Towards Smart Grids and Industry 4.0: Optimal Scheduling of a Steel Plant

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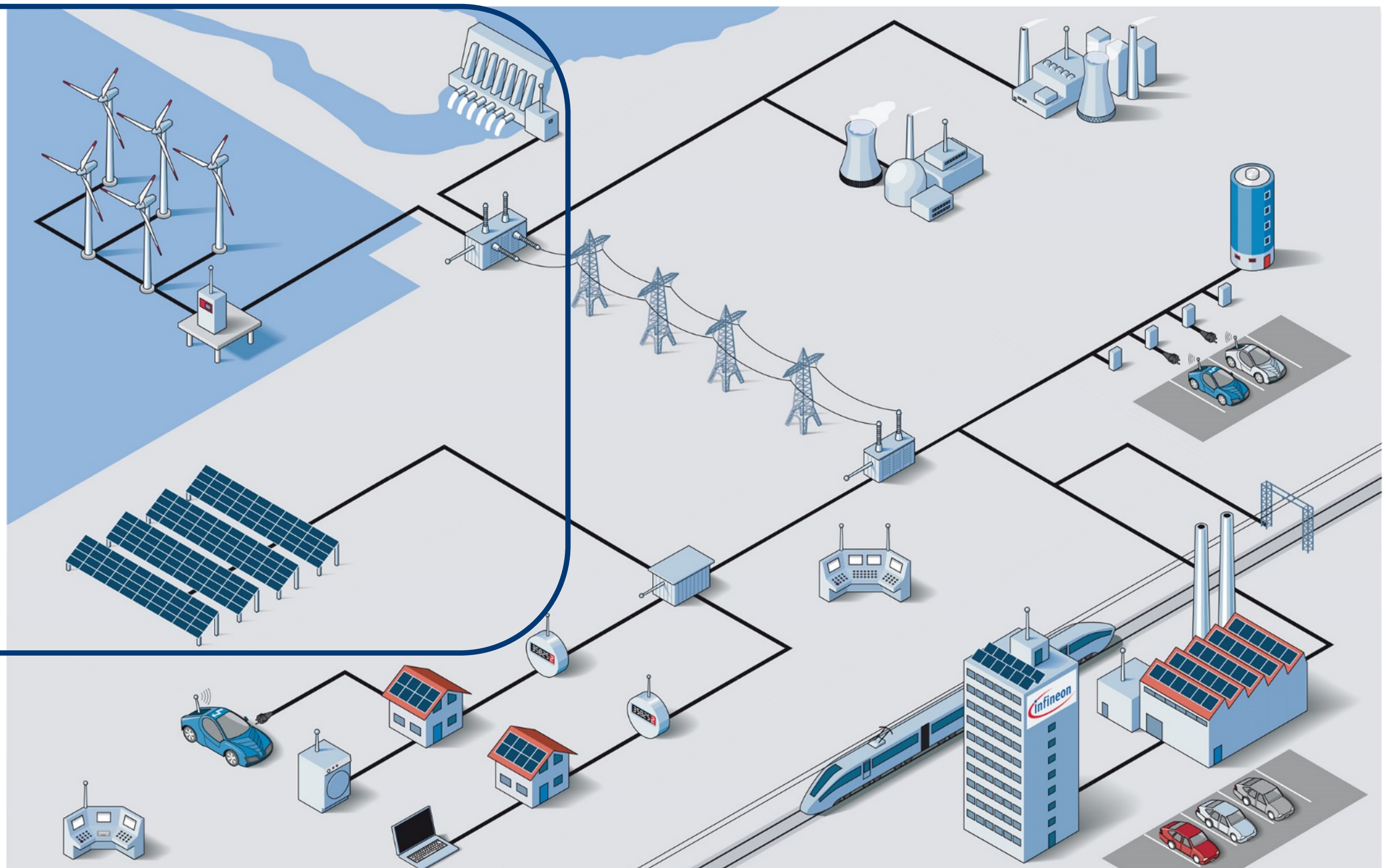
Smart grid

Power grid needs to remain balanced
Production=Consumption (limited storage)

- A real-time dynamic network of electrical demand, supply and control

Increasing penetration of renewables in the grid (volatile energy sources)

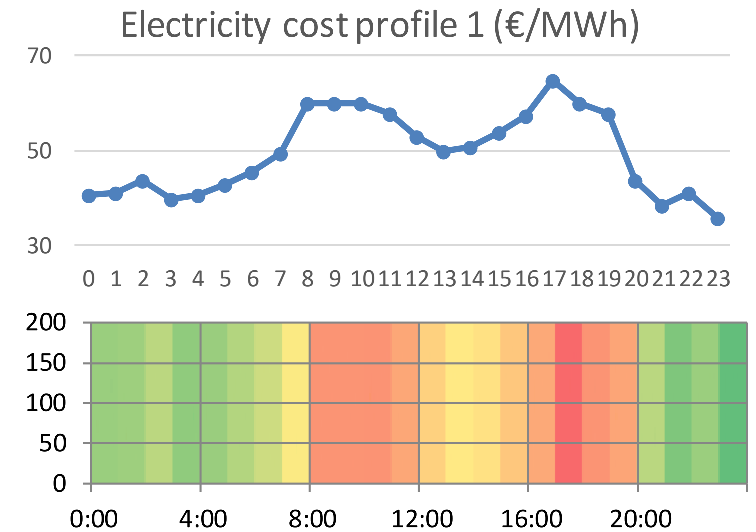


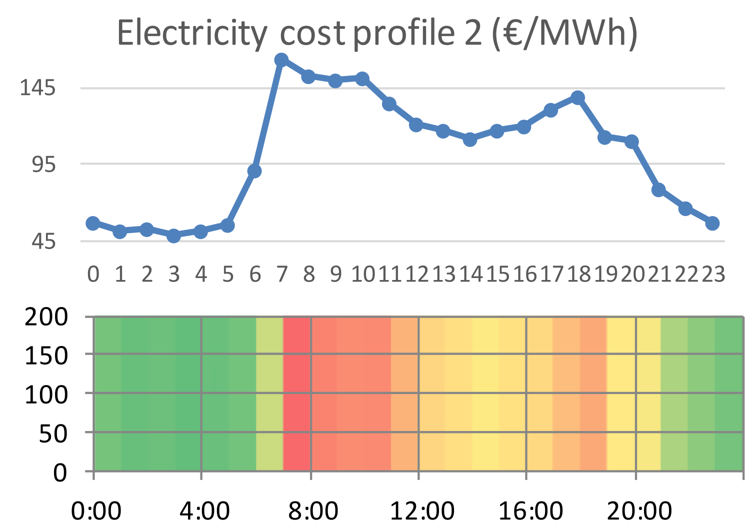
Picture from projects.leitat.org

Demand **S**ide **M**anagement refers to the methods of shaping the energy curve at the consumers' side

Industrial Demand Side Management

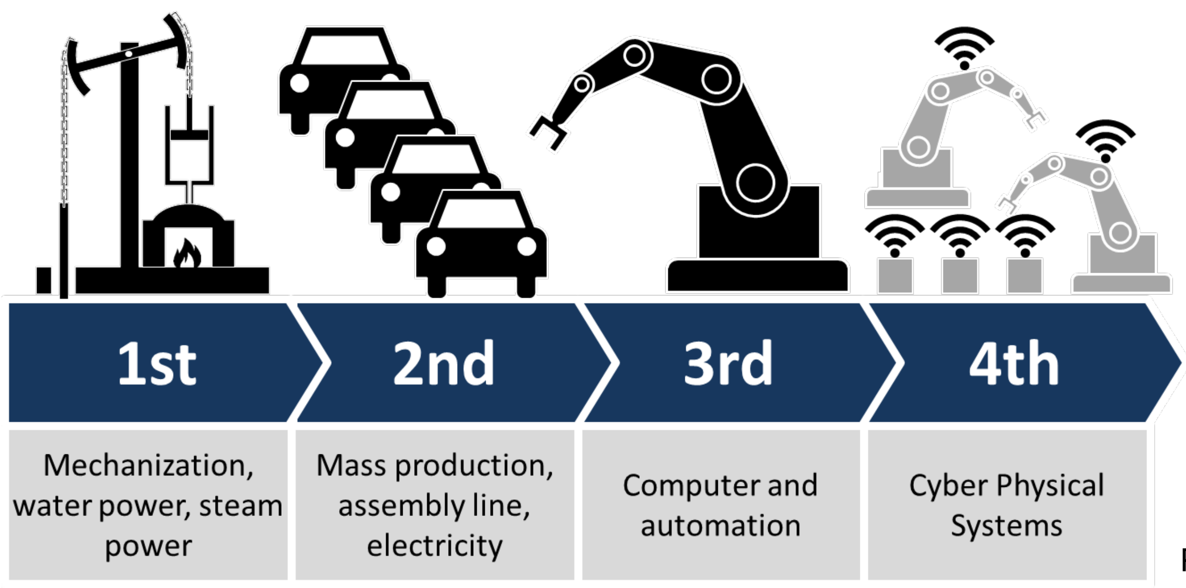
- Critical for energy intensive industries
  - Air separation, cement, pulp & paper, steel
- How to cope with uncertain electricity prices?
  - Diversify electricity purchase options
    - On-site generation
    - Long-term contracts with electricity provider
      - Power curve with on- and off-peak prices
      - Harsh penalties for under/overconsumption
    - Actively participate in energy markets
      - Time of use (TOU) contracts
- This work focuses on the day ahead spot market epexspot
  - Hourly changing prices, known around 12:00 the day before
    - Prefer green and avoid red periods





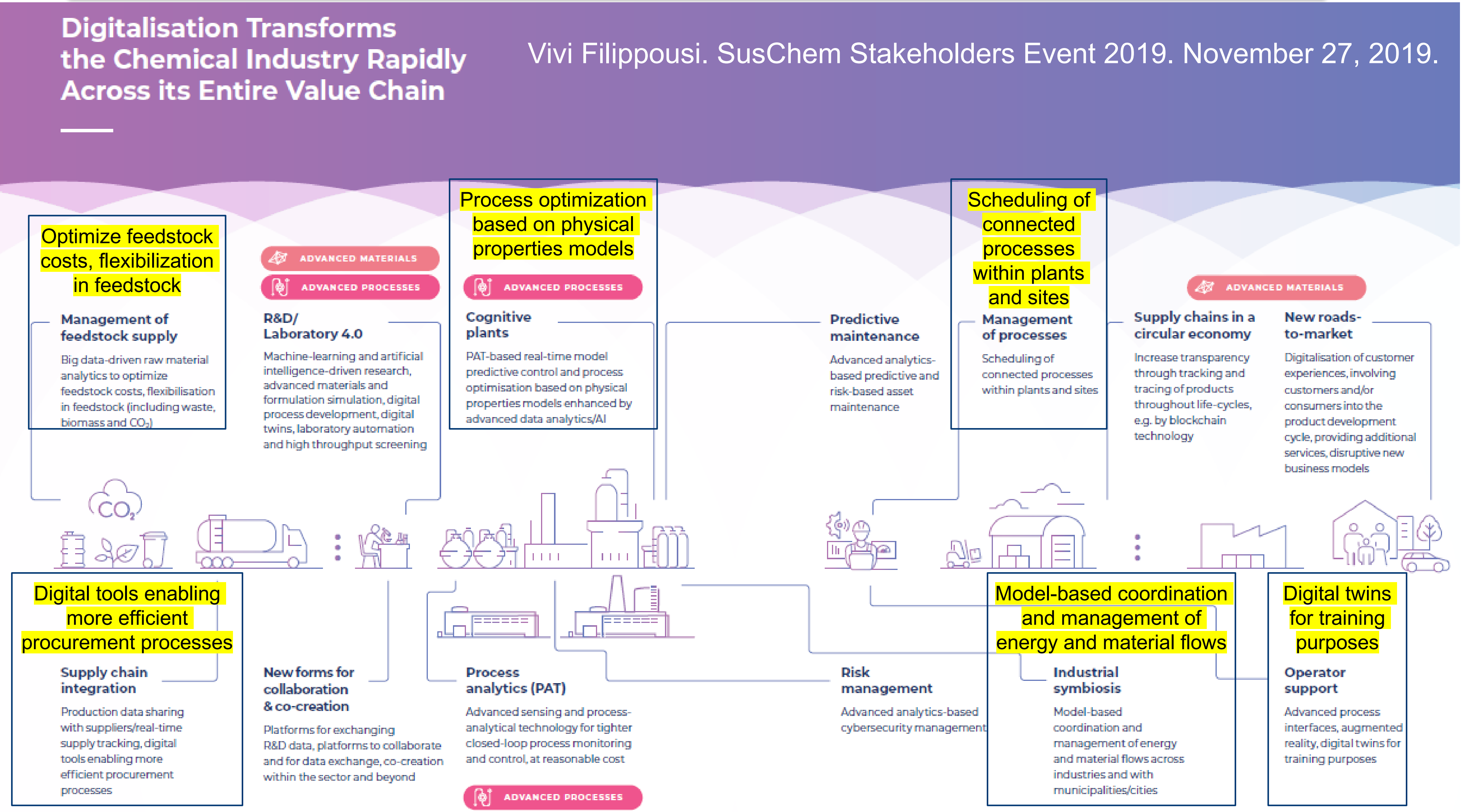
Fourth industrial revolution (Industry 4.0)

- Advanced manufacturing and smart industries
  - Computer-based decision-making tools that enhance system performance
  - Models that mimic the behavior of a physical system
  - Quickly exchange data and information with the different systems of the enterprise



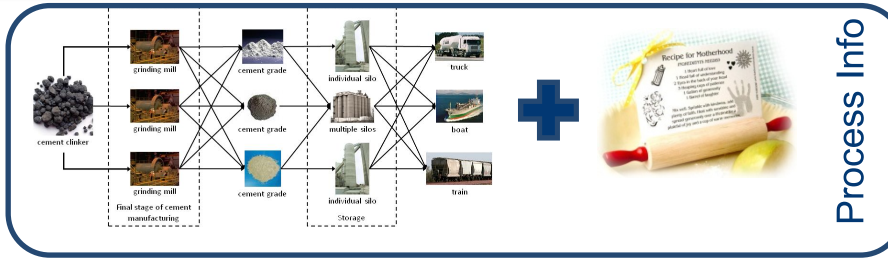
Picture from Wikipedia

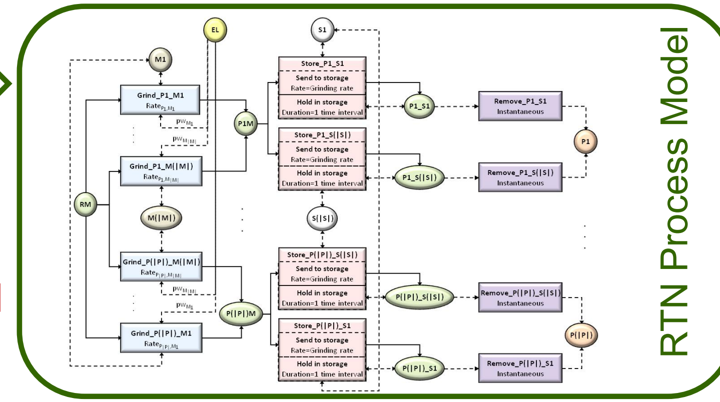
Digitalization in the chemical industry



Mathematical optimization is key

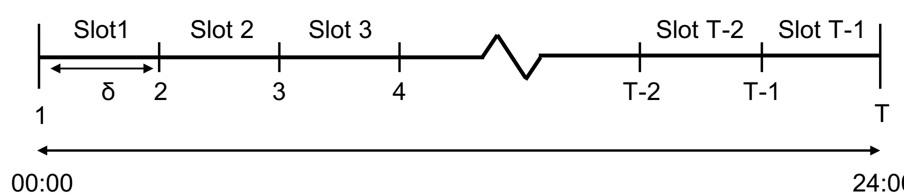
- **M**ixed-**I**nteger **L**inear **P**rogramming
- **R**esource-**T**ask **N**etwork process representation
  - Modelling of complex production recipes/environments
    - Resources (equipment units, material states, utilities, etc.)
    - Tasks (processing, maintenance, storage, etc.)
    - Structural parameters bring process data into mathematical model
- Discrete-time representation
  - Easy modelling of hourly-changing electricity prices
    - Time slots of size δ (min)



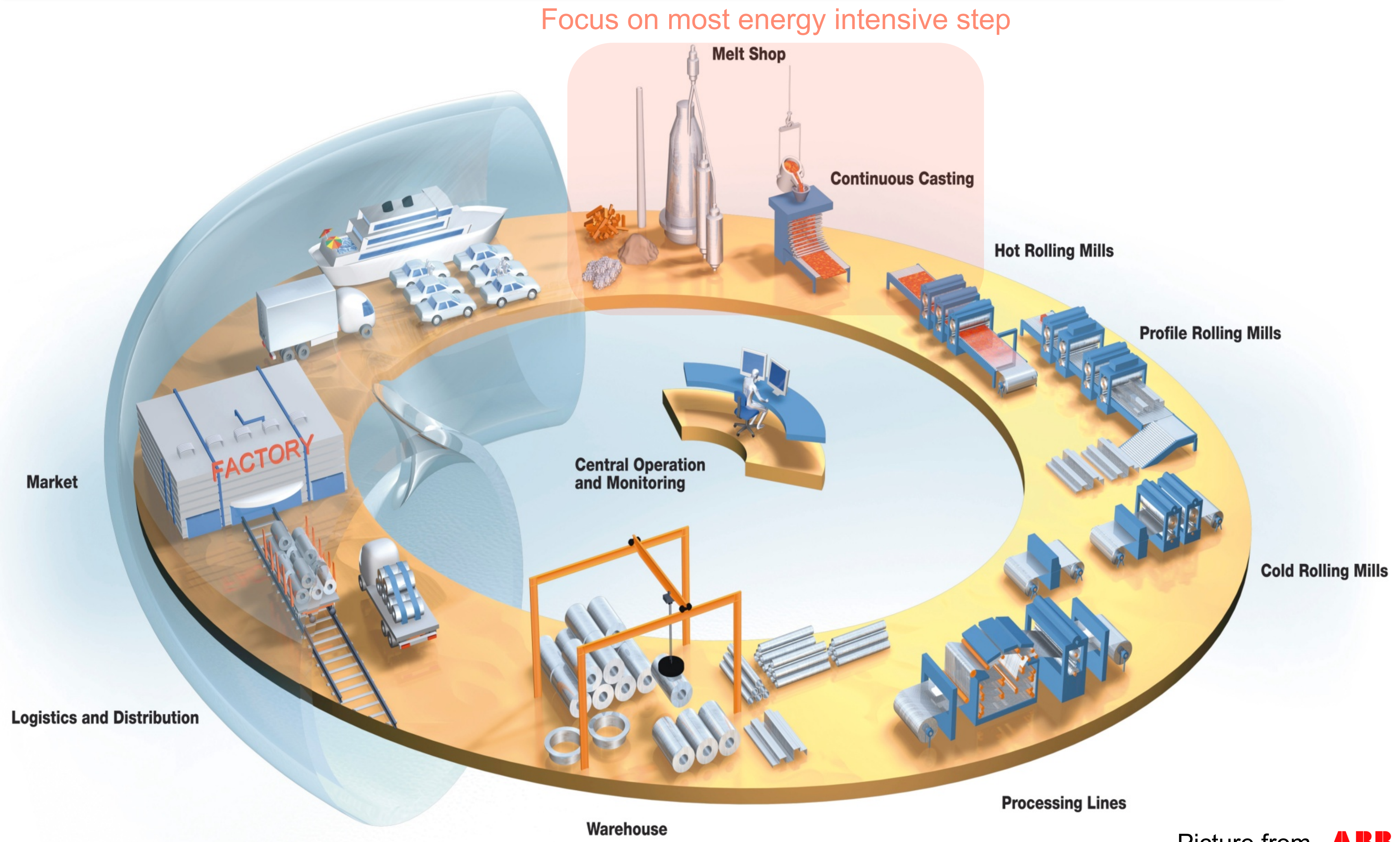


MILP Model

$$R_{r,t} = R_r^0|_{t=1} + R_{r,t-1} + \Pi_{r,t} + \sum_i \sum_{\theta=0:}^{\tau_i} \mu_{r,i,\theta} N_{i,t-\theta} \; \forall r,t$$



Case study from the steel supply chain



Picture from ABB

Steelmaking process at an Italian plant

- 4 stages, 2 units per stage

Electricity costs 50-100 M€/year

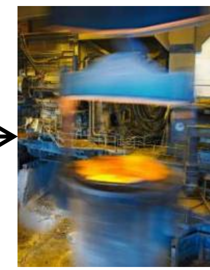
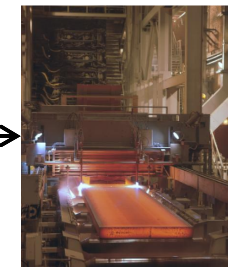
75 MW
Electric **A**rc **F**urnace: melts scrap steel

2 MW
Argon **O**xygen **D**ecarburization: adjusts the chemistry

2 MW
Ladle **F**urnace: adjusts the temperature

7 MW
Continuous **C**asting: creates steel slabs



- Typical power consumption of household appliances

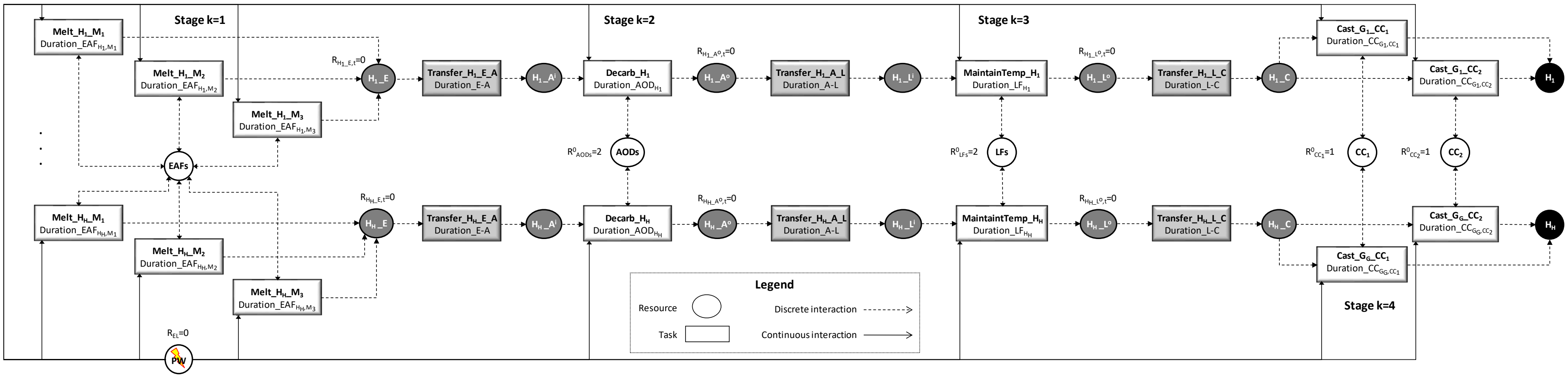

3-5 kW


2.5 kW

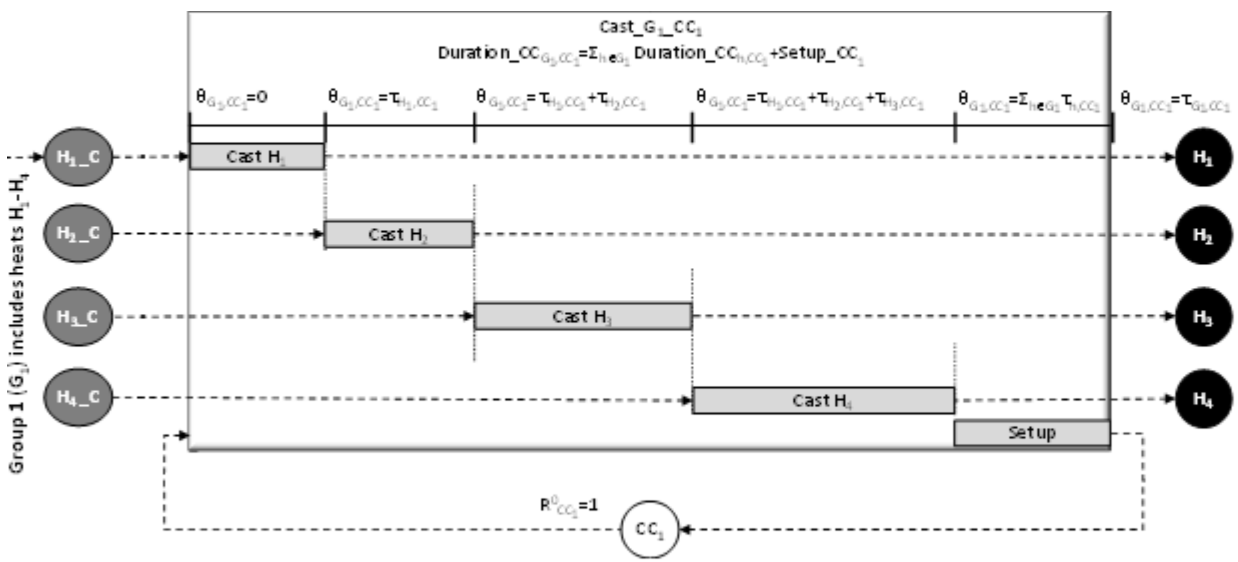
1500 W


1000 W

RTN representation of processing tasks



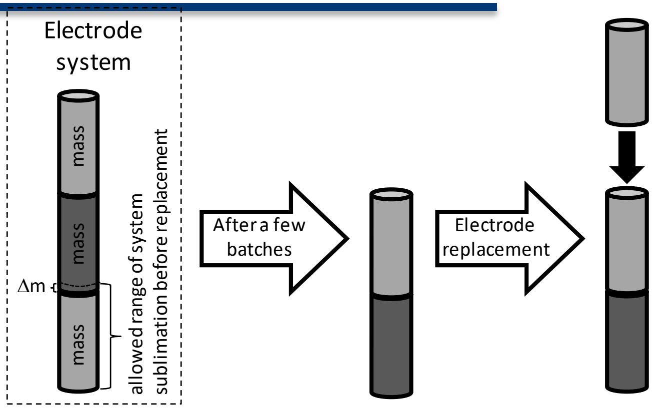
- Casting sequence (last stage) must not be interrupted!

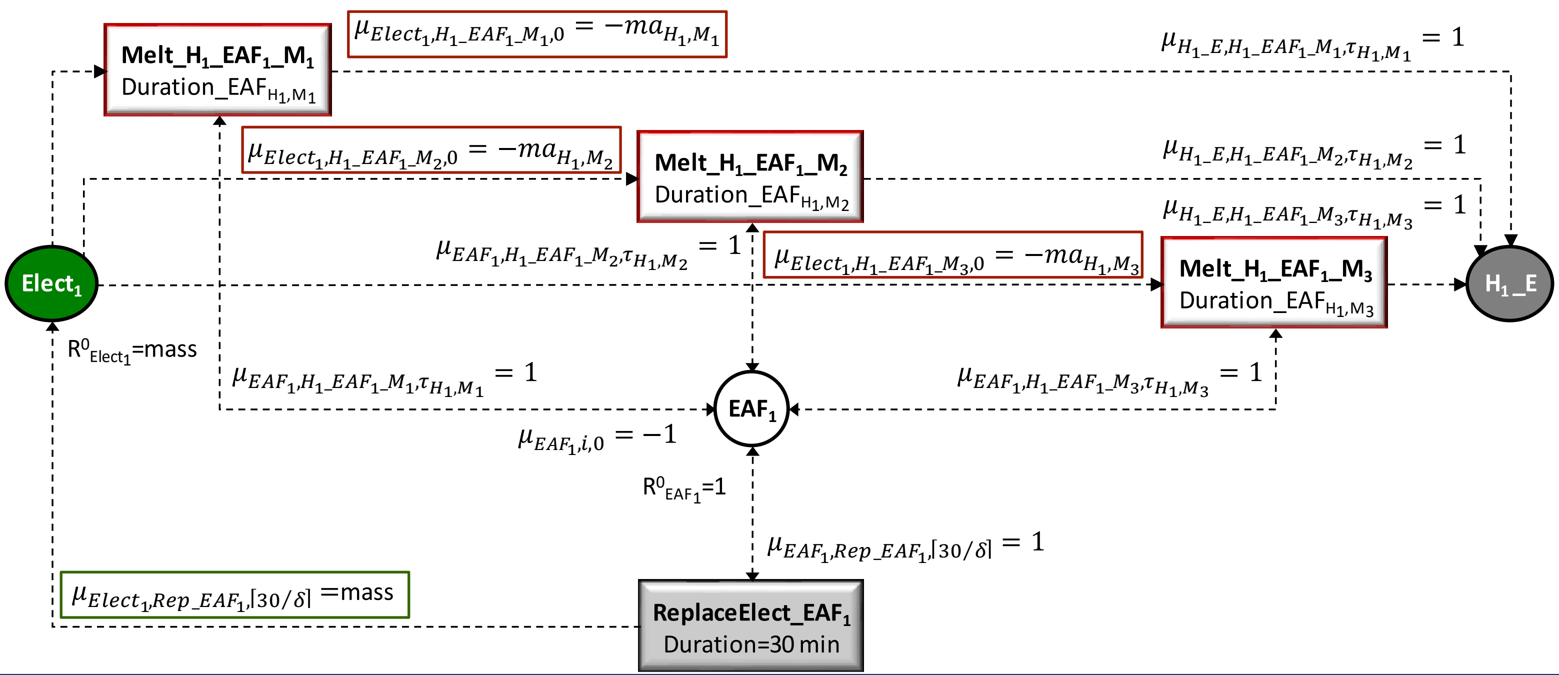


Casting task includes **steel heats of a group** plus setup time

Modelling maintenance tasks

- Electrode mass consumed during melting
- Need to replace one electrode after a few batches
  - How many? Depends on modes selected
  - Force execution of replacement task when electrode mass becomes negative
    - Regenerates electrode to allow EAF to resume operation





EAFs have multiple operating modes

- Flexibility to select power mode for a heat
- Decision not easy due to tradeoff between:
  - Production speed (more tasks in a low-cost period)
  - Energy efficiency
  - Electrode replacement frequency
    - Energy and maintenance costs are comparable

Operating mode m	M_1	M_2	M_3
Power consumption $pw_{k=1,m}$ (MW)	40	60	75
Duration for steel heats H_1-H_8, H_{13}-H_{17}, H_{21}-H_{24} (min)	69	49	41
Duration for steel heats H_9-H_{12}, H_{18}-H_{20} (min)	76	54	45
Electrode mass consumption $ma_{h,m}$ for H_1-H_8, H_{13}-H_{17}, H_{21}-H_{24} (kg)	123.3	131.4	137.4
Electrode mass consumption $ma_{h,m}$ for H_9-H_{12}, H_{18}-H_{20} (kg)	135.7	144.5	151.2

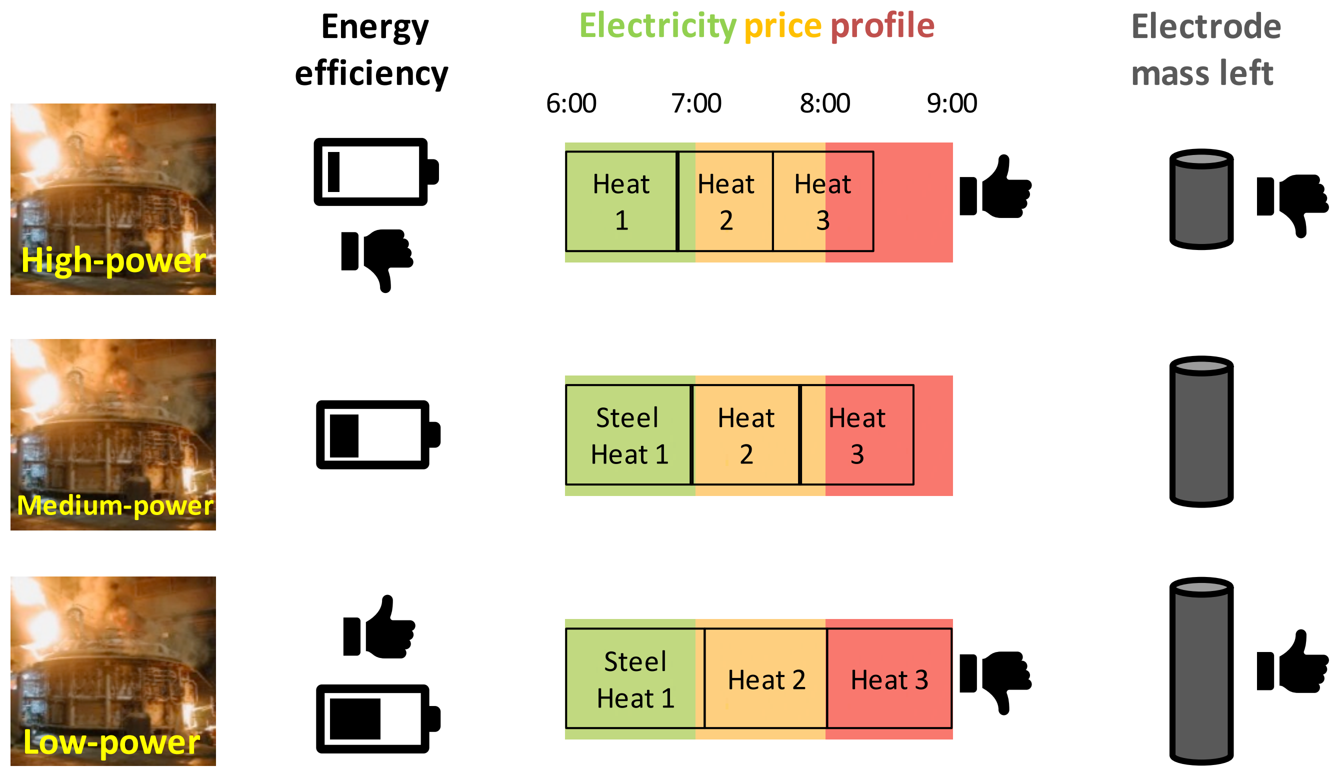
↑ Production speed →

← ↑ Energy efficiency

← ↓ Replacement cost

Problem overview

How to melt scrap steel in **E**lectric **A**rc **F**urnaces?



Total cost = Electricity purchases + Electrode replacement cost

Alternative objective functions

- Include energy cost
- Option 1: discrete electrode replacement cost
  - Accounts for purchase of new electrodes
    - $\min \sum_{r \in R^{EN}} \sum_{hr} price_{hr} \sum_{t \in T_{hr}} \Pi_{r,t} + c^{RE} \sum_{i \in I^{RE}} \sum_{t \in T_i} N_{i,t}$

Electricity price in hour hr (parameter)

Electricity purchased in slot t (continuous variable)

Electrode cost (€20,000)

Replacement task starts in slot t (binary variable)

- Option 2: continuous electrode replacement cost
  - Also accounts for fraction consumed (+) or produced (-) with respect to initial condition
    - $\min \ldots + \frac{c^{RE}}{mass} \sum_{r \in R^{EM}} (R_r^0 - R_{r,|T|})$

Mass of a new electrode (1180 kg)

Electrode mass at the start of scheduling horizon (parameter)

Electrode mass at the end of scheduling horizon (continuous variable)

RTN model constraints

- Excess resource balances
  - $R_{r,t} = R_r^0|_{t=1} + R_{r,t-1}|_{r \notin R^{PW}} + \Pi_{r,t}|_{r \in R^{PW}} + \sum_i \sum_{\theta=0:t-\theta \in T_i}^{\tau_i} \mu_{r,i,\theta} N_{i,t-\theta} \; \forall r,t$

Electrical power resource not allowed to accumulate

Resource consumption/production by processing, transfer and maintenance tasks

- Replacement tasks executed only when mass becomes negative
  - $R_{r,t} + \sum_{i \in I_r^{RE}} \mu_{r,i,\tau_i} N_{i,t} \leq mass \; \forall r \in R^{EM}, t$
    - Electrode mass cannot be greater than when in a condition new
- Steel heat h is processed/transferred once in/from every stage
  - $\sum_{i \in I_{h,k}} \sum_{t \in T_i} N_{i,t} = 1 \; \forall h, k = 1, \dots, 3$
  - $\sum_{i \in I_g} \sum_{t \in T_i} N_{i,t} = 1 \; \forall g, k = 4$ (member of group g in stage 4)
  - $\sum_{i \in I_{h,k}^T} \sum_{t \in T_i} N_{i,t} = 1 \; \forall h, k \leq 3$
- Maximum transfer time between stages
  - $\sum_{r \in R_{h,k}^{IL}} \sum_t R_{r,t} \leq \lfloor (trf_k^U - trf_k^L)/\delta \rfloor \; \forall h, 1 < k \leq 4$

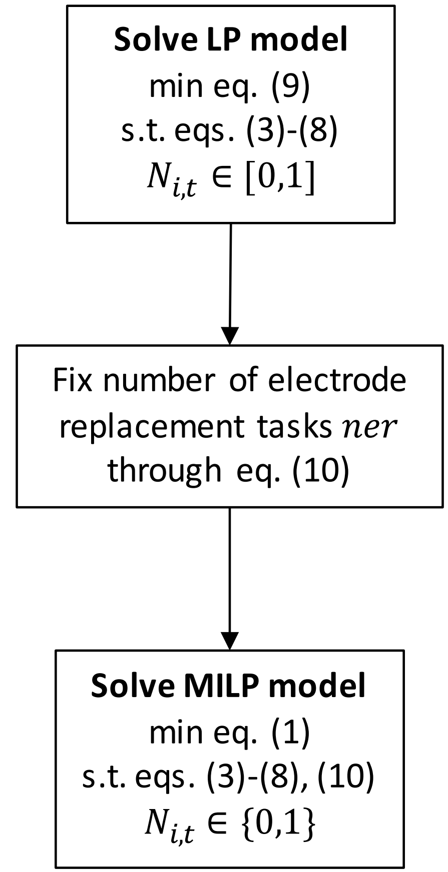
Results for discrete electrode cost

- Direct solution of MILP
  - Poor performance (up to 3600 CPUs)
    - Large optimality gap
    - No solution for δ= 5 min

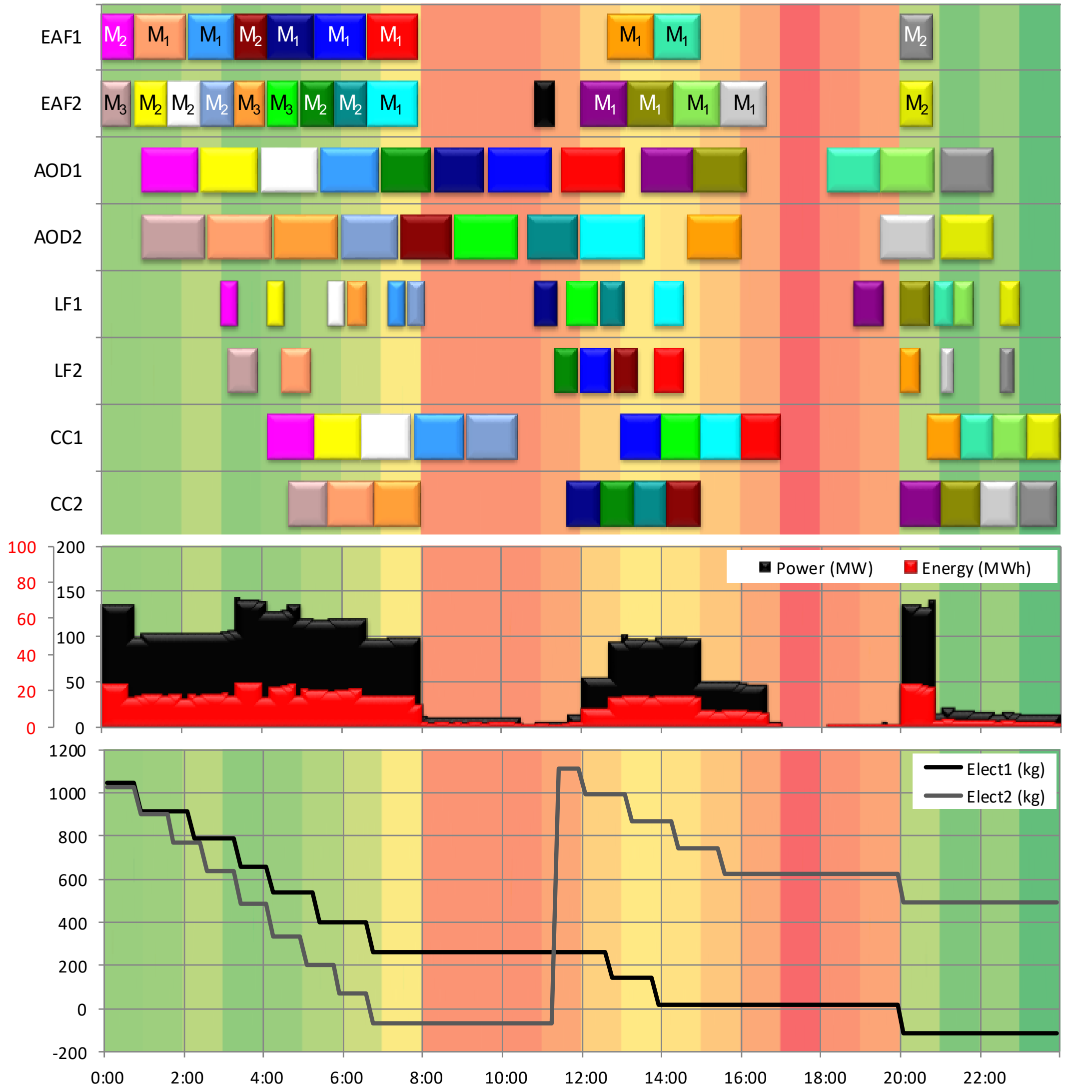
δ (min)	EAF modes	MILP (€)	LP relaxation (€)	Optimality gap
15	(M_1,M_2,M_3)	87,001	75,377	13.3%
10	(M_1,M_2,M_3)	86,827	73,718	15.1%
5	(M_1,M_2,M_3)	no solution	73,671	-

- Two-stage heuristic procedure
  - Better performance
    - Optimality gap reduced by one order of magnitude
    - 1.4% lower cost for δ= 10 min

δ (min)	EAF modes	MILP (€)	LP relaxation (€)	Optimality gap
15	(M_1,M_2,M_3)	87,086	86,297	0.83%
10	(M_1,M_2,M_3)	85,593	85,210	0.42%
5	(M_1,M_2,M_3)	no solution	85,153	-

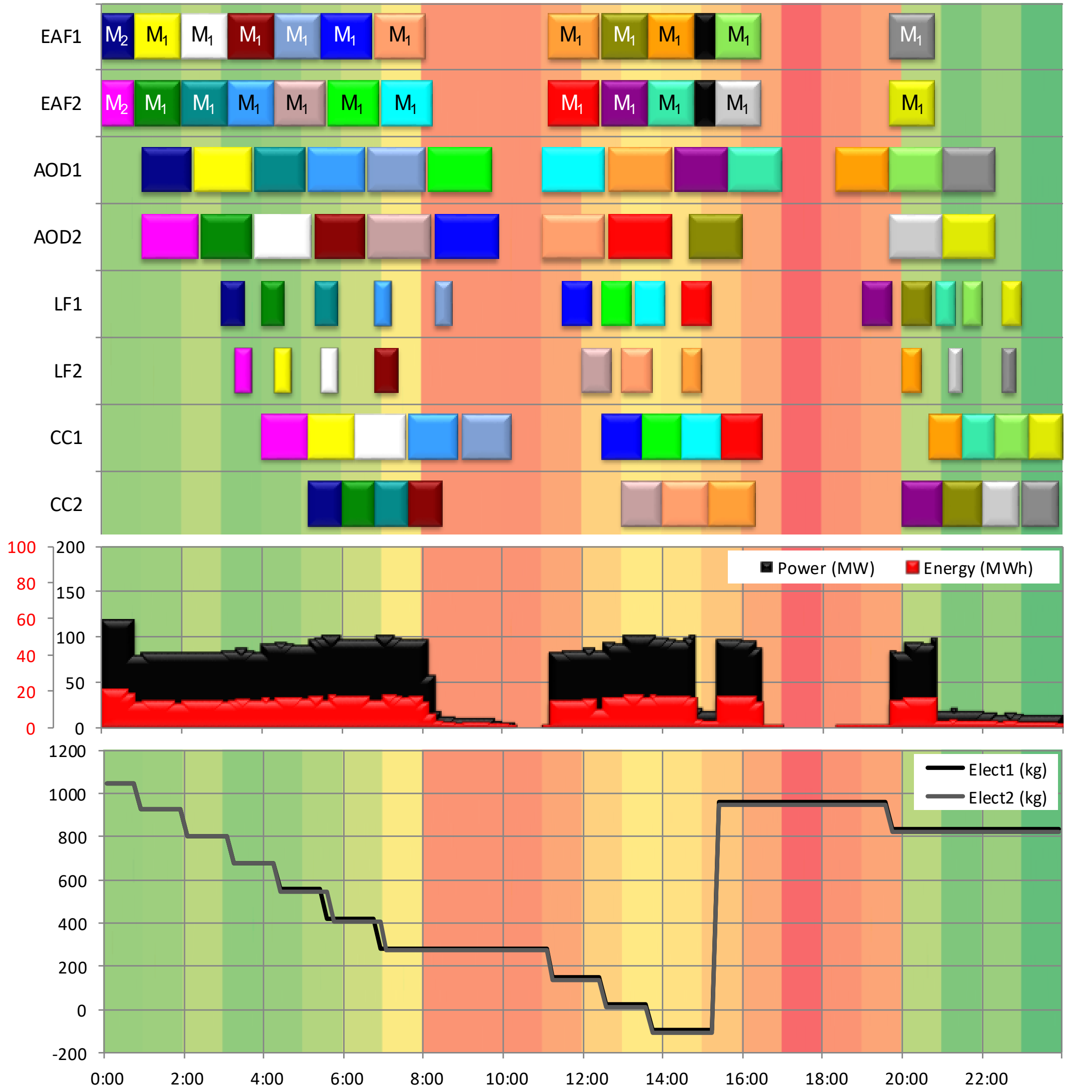


Optimal schedule for δ=10 min (€85,593)



- Optimization takes full advantage of flexible operating modes
  - (12,9,3) heats in (M_1,M_2,M_3)
- EAFs do not operate in high-cost periods and follow different strategies
  - EAF2 goes for shorter tasks
    - 1 electrode replacement
  - EAF1 prefers low power mode (10 batches)
    - Depleted electrode at the end

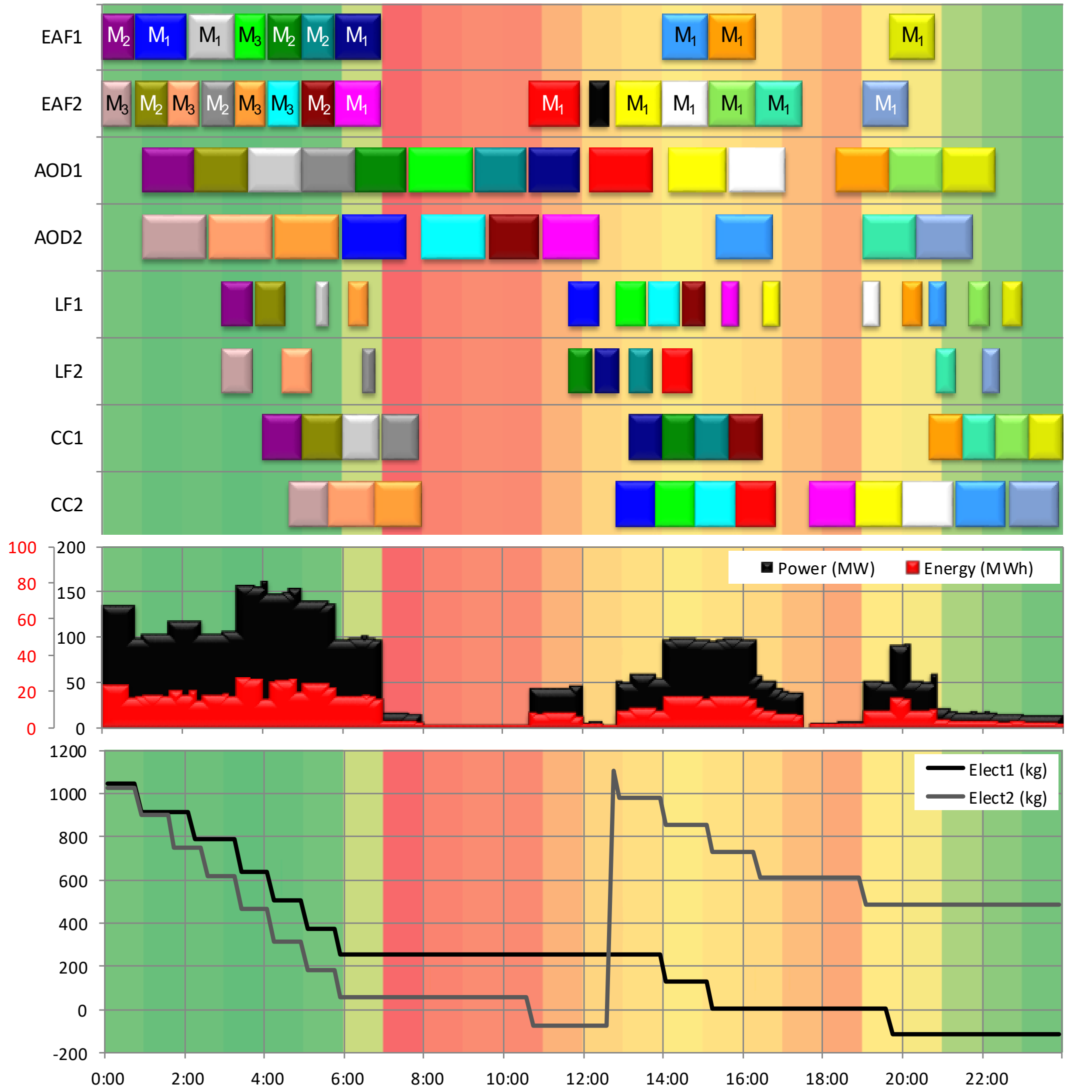
Continuous replacement cost (€118,143)



δ (min)	# heats in (M_1,M_2,M_3)	MILP (€)	Optimality gap
15	(21,3,0)	119,886	0.23%
10	(22,2,0)	118,143	0.18%
5	(21,3,0)	118,260	0.33%

- Similar strategies for EAFs
  - 1 replacement task
  - Ready for next horizon
- High-power mode completely avoided
  - Larger contribution of electrode mass in objective
  - Longer tasks ⇒ more heats in medium cost periods

Flexible operation vs. single mode



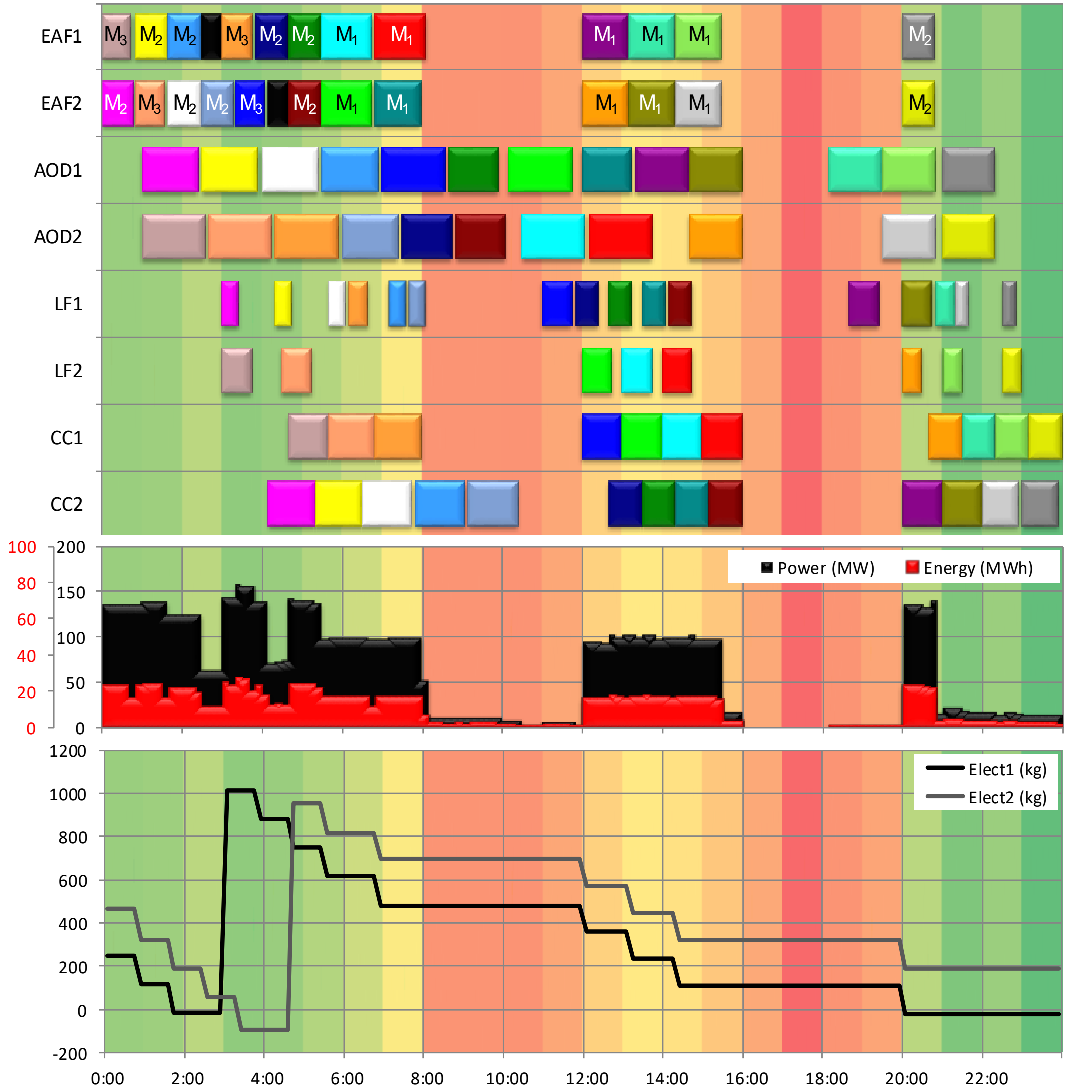
- Low-power mode is the best
  - Negligible cost increase

Mode	Cost (€)	Increase
M_1	118,146	0.00%
M_2	122,089	3.34%
M_3	126,675	7.22%

- What if we double the average electricity price?
  - (13,6,5) heats in (M_1,M_2,M_3)
  - M_2 preferred for single mode operation

Mode	Cost (€)	Increase
M_1	180,646	3.76%
M_2	174,417	0.18%
M_3	186,436	7.08%

Influence of initial electrode mass



- Electrodes not need to be new at the start
  - Rolling horizon scheme
    - R_r^0= 400 kg for EAF1
    - R_r^0= 600 kg for EAF2
      - Partly consumed at 0:00
- Replacement tasks now in green region
- Schedule very similar to before

Conclusions

- New scheduling formulation for Italian steel plant purchasing electricity from day-ahead market
  - Flexible operating modes for EAFs together with the maintenance of their electrode systems
- Optimal results for a typical price profile show majority of tasks processed in low-power mode
  - Most energy efficient, consumes the least electrode mass
  - Benefits can reach 7.2% compared to operating in single mode
- Model almost ready for everyday decision-making!
- Further details: https://doi.org/10.1021/acs.iecr.0c01714
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