Planning of energy efficiency investments in a pulp mill

A stochastic programming model with multiple objectives

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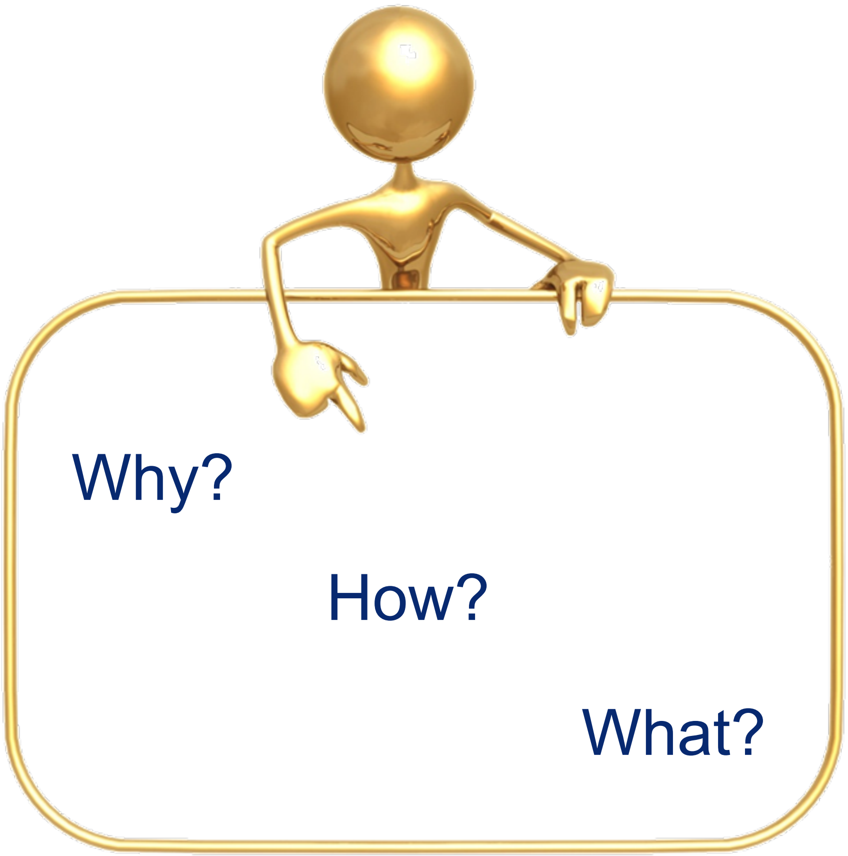
2010-05-06

Outline of the lecture

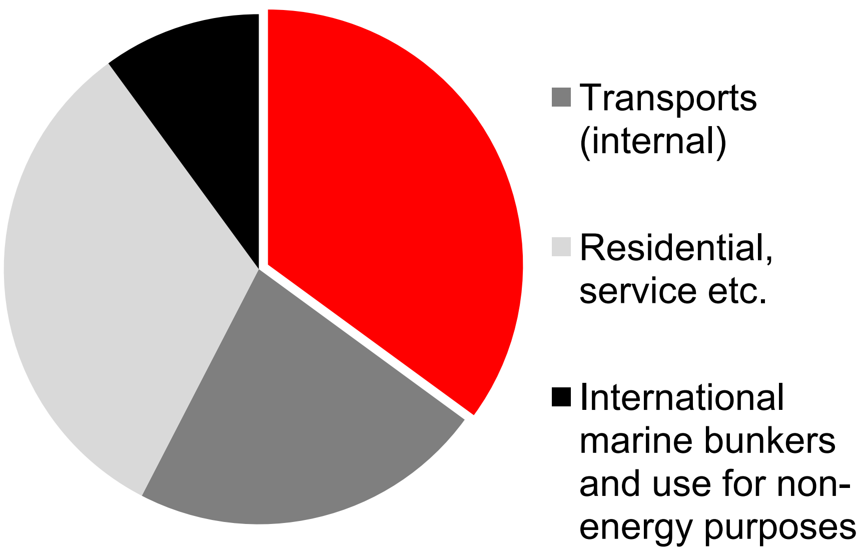
- Background
- Optimization model
- Assignment



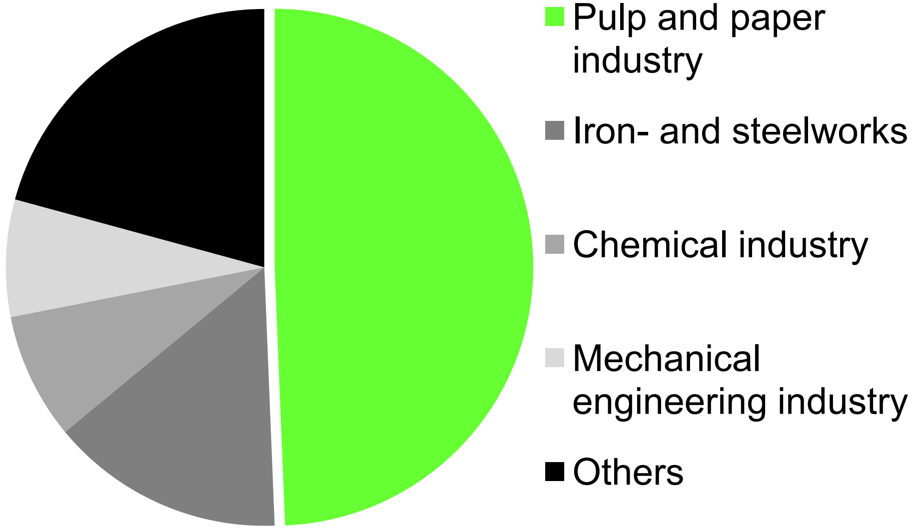
Background

Energy use in Swedish industry

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



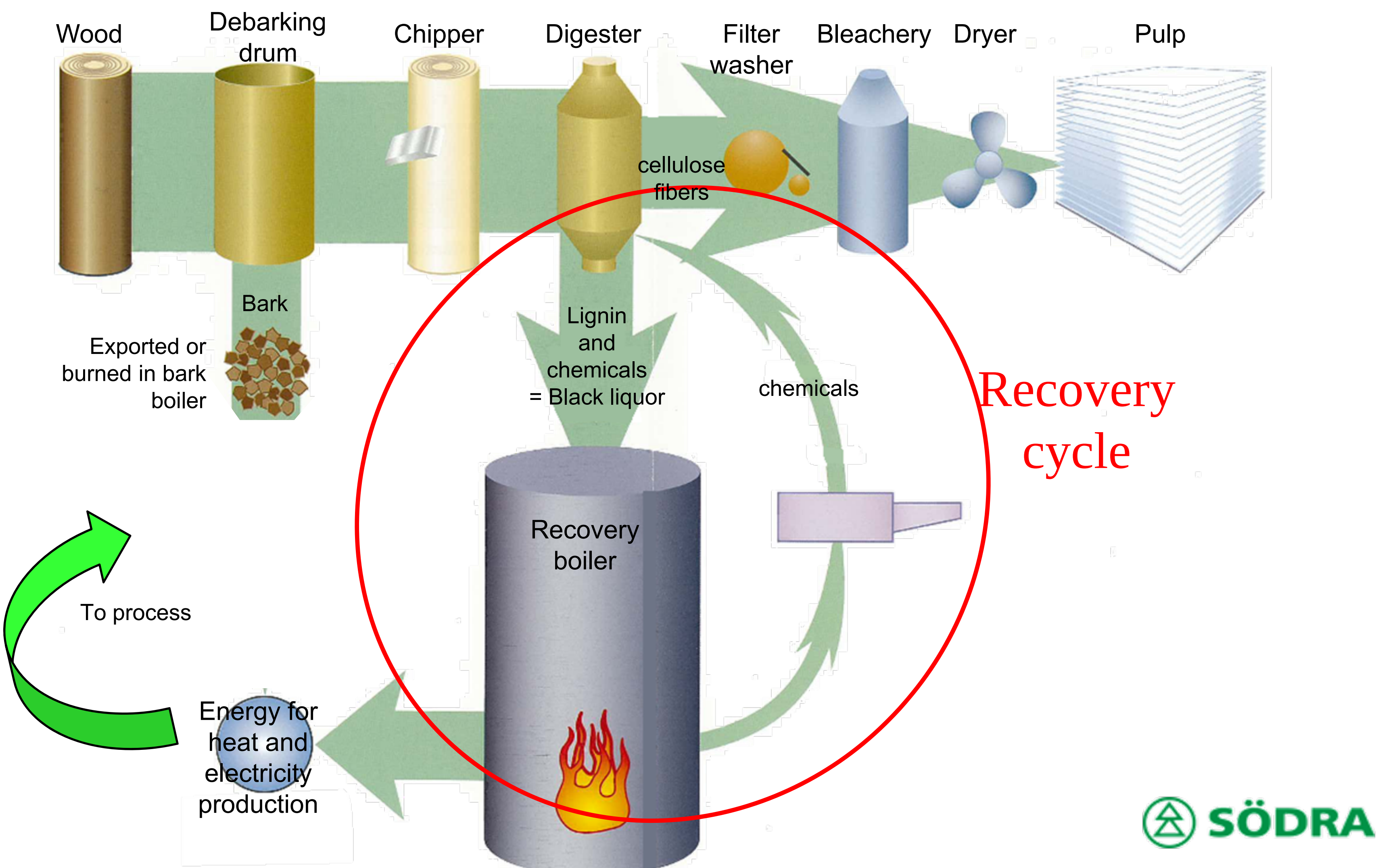
Energy use in Swedish industry 2006
(~160 TWh)



*Excluding nuclear power losses, transmission and distribution losses

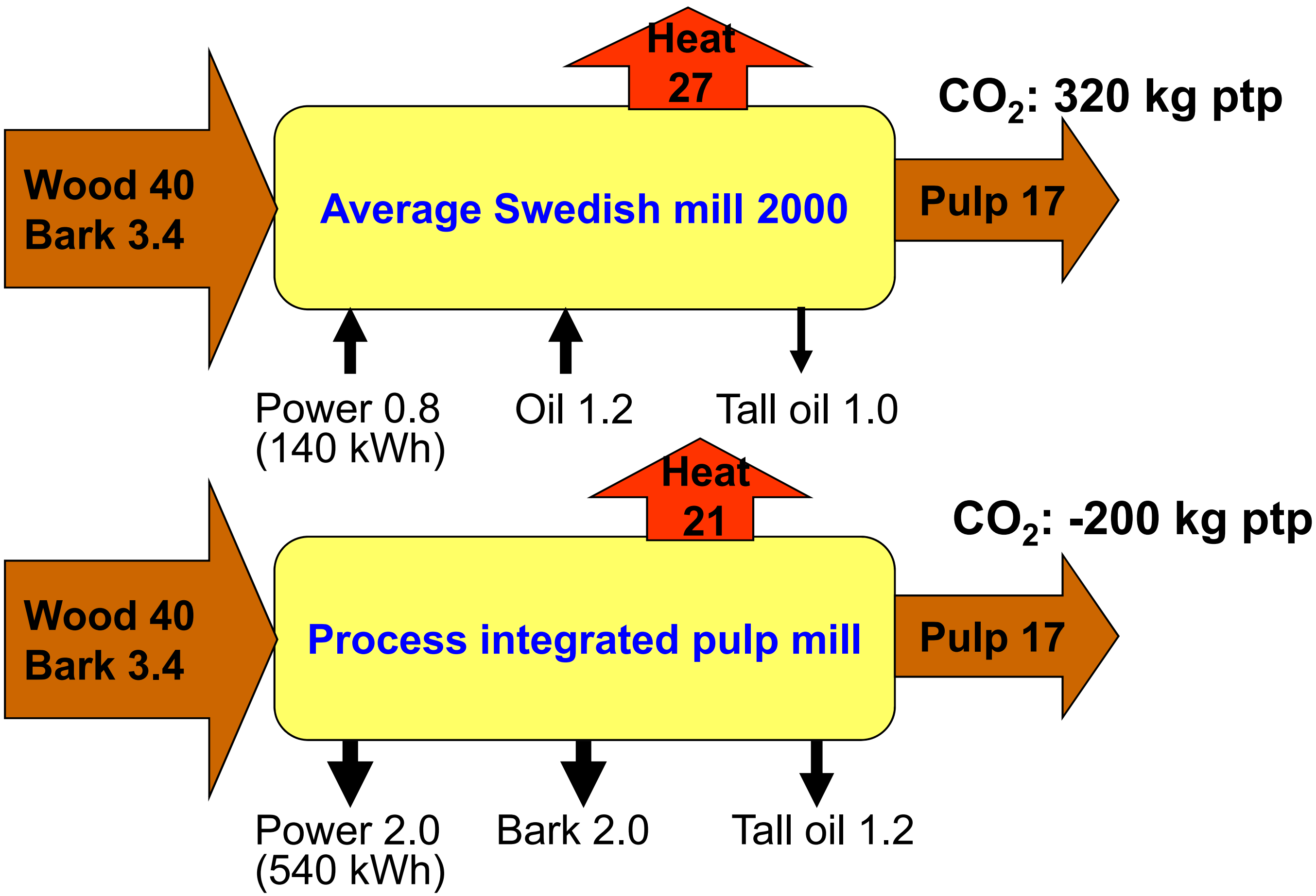
Based on data from the Swedish Energy Agency

Background - The pulp mill



Background

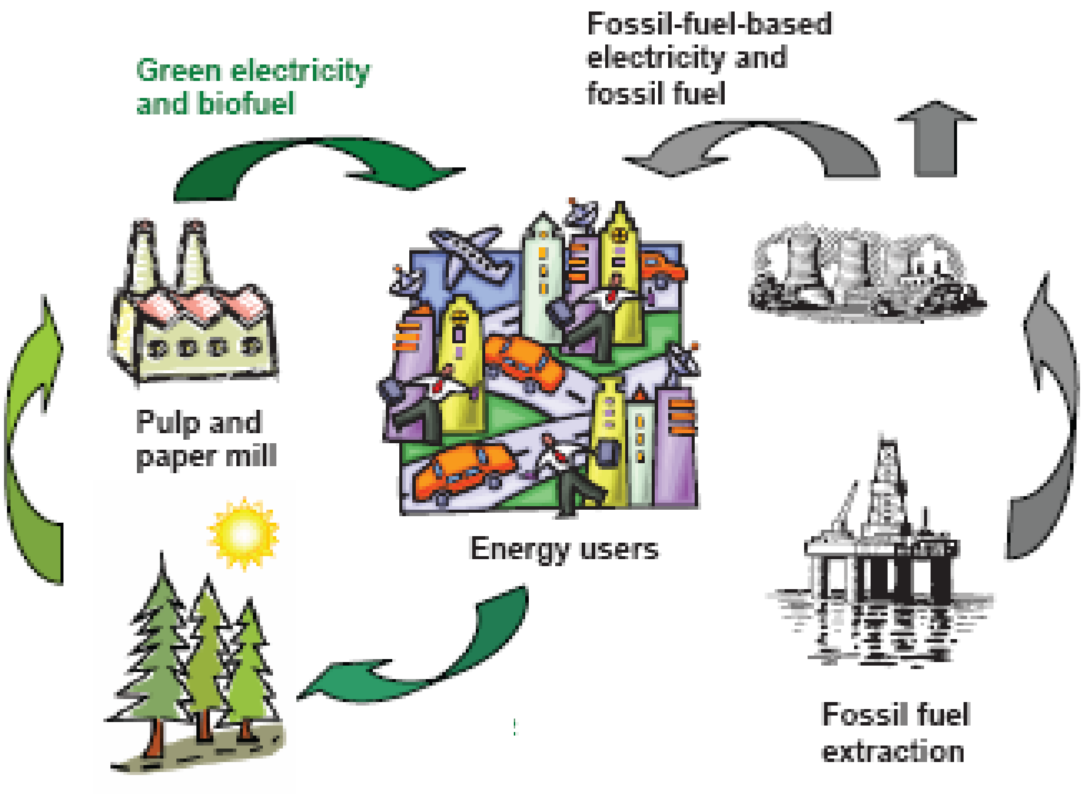
Pulp mill energy balances



New energy products for sale → Good business!

Background

A pulp and paper mill

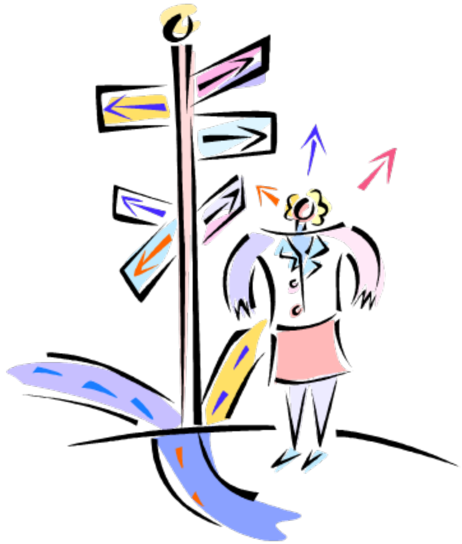


Axelsson (2008) Energy Export Opportunities from Kraft Pulp and Paper Mills and Resulting Reductions in Global CO_2 Emissions

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

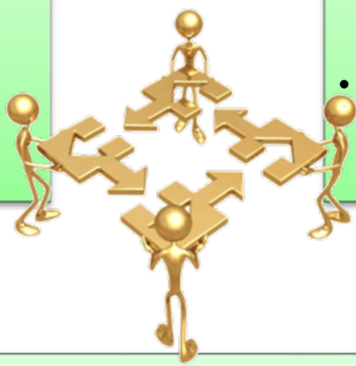
Important features

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

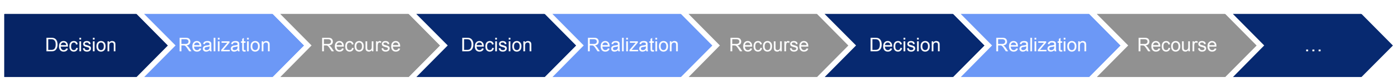
- Two objective functions:
  - E[NPV] : The *expected* net present value
  - E[CO_2]: The *expected* CO_2 emissions reductions

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

- Long-term uncertainties are there because we expect changes in policy instruments and regulations, but we do not know when or with what magnitude.
- We cannot look at history and extrapolate, since these changes has never happened before (Emmision rights, oil depletion, etc.)
- Uncertainties are not easily described by a stochastic function. They are not what we normally call ”random” fluctuations, but rather big step changes.

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

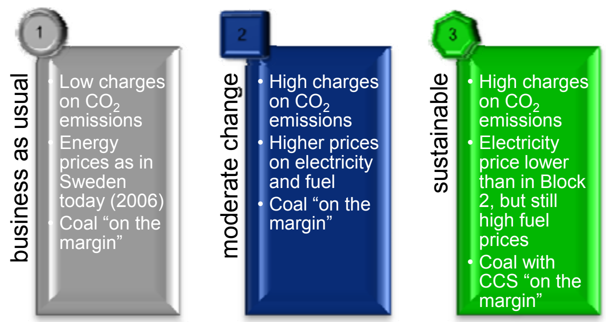
- High charges on CO_2 emissions
- Higher prices on electricity and fuel
- Coal "on the margin"

3 sustainable

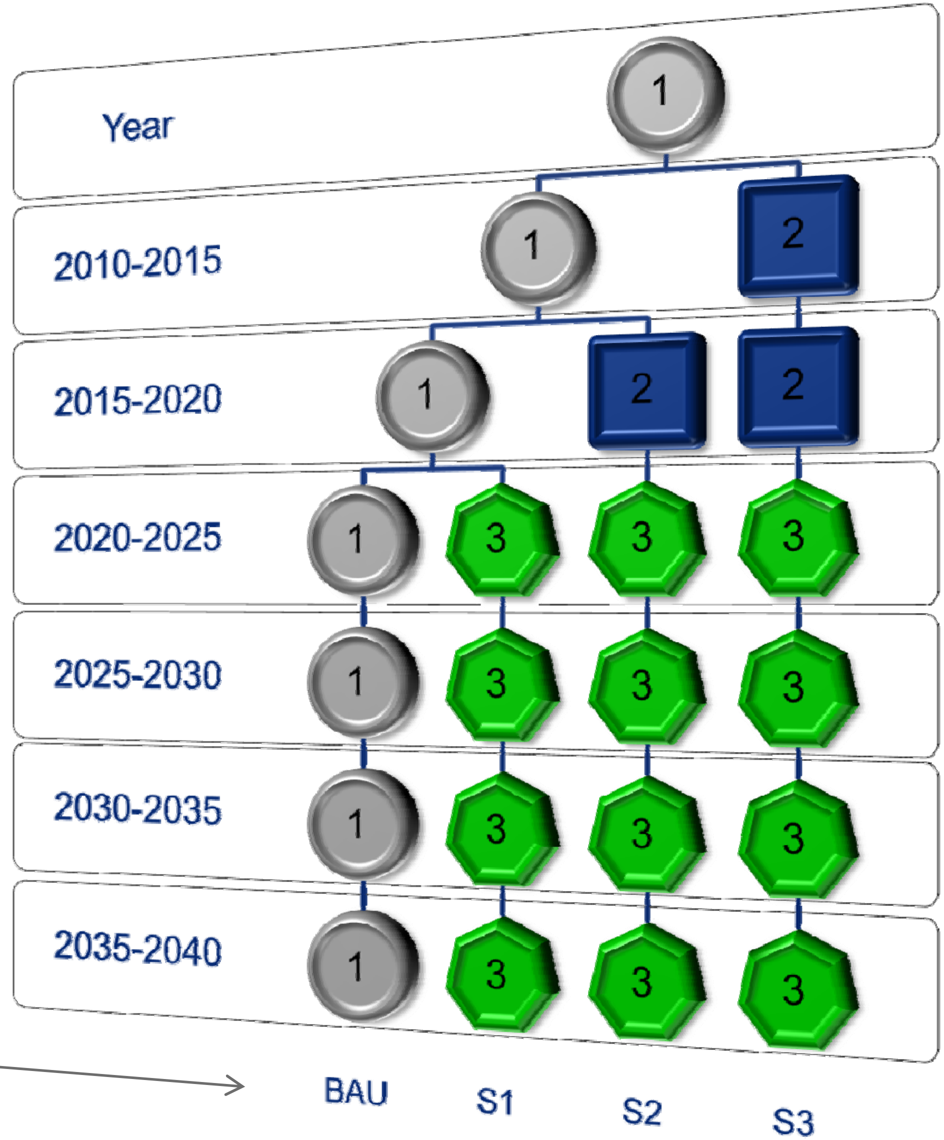
- High charges on CO_2 emissions
- Electricity price lower than in Block 2, but still high fuel prices
- Coal with CCS "on the margin"

Optimization model

Scenario model



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



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

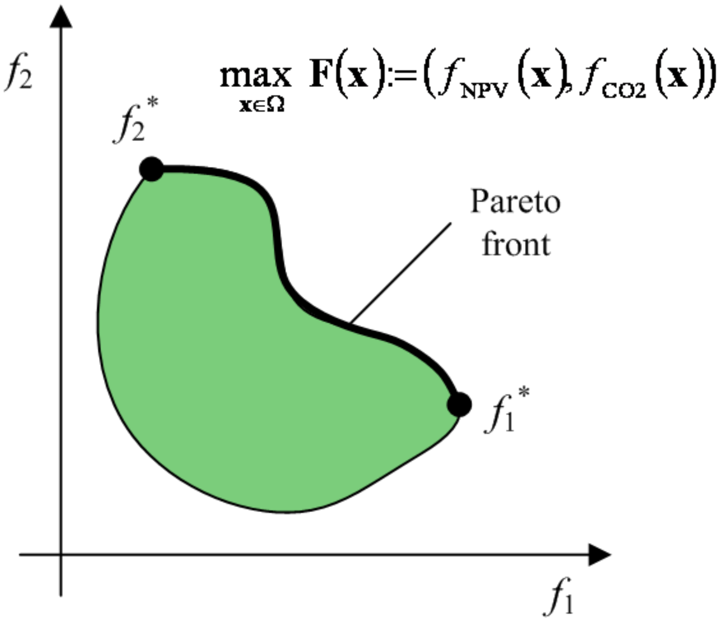
$$\text{maximize } \mathrm{E}[\mathrm{NPV}(x)] := -C_0(x_0) + \sum_{s \in S} p_s \sum_{t=1}^{T} \frac{C_t(x_0, x_s, \omega_s)}{(1+r)^t}$$

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

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

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

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

Optimization model

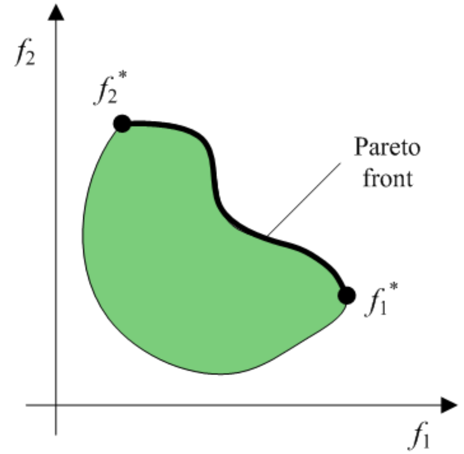
Finding Pareto optimal solutions

- MILP problem = > discontinuous Pareto front
- Here we choose **ε-constraint method** instead of the simpler (?) weighted sum approach.
  - MILP problem => non-convex set => might not be possible to find all Pareto optimal solutions using, e.g. weighted sum approach.
  - Incommensurable objectives with different magnitudes => difficult to choose weights in weighted sum approach.

Optimization model

The ε-constraint method

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



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

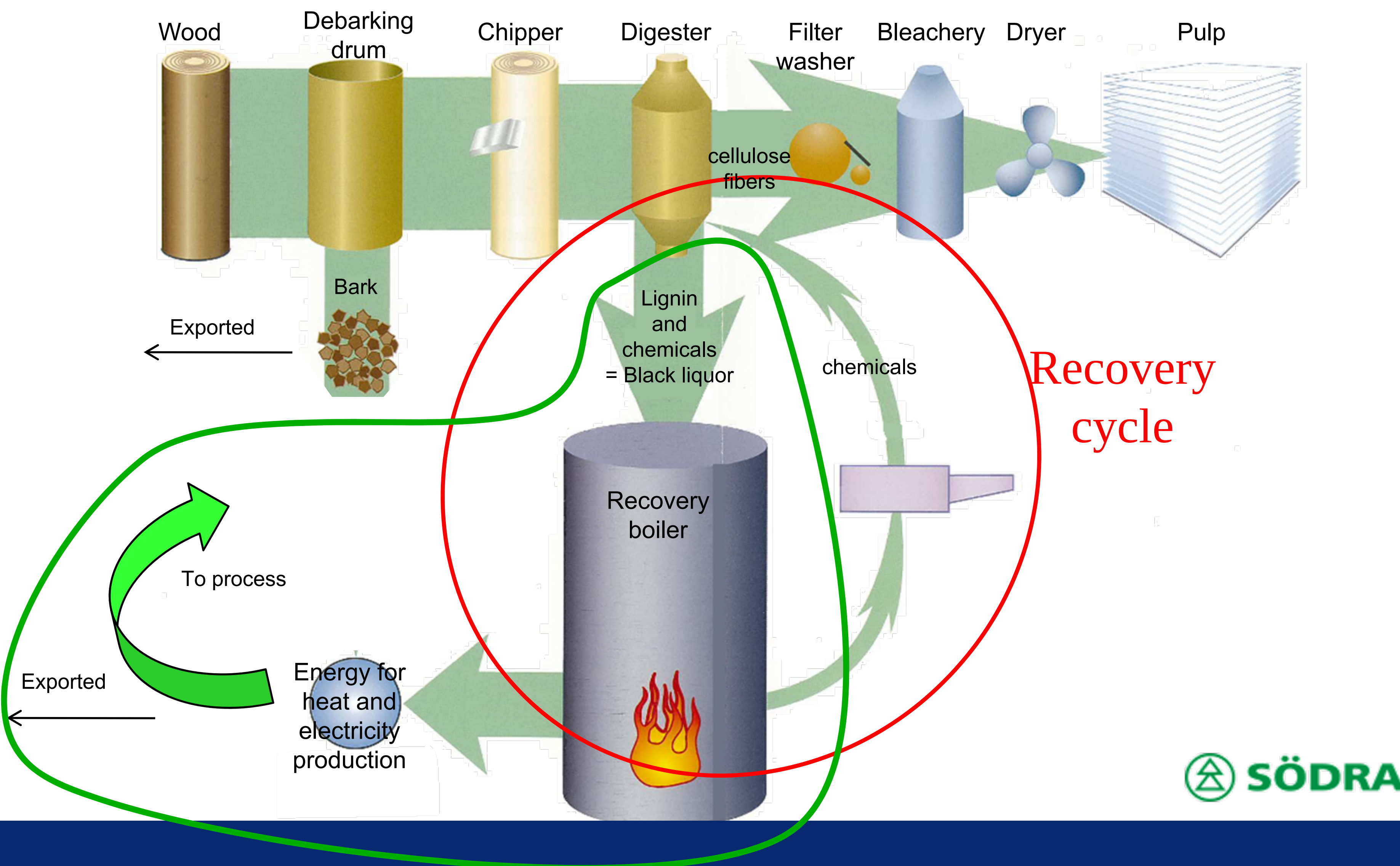
Articulates the preference of the decision-maker

<u>Extreme values of ε.</u>

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

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

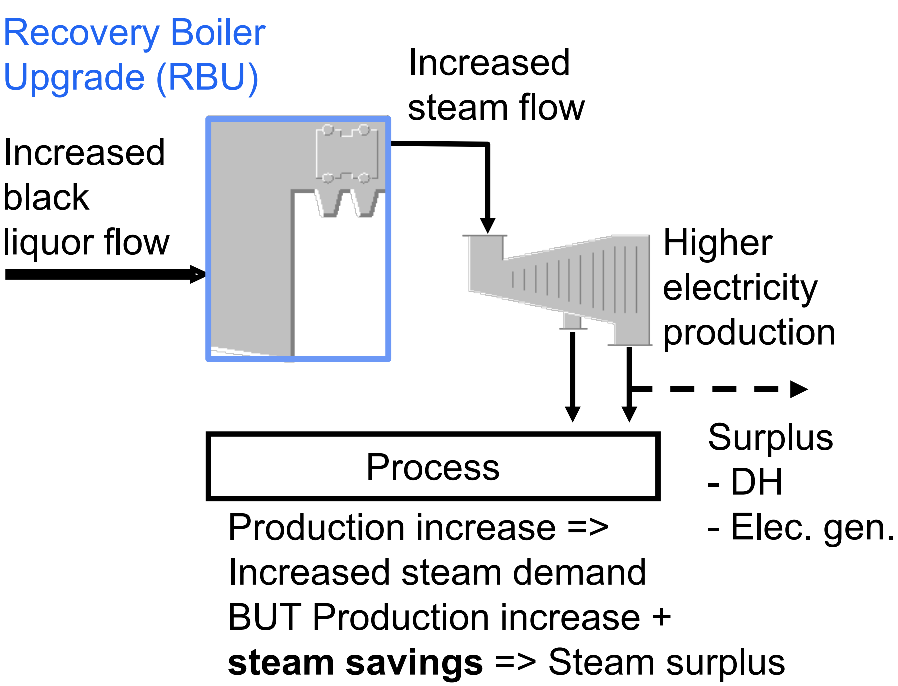
Assignment - The pulp mill

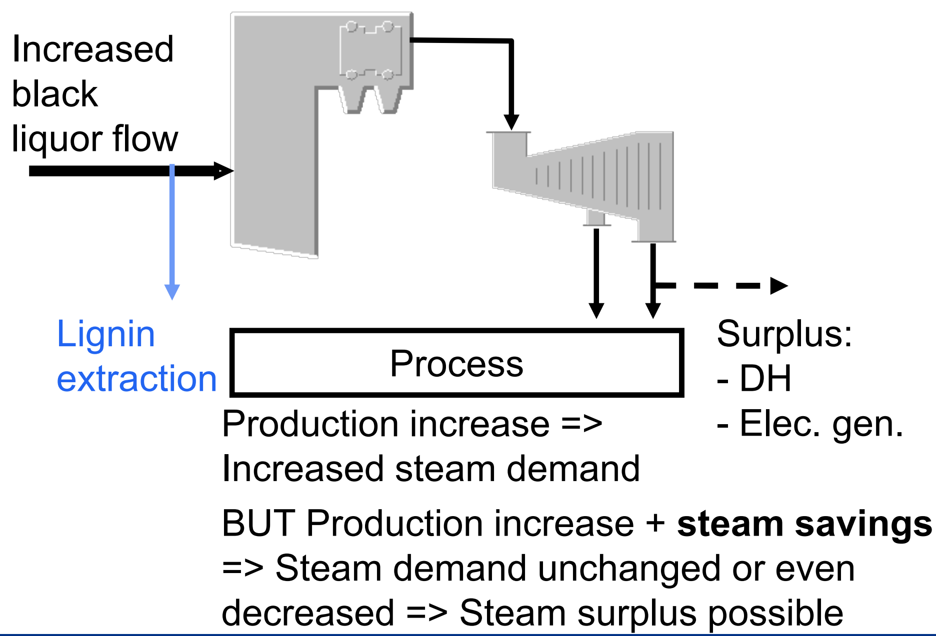


Assignment

A production increase at the pulp mill

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





Optimization model

Optimal solution – The optimal investment plan

- Which investments are made and when
  `AMPL: activate` $\hat{x}_m^{p(n)}$
- What capacities of turbines, lignin extraction, etc have been invested in
  `AMPL: size` β_u^n

Optimization model

Examples of constraints

- Active investments

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

Binary variables: ”active now = active before + activation - deactivation”

- Steam balances

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

Steam flows relative today (i.e. might be negative)

Steam available through steam-saving measures

- Energy conversion

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

”Free output”

Output relative today (i.e. might be negative)

Optimization model

Examples of constraints

- Installed capacity

$$\beta_u^n = \beta_u^{p(n)} + \sum_{i \in I_u} \delta_{ui}^{p(n)}, \qquad n \in N \setminus R, u \in U,$$

New capacity connected to activation

Total capacity

- Capacity constraint

$$\alpha_u^n \leq \beta_u^n - g_u y_u^n, \qquad u \in U \setminus L, n \in N.$$

Today's capacity for existing equipment only.
(Needed because α denotes change relative to today, but β denotes actual capacity.)

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

Last year's most common questions

Q. There are so many parameters and variables in the model and investigating all of them requires too much time. How deep should we go into details?

A. Yes, there are a lot of variables and parameters in the model. You do not have to investigate all of them in detail. Also for me, the model is extensive, and I had a difficult task choosing which variables to describe and discuss in the lecture and in the project description. So, try to explain your results as good as possible according to your understanding of the problem.

Assignment

Last year's most common questions

Q. What is the variable output (α) really representing?

- **Why is it sometimes negative?**
- **Why is it sometimes substantially smaller than the capacity?**

A. The variable represents the change in energy export compared to the situation today.

- Since there is an existing turbine at the mill today, the output of this turbine can be negative if the electricity production is decreased.
- If investment is made in a new larger turbine (which means that the old one has to be scrapped), the maximum possible increase in electricity production (i.e. the maximum output, α) is only the increase in capacity for the new turbine compared to the old one. The capacity variable, however, always represent the total, existing capacity (in this case of the new turbine).

Assignment

Last year's most common questions

Q. What does it mean when an investment is activated at more than one occasion?

A. Investment activations which occur when the investment is already active can be explained by one of the three different situations:

- The capacity of the equipment needs to be further increased, in which case a ”reactivation” is needed.
- The investment cost might be zero, in which case activation or no activation will give the same solution value. In these cases, the investment activation does not have to be considered.
- There might be constraints requiring activation in order for other variables to take certain values. These are special cases that need not be considered in this project.

Assignment

Last year's most common questions

- **We get really low values for some variables (~10^{-12}). Why is that?**
- This is because the solver reached its optimality criteria at this point, i.e. the difference between the upper limit of the solution value and the lower limit is sufficiently small. To guarantee optimality, this difference should of course be exactly zero, but in practise, it is set to a very small positive value. If the solution had converged to exact optimality the true optimal solution would most probably have a value of the variable equal to zero. Values this small can therefore be neglected.

Assignment

Consultation

- My office at Heat and Power Technology
Room 1208, Chemistry building

- Or by e-mail:
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Good luck!