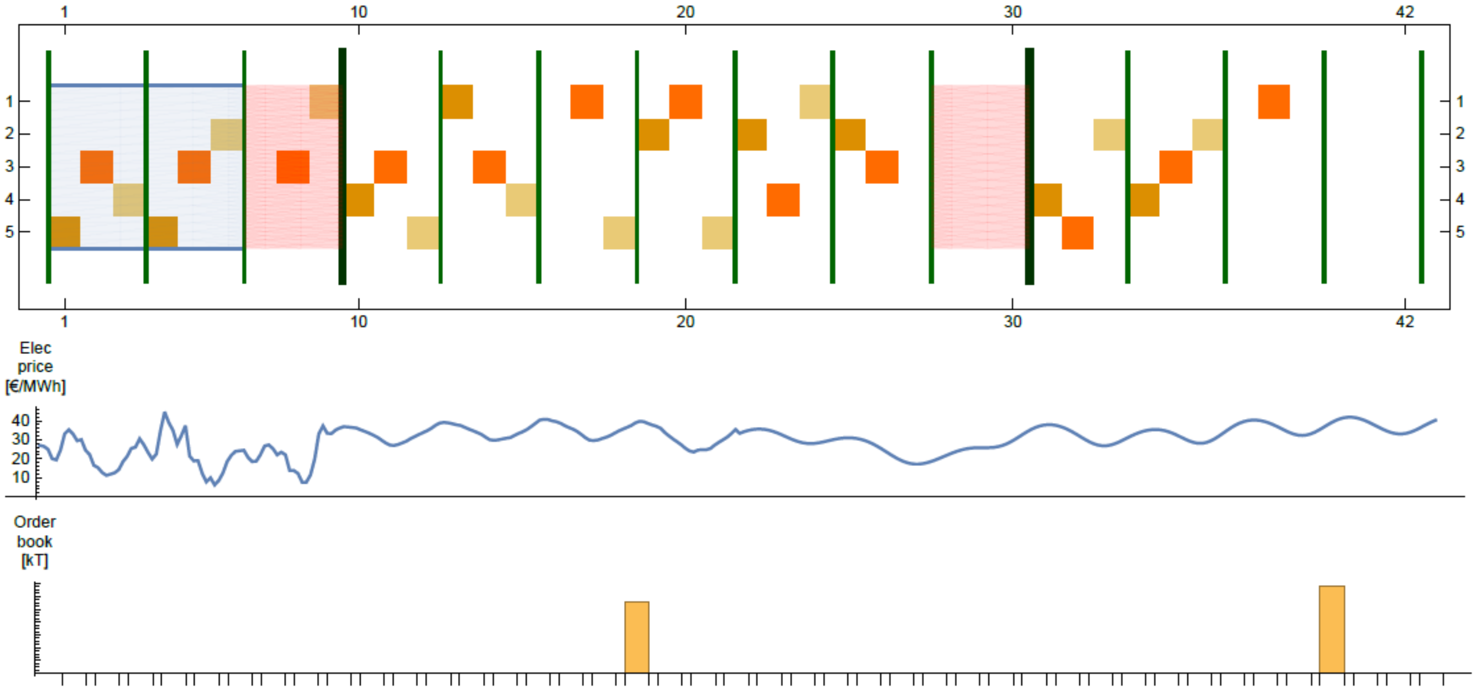
Team	#1	#2	#3	#4	#5
Sequence night–rest	0	0	0	0	0
Sequence rest–night	0	0	0	0	0
Clockwise transitions (MA, AN, NM)	0	0	0	0	0
Counterclockwise transitions (AM, MN, NA)	0	0	0	0	0
No transition (MM, AA, NN)	1	3	4	1	2
Night shifts	2	3	0	2	3
Average hours per day	3.4	3.4	4.0	3.4	3.4

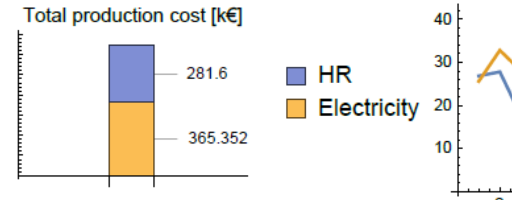
Social KPIs (14 days)

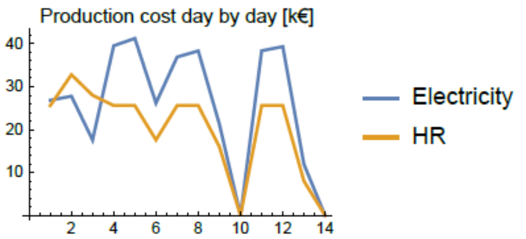
Team	#1	#2	#3	#4	#5
Morning shifts	1	3	0	3	2
WE shifts	0	0	0	0	0

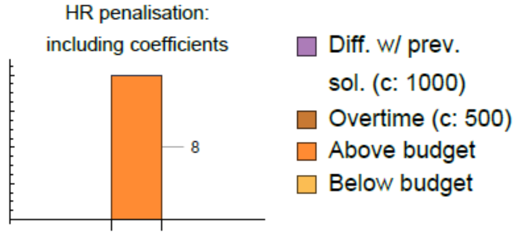
Economical KPIs (14 days)

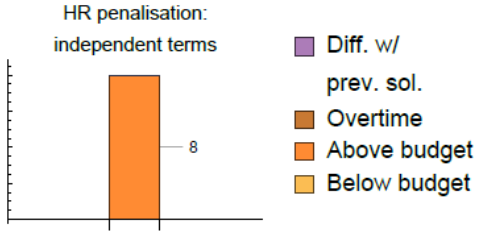
Team	#1	#2	#3	#4	#5
Total shifts	6	6	7	6	6
Diff. with max (%)	14.2857	14.2857	0.	14.2857	14.2857
Total wage	6000.	6000.	7000.	6000.	6000.
Diff. with max (%)	14.2857	14.2857	0.	14.2857	14.2857
Hourly wage	125.	125.	125.	125.	125.











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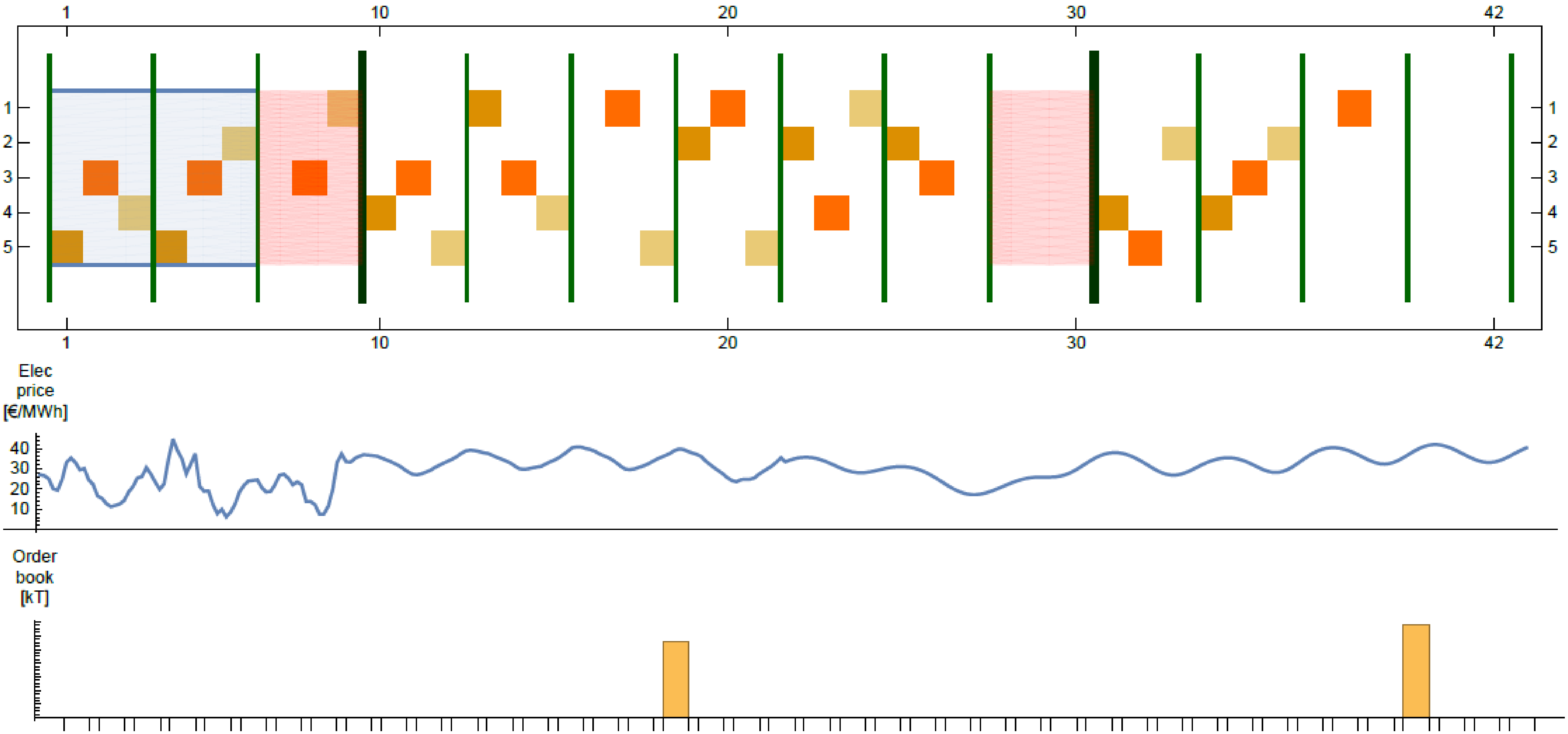

1
10
20
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42
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2
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Elec
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[€/MWh]
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10
Order
book
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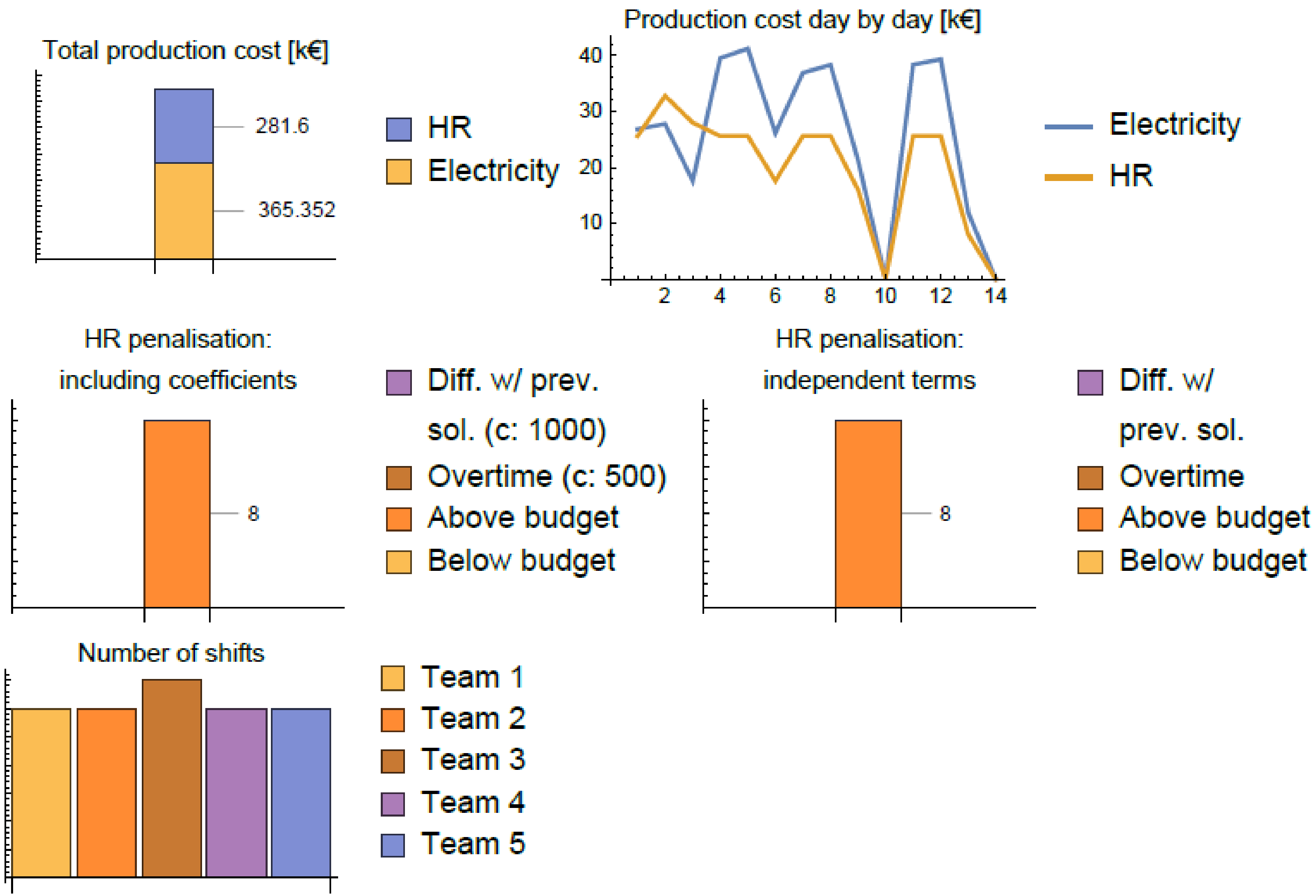
Total production cost [k€]
281.6
365.352
HR
Electricity
Production cost day by day [k€]
40
30
20
10
2
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6
8
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14
Electricity
HR
HR penalisation:
including coefficients
8
Diff. w/ prev.
sol. (c: 1000)
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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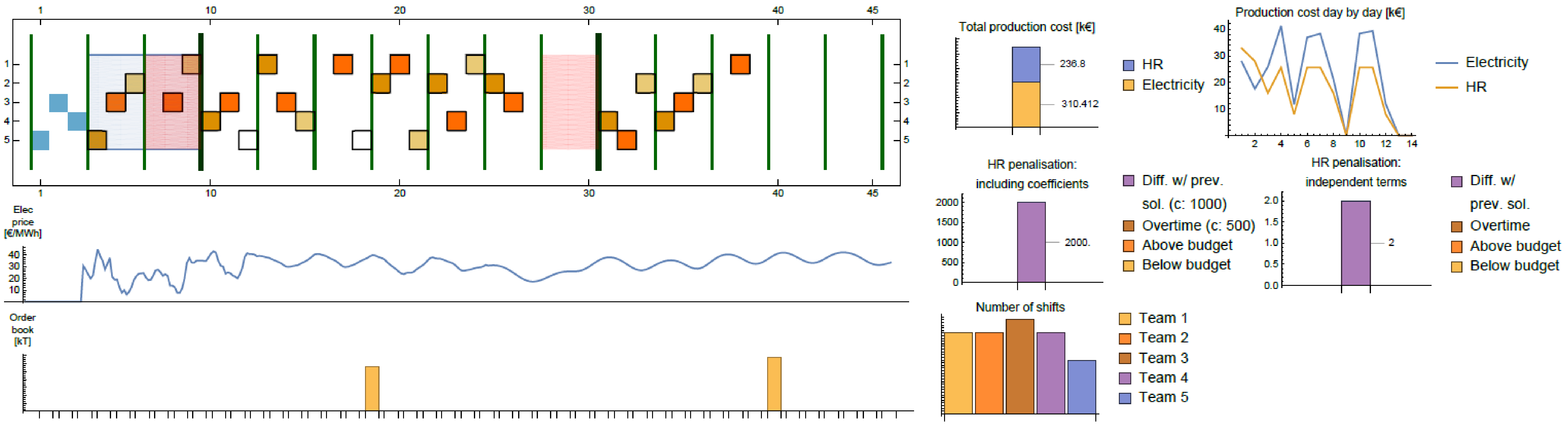

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Counterclockwise transitions (AM, MN, NA)	0	0	0	0	0
No transition (MM, AA, NN)	1	3	3	1	0
Night shifts	2	3	0	1	1
Average hours per day	3.4	3.4	3.4	2.9	1.7

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.