Actemium Chair on Sustainable Energy

Actemium-leerstoel duurzame energie: energie-bewuste planning en optimalisatie

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Energy-aware planning and optimisation

Help companies get ready for the upcoming energy transition

Energy becomes a valuable but flexible resource — 'Bill of Energy'

Existing sustainable technologies

What infrastructure does the company need? What to invest in?

- Energy generation: solar, wind, CHP — in-plant or buy?
- Energy storage: batteries, chemical, reservoirs, tanks — cost?
- Energy conversion: turbines, heat pumps, fuel cells — losses?

clean, renewable, sustainable
but variable & limited capacity

But how to be smart about using these technologies?

Develop innovative and efficient energy-aware planning tools for production & logistics:

> When to produce what, *using which source of energy*?

Mathematical optimisation

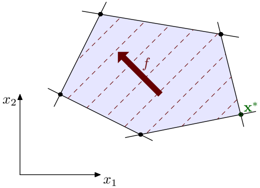
Find $\mathbf{x}^* = \arg\min_{\mathbf{x}} f(\mathbf{x})\,, \qquad \mathbf{x} \in \mathcal{S} \subset \mathbb{R}^n$

- $\mathbf{x}$ a solution
  a particular setting of all n decision variables: $\mathbf{x} = (x_1, x_2, \ldots, x_n)$
  e.g. production/transportation schedule,
  when to charge/discharge battery,
  when to convert H2 to electricity

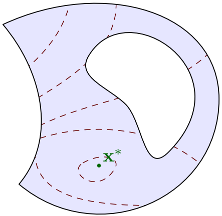
- $\mathcal{S}$ solution space, search space
  set of all feasible solutions
- f the objective function
  typically combination of: production costs, CapEx/OpEx, lead times, makespan, energy costs
- $\mathbf{x}^*$ an optimal solution (not necessarily unique)

Mathematical optimisation

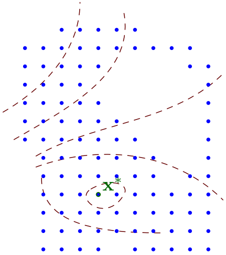
Formulations of a problem



Linear Programming (LP)
Simplex algorithm (Dantzig)
work horse of OR since 1950s



Nonlinear



Integrality of $\mathbf{x} \in \mathcal{S}$

(Computational) challenges for real-life problems

Actually solving a formulation can be difficult because of:

- very large solution space $\mathcal{S}$, high number of decision variables
- shape of solution space: many constraints, nonlinear constraints, feasibility pockets, integrality constraints
- nonlinear, nonconvex objective function f

Mathematical optimisation

Fundamental tradeoff between computation time and quality of solution

- Exact algorithms: guarantee optimality, but possibly after very long time

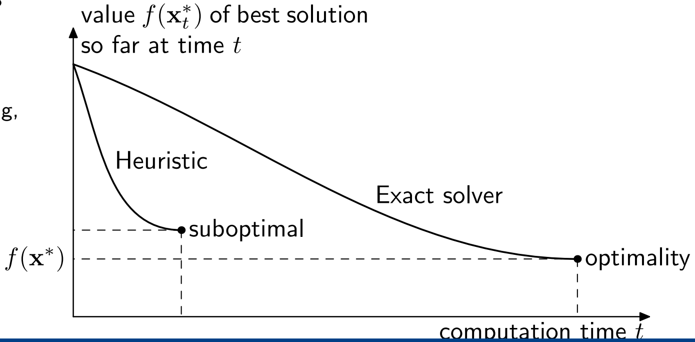
  Solvers: advanced general-purpose algorithms that take full advantage of the *formulation's* structure

  GUROBI OPTIMIZATION   IBM CPLEX

- Heuristic algorithms:
  no guarantee for optimality, but fast
  a good heuristic cleverly exploits the *problem's* structure

  genetic algorithms, simulated-annealing, ant-colony, . . .

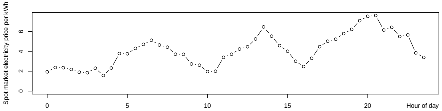
  'the heuristics zoo'



Application energy-aware scheduling

Client

- Assembly station: schedule 48 orders over one day
  All orders take 30 minutes to assemble,
  but require different amounts of electric energy (in kWh)
- Grid electricity at spot market prices



Price evolution over day known beforehand

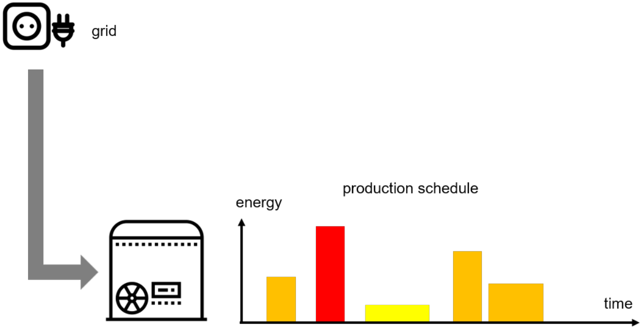
Phases of increasing commitment for client

0. As-is situation: existing schedule, regardless of energy cost
   Current objective: lead-time of orders, assembly cost, set-ups, changeovers, ...
1. Change assembly schedule to minimise energy cost
2. Invest in on-site wind turbine ...and schedule to minimise energy cost
3. Additionally invest in on-site battery
   optimal assembly schedule, optimal charge/discharge plan for battery

$\longrightarrow$ Good problem formulation?

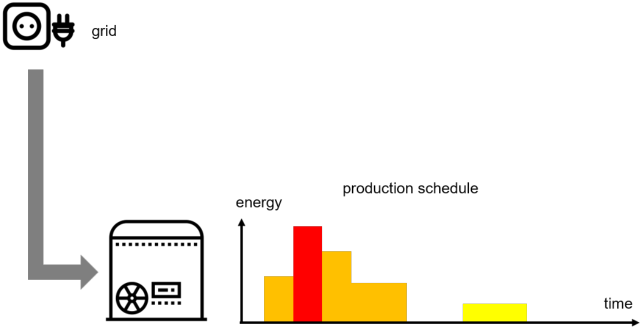
Application energy-aware scheduling

Phase 0, as is



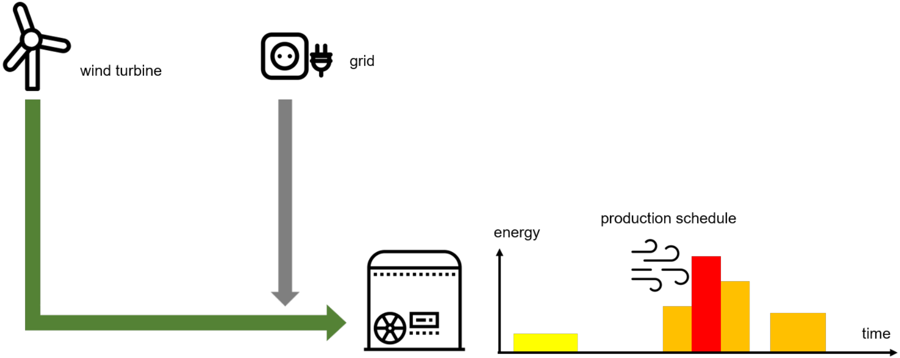
Application energy-aware scheduling

Phase 1, optimise schedule: produce when electricity is cheap



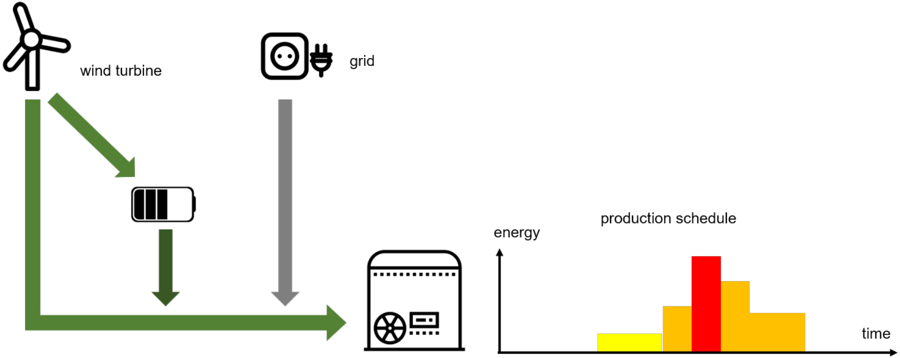
Application energy-aware scheduling

Phase 2, invest in wind turbine



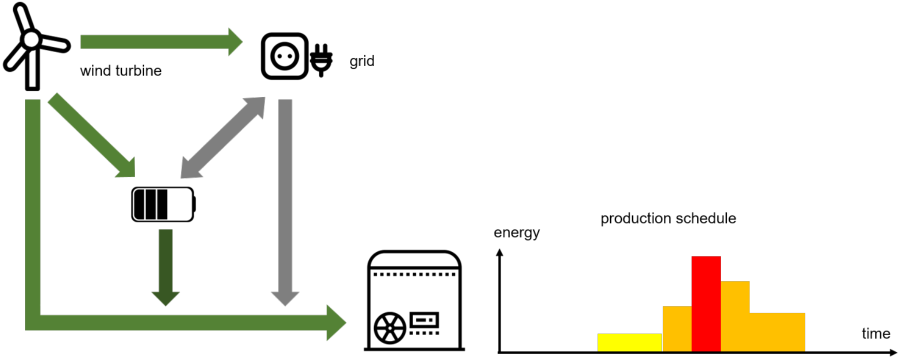
Application energy-aware scheduling

Phase 3, invest in battery



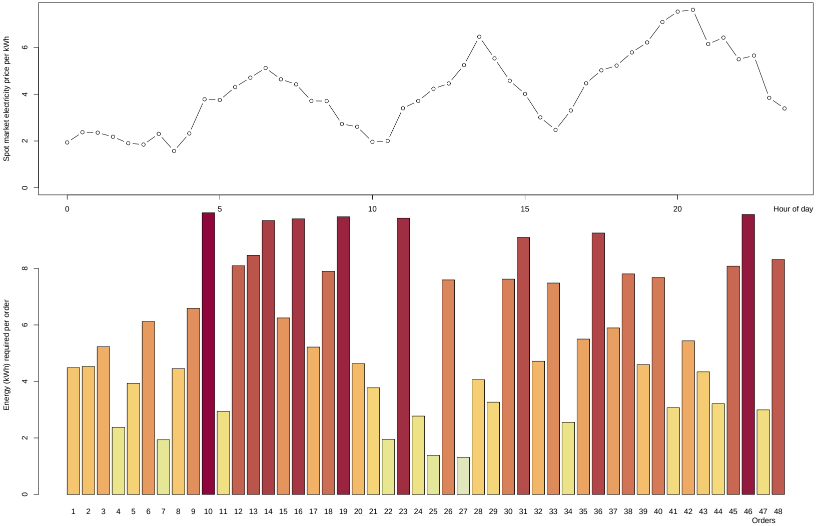
Application energy-aware scheduling

Phase 4, possibly, use battery and wind turbine to supply electricity back to the grid



Application energy-aware scheduling

Phase 0, as is

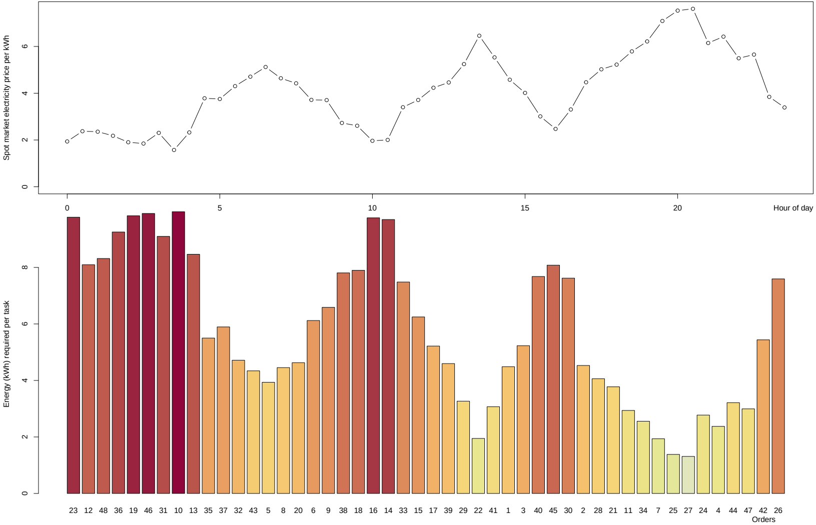


Energy cost

1155 €

Application energy-aware scheduling

Phase 1, schedule to electricity prices

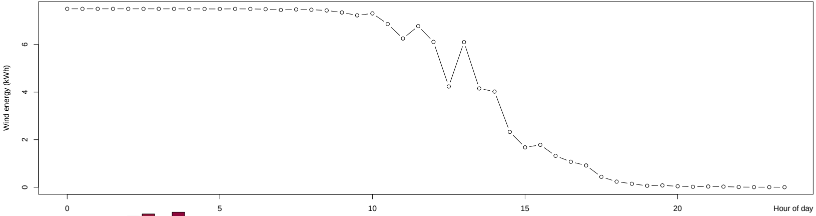


Energy cost

932 €

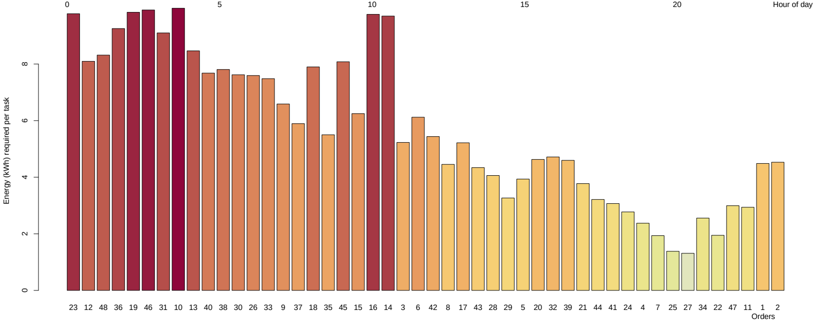
Application energy-aware scheduling

Phase 2, wind turbine



wind energy (kWh)
per half-hour interval

wind drops around noon



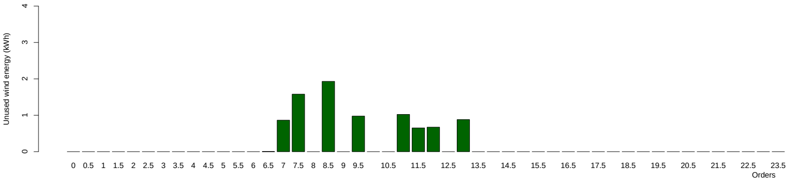
use wind if available
but grid otherwise

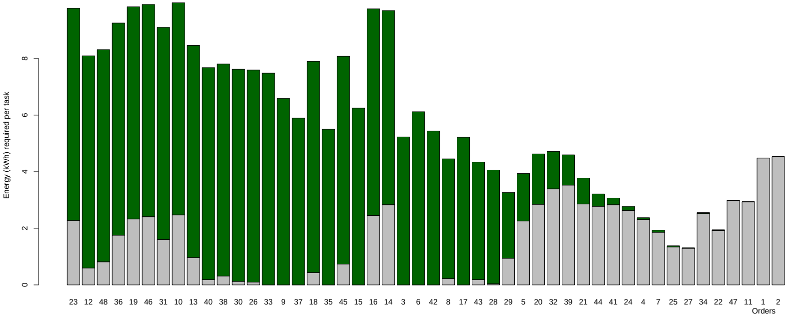
Energy cost

289 €

Application energy-aware scheduling

Phase 2, wind turbine





8.6 kWh of wind energy is not used

Application energy-aware scheduling

Phase 3, wind turbine and battery

In this case, a battery with optimal charge/discharge control will likely allow to use *all* generated wind energy of the day

Energy cost

255 €

Generalisation to real-life cases

- Optimal control of energy storage devices (e.g. batteries) is active area of research

  nonlinear charging characteristics, conversion losses, storage losses, transmission losses

- Multiple sources of energy,

  Many more degrees of freedom in the schedule

  $\longrightarrow$ complexity

  When to use energy for what? When to convert one form of energy to another?

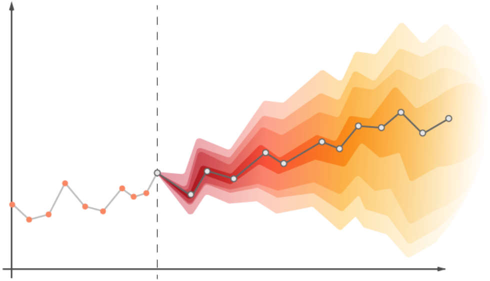
Requires detailed modeling of client's Bill of Energy

Modeling uncertainty

Obviously, future evolution of energy prices, yield of solar, wind are uncertain at time of scheduling.

We can propose a stochastic generative model (SGM) that generates possible futures ω

- A scenario ω_i is one possible future outcome
- The ensemble of all possible scenarios according to SGM is $\Omega = \{\omega_1, \omega_2, \ldots\}$



'Forecasting trumpet of doom'

Limits on predictability!

SGM: state-space models, Markov models, ...

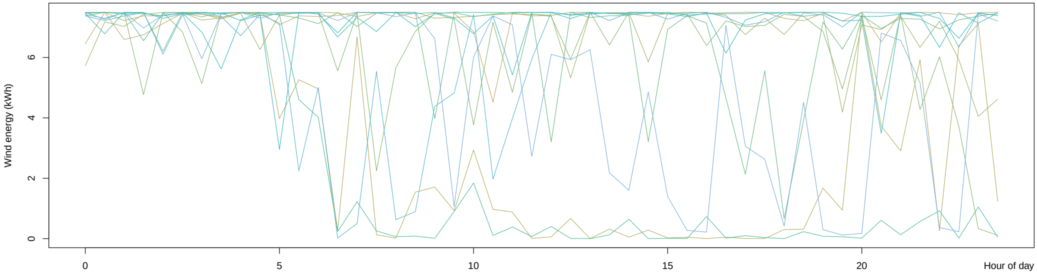
Modeling uncertainty

Scenarios wind turbine yield for client

10 scenarios $\omega_1, \ldots, \omega_{10}$ for half-hourly wind turbine yield

SGM: 6-state Markov-modulated Gaussian process (not necessarily most realistic)

$\longrightarrow$ Useful predictability only for a few hours



Modeling uncertainty

Scheduling pitfalls

× Scheduling based on a single scenario ω

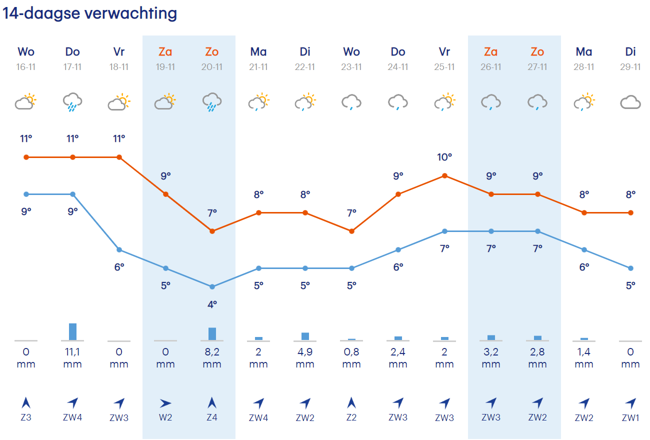
…even if it is the most likely one

× Scheduling based on an average scenario $\bar{\omega} = \frac{1}{n}\sum_{i=1}^{n} \omega_i$

…note that often $\bar{\omega} \notin \Omega$ is impossible scenario (!)

× Scheduling based on a single forecast without any idea of the forecast's precision

e.g. today's Buienradar for Ghent



Stochastic optimisation

Find $\quad \mathbf{x}^* = \arg\min_{\mathbf{x}} \mathsf{E}_{\omega\in\Omega}\left[f(\mathbf{x},\omega)\right], \qquad \mathbf{x} \in \mathcal{S} \subset \mathbb{R}^n$

- $f(\mathbf{x},\omega)$ objective function assuming the future plays out to be scenario ω
- $\mathsf{E}_{\omega\in\Omega}\left[f(\mathbf{x},\omega)\right]$ is the expected objective cost over the ensemble Ω

  Often difficult to evaluate for infinite Ω, but for k (small) possible scenarios:

$$\mathsf{E}_{\omega\in\Omega}\left[f(\mathbf{x},\omega)\right] = \sum_{i=1}^{k} f(\mathbf{x},\omega_i)\mathsf{Prob}[\omega_i]$$

Now, the scheduling is based on all or a representative subset of scenarios $\{\omega_1,\ldots,\omega_k\}$

However, more scenarios $\rightarrow$ higher complexity:

any considered solution $\mathbf{x}$ must be evaluated in all the scenarios

Robust optimisation

Can we find a solution $\mathbf{x}$ that, limits the risk of a high cost, whatever scenario plays out:

$$\mathbf{x}^{**} = \arg\min_{\mathbf{x}} \max_{\omega\in\Omega} f(\mathbf{x},\omega)$$

Takeaways

- Actemium leerstoel: onderzoek naar modellen en snelle optimalisatiemethodes voor energiebewuste planning en scheduling
  $\longrightarrow$ softwaretools
- Onzekerheid expliciet in rekening brengen, robuuste oplossingen
- Toelaten dat productieplanning wordt gewijzigd op basis van energie-objectief kan veel kosten besparen
- Welk contracttype met energieleverancier is ideaal voor uw bedrijf?
  variabiliteit van de energiekost ook belangrijk
  balanceringsmarkt, spot market, ...
- Energiemarkt op dit moment in snelle verandering.
  Bedrijven worden meer en meer naast afnemers ook producenten