Planning of energy efficiency investments in a pulp mill

A stochastic programming model with multiple objectives

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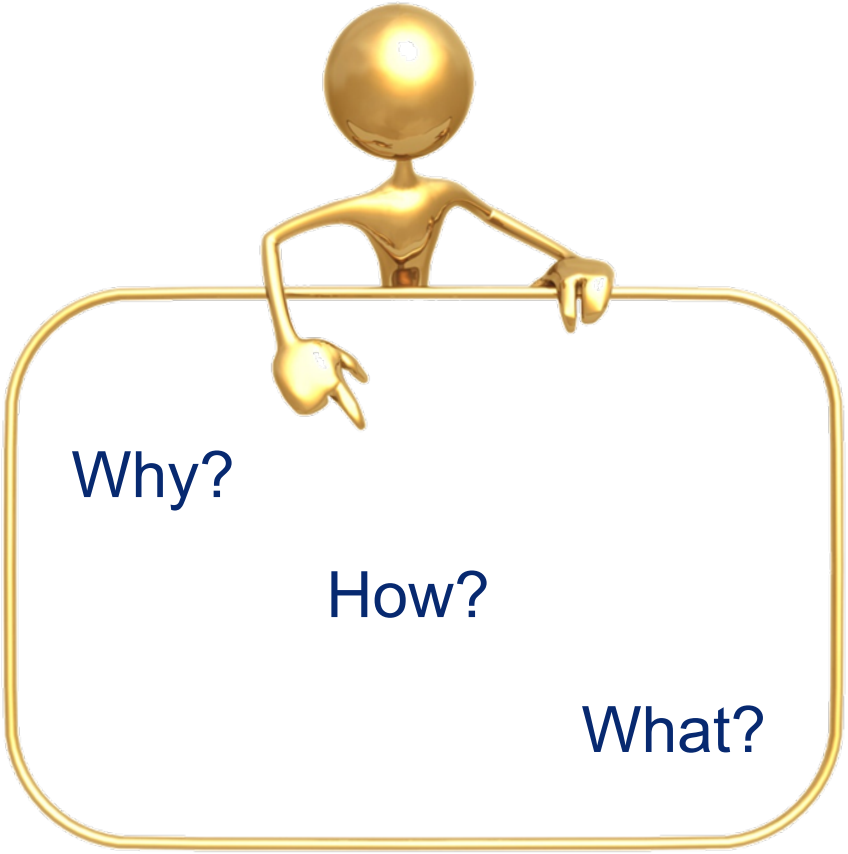
Outline of the lecture

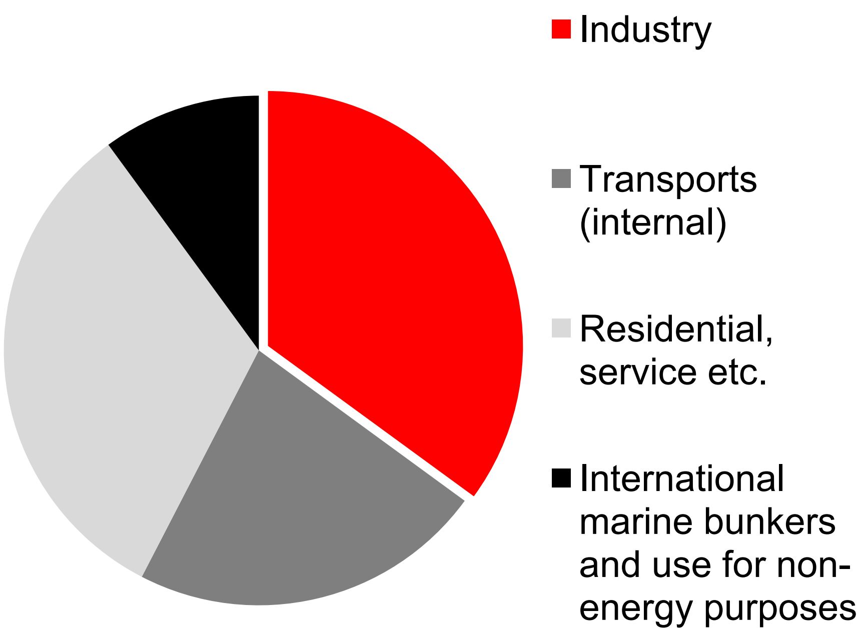
- Background
- Optimization model
- Assignment



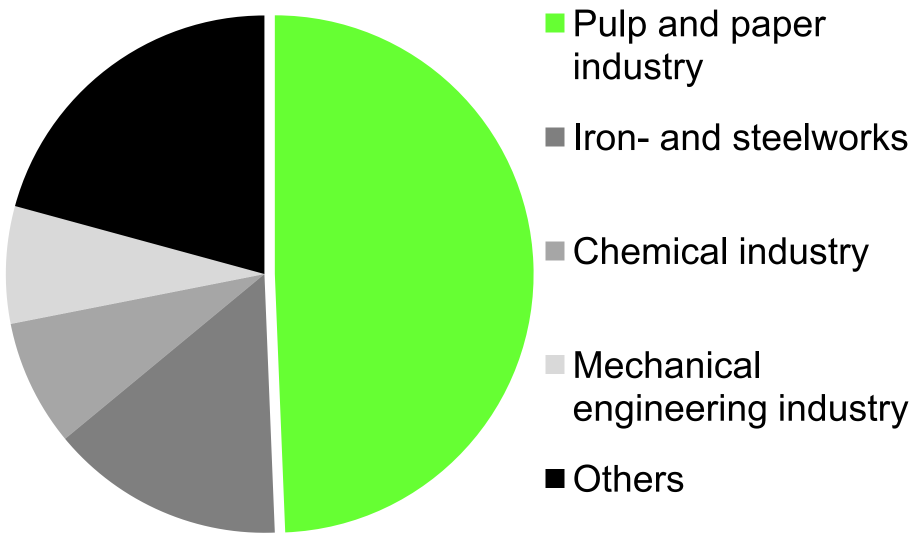
Background

Energy use in Swedish industry

Total energy use in Sweden 2006* (~450 TWh)



Energy use in Swedish industry 2006 (~160 TWh)

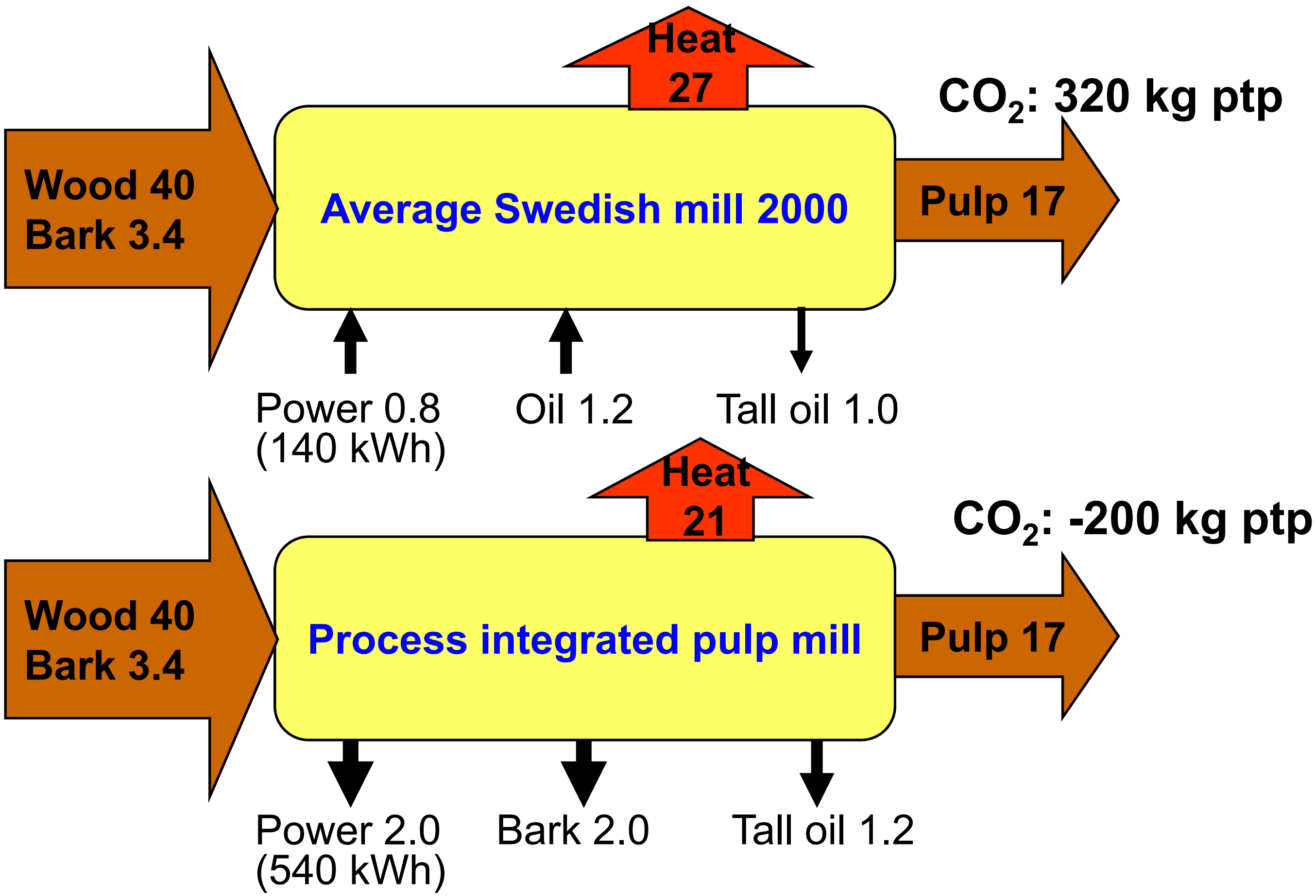


*Excluding nuclear power losses, transmission and distribution losses

Based on data from the Swedish Energy Agency

Background

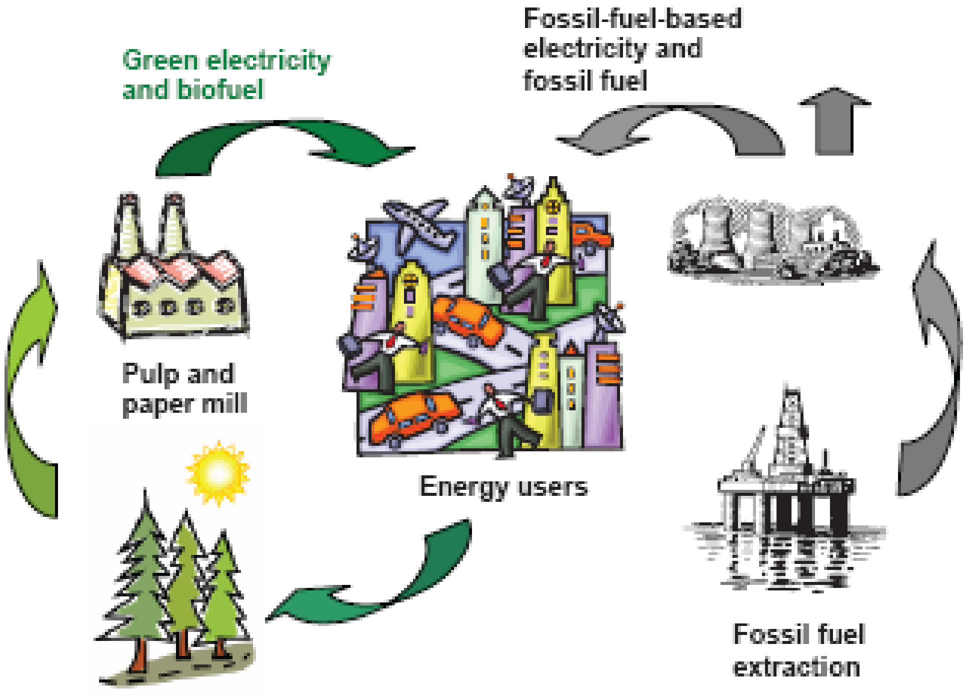
Pulp mill energy balances



New energy products for sale → Good business!

Background

A pulp and paper mill

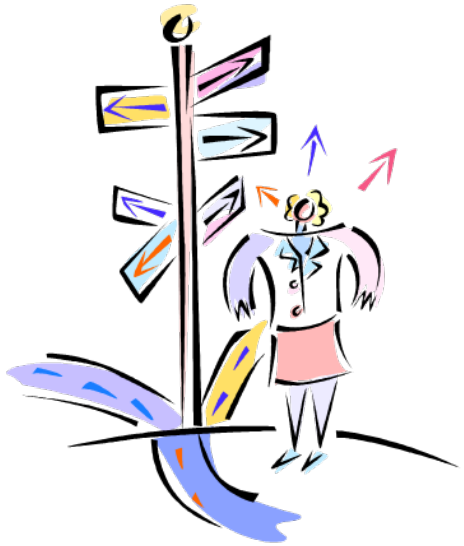


Axelsson (2008) Energy Export Opportunities from Kraft Pulp and Paper Mills and Resulting Reductions in Global CO_2 Emissions

Background

Difficult decisions

- Not all energy saving measures can be combined --> We have to choose!
- Uncertain future energy market
  - Electricity and fuel prices
  - Emissions charges and taxes
- Several objectives
  - Economy
  - CO_2 emissions
  - Etc



Optimization model

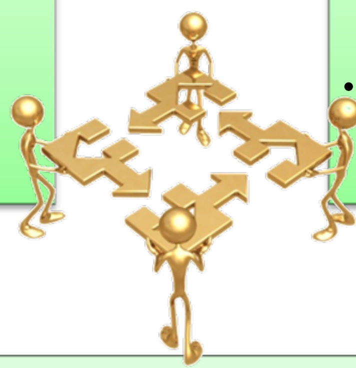
Important features

Mixed-integer programming

- Decision variables:
  - Typically binary

Multistage stochastic programming

- Decision structure:
  - Decisions → Realizations → Decisions
- Uncertainty modelling:
  - Energy market scenarios with assumed *probability distribution*



Multiobjective programming

- Two objective functions:
  - E[NPV] : The *expected* net present value
  - E[CO_2]: The *expected* CO_2 emissions reductions

Optimization model

Stochastic programming

- Two-stage decision model

- Favours **flexible** and **robust** solutions, and solutions **hedging** against uncertainty
- **Multistage models** are also possible

- Maximization of the expected value – **probability distributions** are required

Optimization model

Modelling the future energy market

How would you model future energy prices?

What are the difficulties?

Discuss in small groups

Optimization model

Scenario model

1 — business as usual

- Low charges on CO_2 emissions
- Energy prices as in Sweden today (2006)
- Coal “on the margin”

2 — moderate change

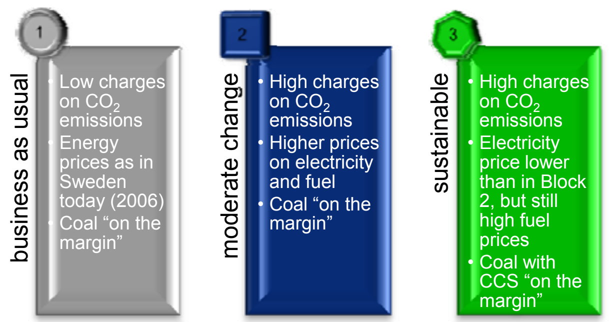
- High charges on CO_2 emissions
- Higher prices on electricity and fuel
- Coal “on the margin”

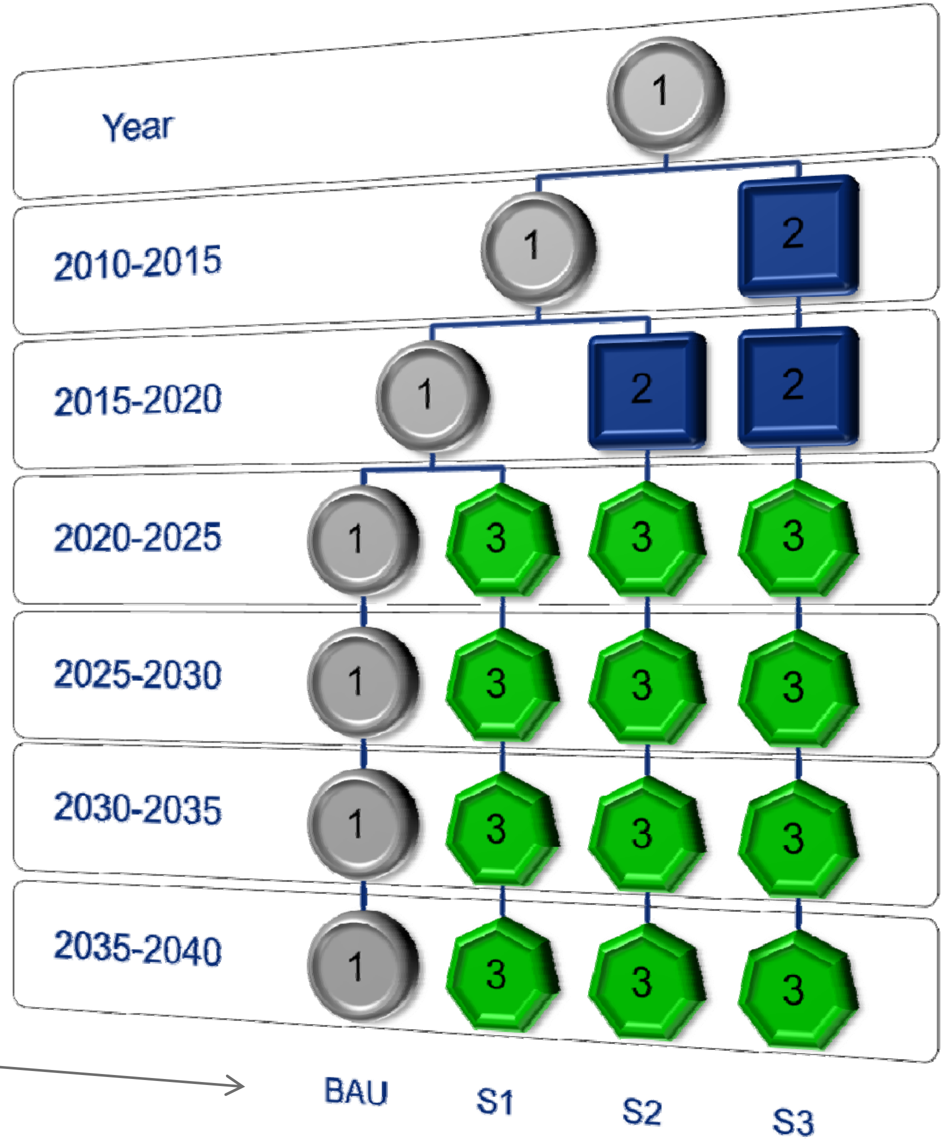
3 — sustainable

- High charges on CO_2 emissions
- Electricity price lower than in Block 2, but still high fuel prices
- Coal with CCS “on the margin”

Optimization model

Scenario model





BAU	Business As Usual
S1	Sustainability, distant future
S2	Sustainability, near future
S3	Sustainability, very soon

Time for a break?

Optimization model

Evaluating investments

Net present value

$$\mathrm{NPV} = -C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

Rule for 1 investment option: Invest if NPV > 0
For several options: Invest in the options which gives the highest NPV

Optimal investment plan = The investment plan with maximum *expected* NPV

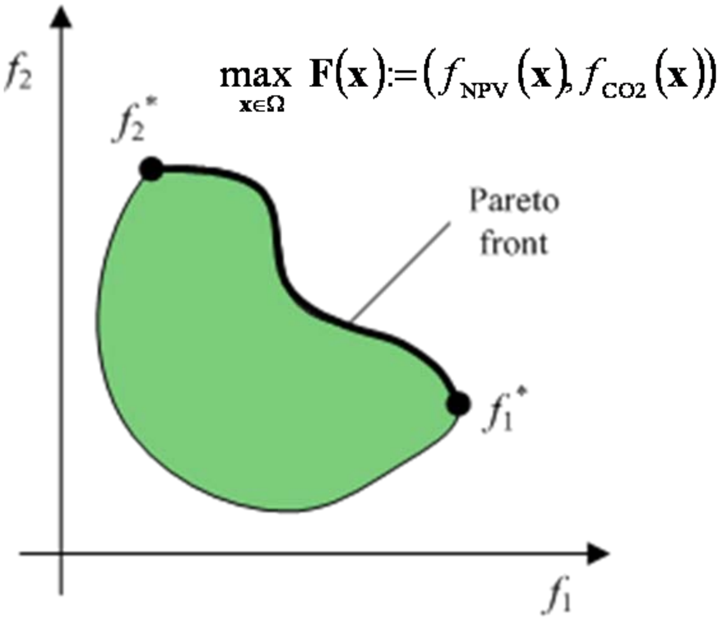
$$\text{maximize } \mathrm{E}[\mathrm{NPV}(x)] := -C_0(x_0) + \sum_{s \in S} p_s \sum_{t=1}^{T} \frac{C_t(x_0, x_s, \omega_s)}{(1+r)^t}$$

Optimization model

Multiobjective programming

Pareto-optimal solutions

One objective cannot be improved without worsening at least one other objective. Also known as non-dominated solutions.



Optimization model

Objective functions

The economic objective:
The expected net present value of the investments

$$f_{\mathrm{NPV}} := \sum_{n \in N} \mathrm{pr}^n \left(\phi(\ell(n)) f_R(\alpha^n, \xi^n) - \psi(\ell(n)) f_C(\hat{x}^n, \hat{y}^n, \delta^n) \right)$$

The CO_2 objective:
The expected ”net present value” of the emissions reductions

$$f_{\mathrm{CO2}} := \sum_{n \in N} \mathrm{pr}^n \phi(\ell(n)) f_{\mathrm{Em}}(\alpha^n, \xi^n)$$

Optimization model

Finding Pareto optimal solutions

How will the Pareto front look like for a MILP problem (like this one)?

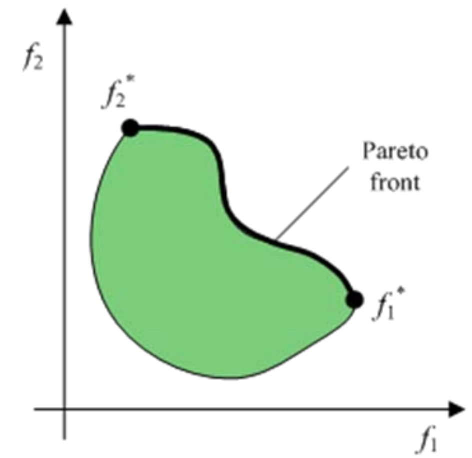
Which methods can be used to find the Pareto optimal solutions?

Discuss in small groups

Optimization model

The ε-constraint method

$$\max_{\mathbf{x}\in\Omega} \mathbf{F}(\mathbf{x}) := \left(f_{NPV}(\mathbf{x}), f_{CO2}(\mathbf{x})\right)$$



$$\left.\begin{array}{ll} \max & f_{NPV}(\mathbf{x}) \\ \text{subject to} & f_{CO2}(\mathbf{x}) \geq \varepsilon \\ & \mathbf{x}\in\Omega \end{array}\right\}$$

Articulates the preference of the decision-maker

Extreme values of ε.

Upper limit =
Maximum value of f_{CO2}(**x**) for **x** in Ω

Lower limit =
Value of f_{CO2}(**x***) where **x*** is the optimal solution to the maximization of f_{NPV}(**x**) for **x** in Ω.

Optimization model

Examples of constraints

- Active investments

$$x_m^n = x_m^{p(n)} + \hat{x}_m^{p(n)} - \check{x}_m^{p(n)}, \qquad m \in M, \; n \in N \setminus R$$

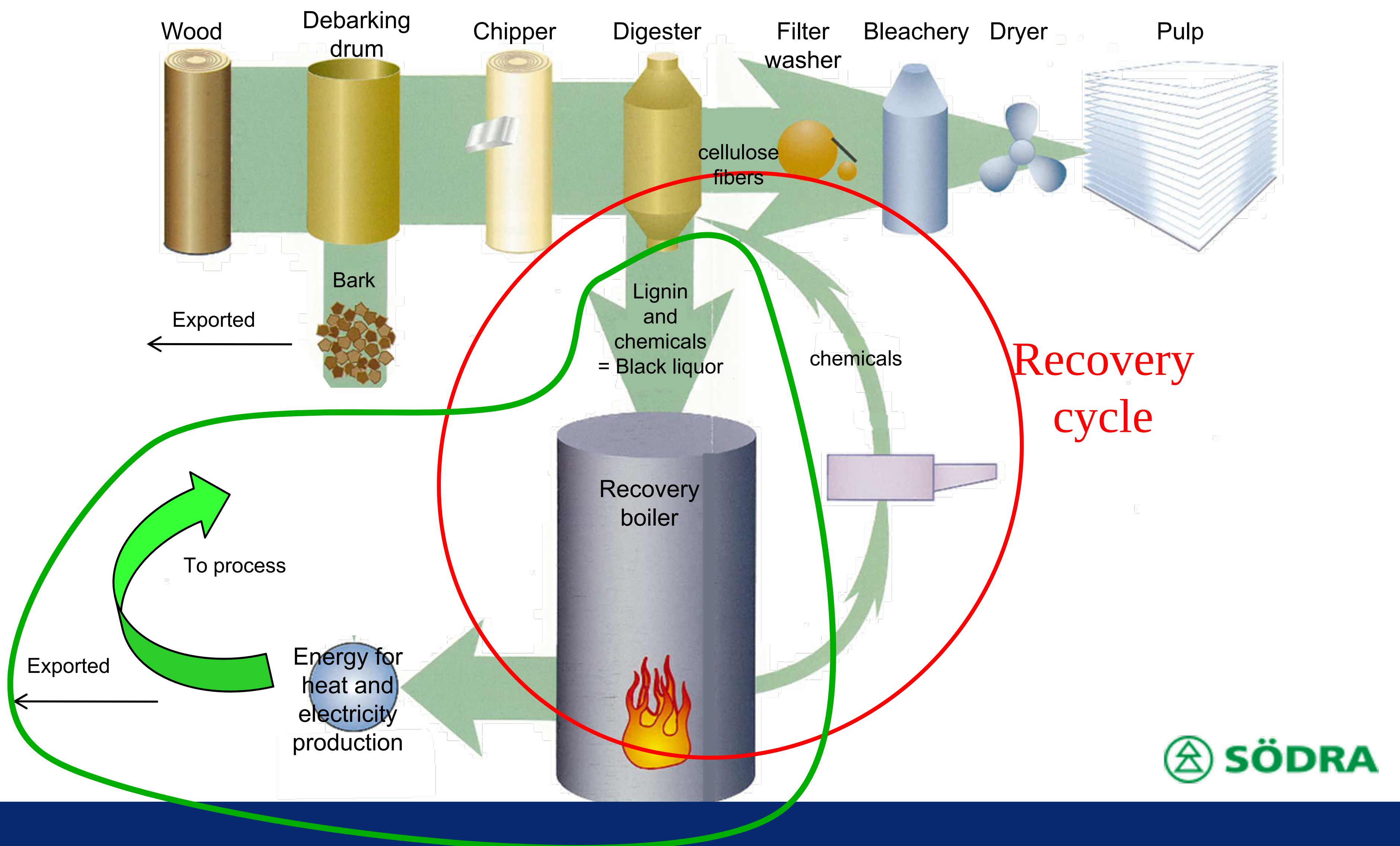
- Steam balances

$$\sum_{u \in U \setminus (Q \cup L)} \rho_{u,\mathrm{MP}}^n \leq \sum_{m \in M} x_m^n s_{m,\mathrm{MP}} + \sum_{u \in Q} \left(\rho_{u,\mathrm{HP}}^n - \rho_{u,\mathrm{MP}}^n\right) h_{u,\mathrm{MP}}, \qquad n \in N$$

- Energy conversion

$$\alpha_u^n \leq \sum_{p \in P} q_{up} \rho_{up}^n + \gamma_u^n, \qquad u \in U \setminus L, \; n \in N$$

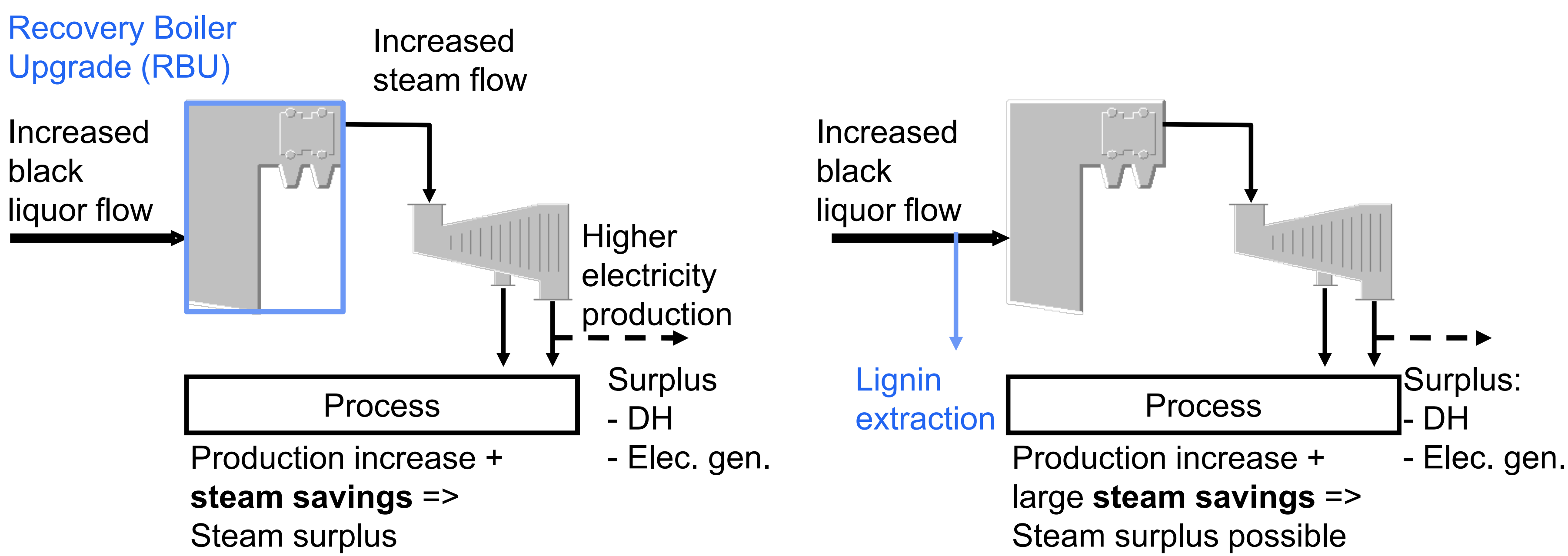
Assignment - The pulp mill



Assignment

A production increase at the pulp mill

Decision taken to increase the pulp production by 25%. The recovery boiler is a bottleneck.



Assignment

Optimal solution – The optimal investment plan

- Which investments are made and when
  `AMPL: activate`
- What capacities of turbines, lignin extraction, etc have been invested in
  `AMPL: size`

Assignment

Exercises

1. Find the economically optimal investment plan => ε_{low}
2. Find the investment plan that maximizes the CO_2 emissions reductions => ε_{high}

3-4. Construct a Pareto graph and discuss its appearance

5-6. Investigate the sensitivity of the solution to variations in various parameters

Assignment

Consultation

- Before the end of this week
  My office at Heat and Power Technology
  Room 1208, Chemistry building

- After Friday, by e-mail only:
  elin.svensson@chalmers.se

Good luck!

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