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Considering the Direct and Indirect Environmental Effects in a Multiobjective Synthesis of Bioenergy Systems

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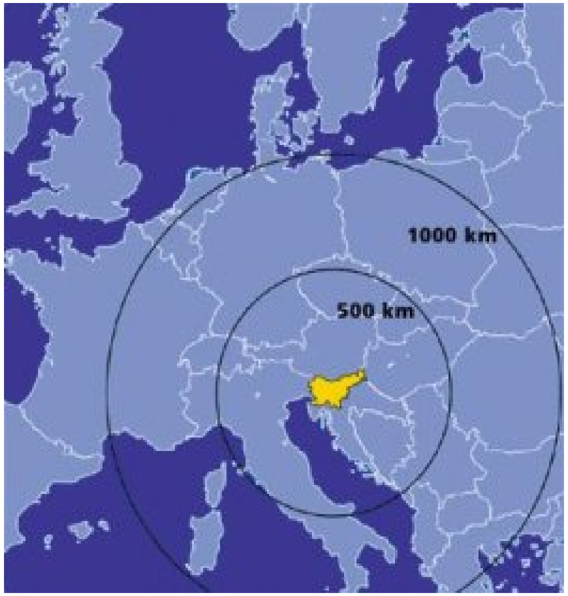

Slovenia in Pictures

Area: 20,273 km2
Population: 2.0 million
Capital city: Ljubljana
Language: Slovenian; also Italian and Hungarian in nationally mixed areas
Currency: EURO, €
Member of EU - 1 May 2004
EU Presidency for 2008

Four Universities:

University of Maribor

University of Ljubljana

University of Nova Gorica

University of Primorska

MARIBOR2012
European Capital of Culture

maribor2013
26th Winter Universiade

OUTLINE

- Incentives and Different Views on Sustainability
- LCA-based Mathematical Programming Approach to the Sustainable Bioenergy System Synthesis:
  - New Concept Considering Direct and Indirect Effects on Environment
  - Upgraded Methods (Total LCA Index, Total Footprints, and Eco-profit)
  - Upgraded Tools (MINLP Synthesizer MIPSYN)
  - More Sustainable Applications
- Synthesis Applications for the Production of Bioenergy
- Conclusion

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Incentives for Sustainable Development

- How prevent the warming for 2^{o}C in the next 2 decades?!
- General problems that have to be circumvented:
  - Population growth
  - Limited resources
  - Environmental and society destruction
- Renewables are becoming important as energy and raw materials for different supply-chains:
  - Prices of renewables have been rising substantially
  - Competition:
    - Food and energy sector when utilizing e.g. corn
    - Furniture industry and energy utilizing wood biomass
    - Using land for biomass, food, photovoltaic or wind energy, etc.

Sustainable Development

Environmentally conscious economical and social progress

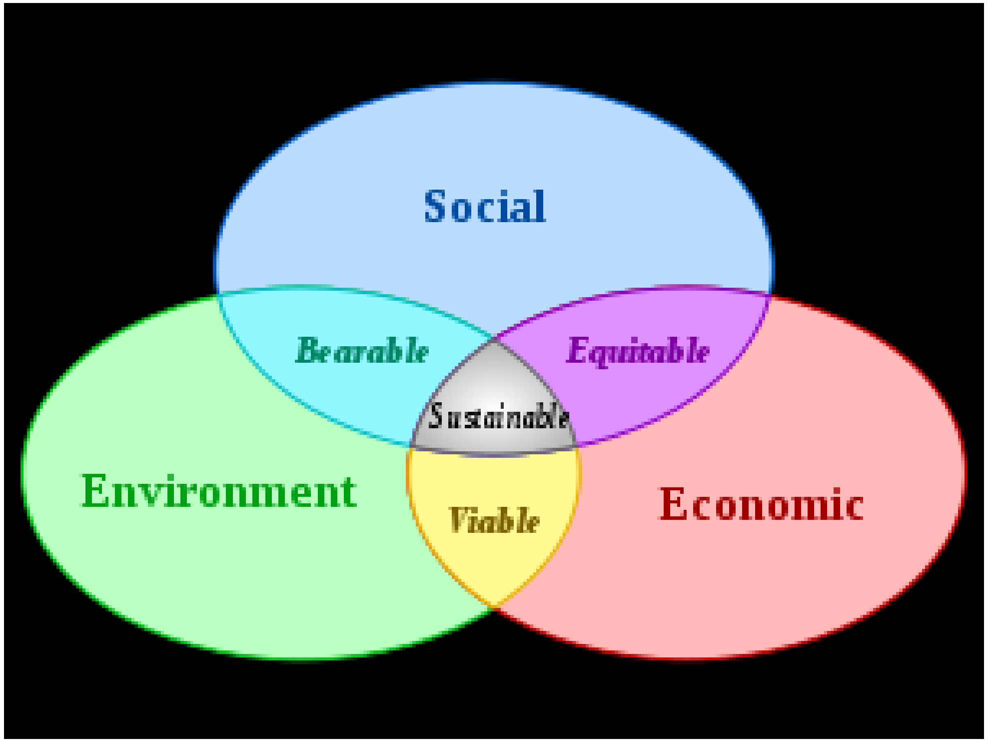


Figure 1: Overlapping three dimensions of sustainability

3x3x3 Matrix of Sustainability

(M. F. Jischa, Chem. Eng. Technol. 21, 1998)

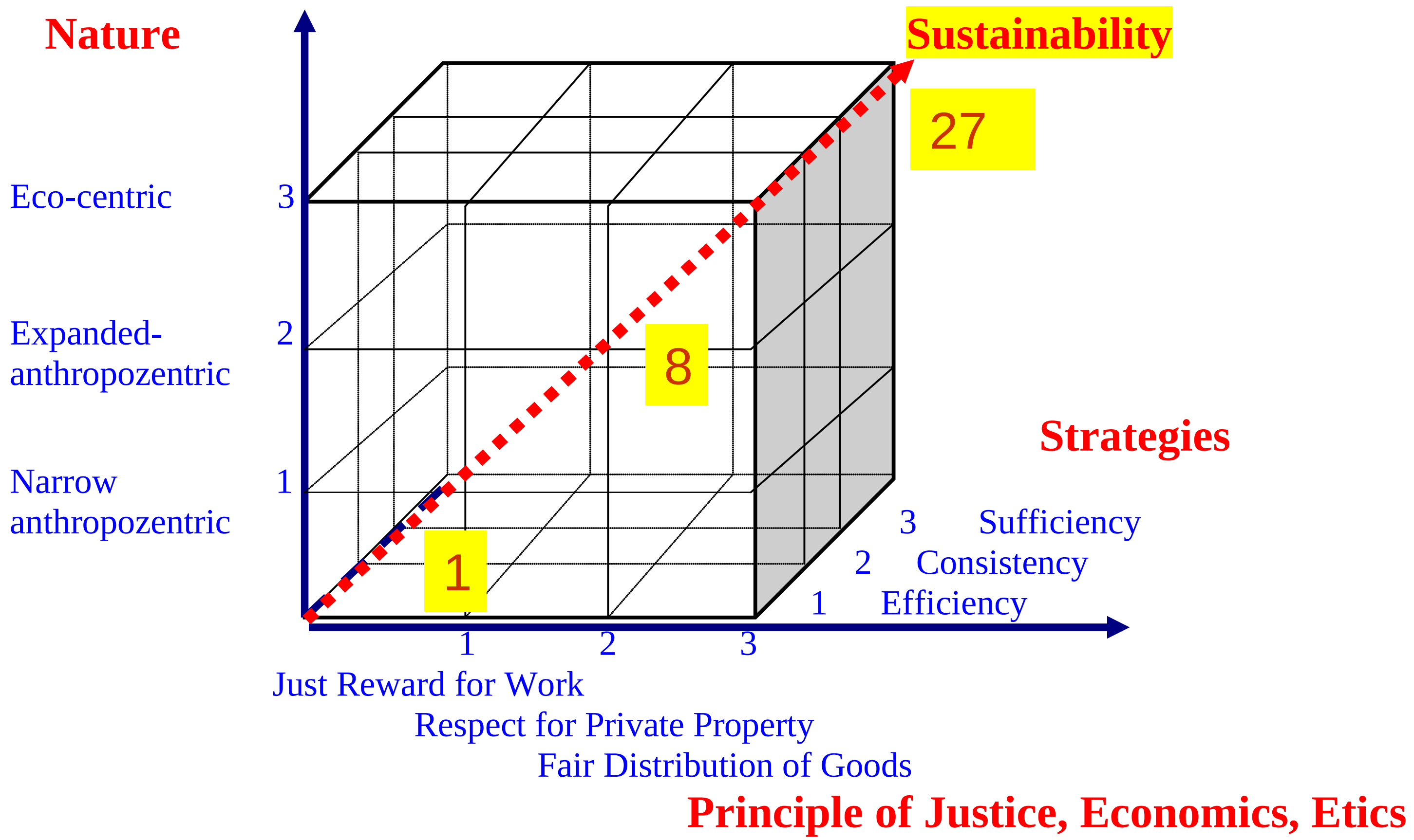


Figure 2: Diagonal as a measure of sustainability

Key Idea for Tomorrow

Obtain efficient, consistent and sufficient solutions that are more profitable and yet socially more acceptable and environmentally less harmful.

How?

The LCA-based systems approach with its mathematical programming can in many respects provide such an advanced solution framework for the sustainable synthesis of complex supply-chains and supply-networks.

Sustainable Bioenergy System Synthesis I.

New Concept?

Upgraded Methods

Upgraded Tools

More Sustainable Applications

Expanding the Scope of the Synthesis

Synthesis is the automatic generation of design alternatives and the selection of the better ones

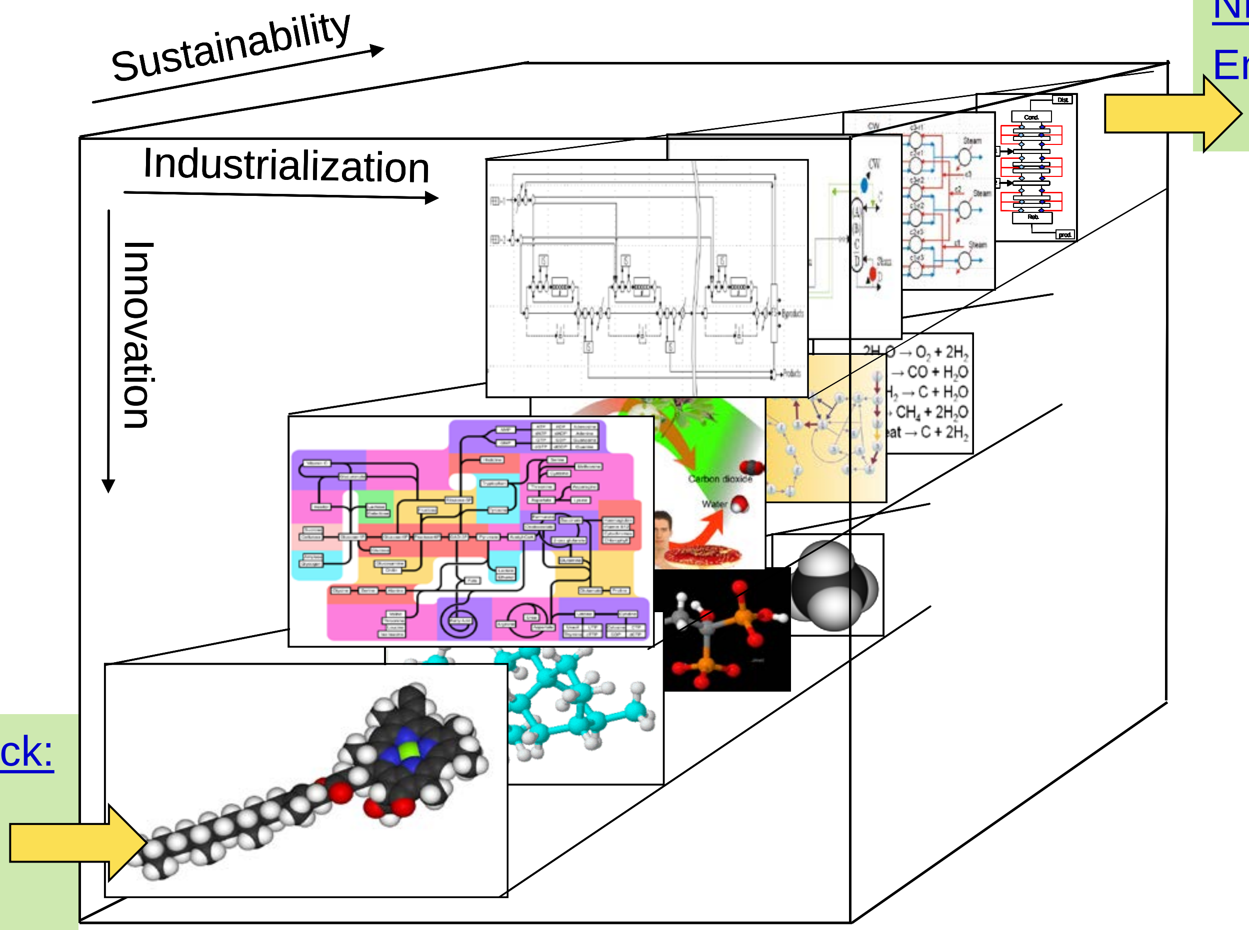
A. W. Westerberg, 1991

1. System boundaries expanded to the synthesis of whole supply-chains and their networks comprising of sustainable alternatives
2. Multiobjective LCA-based system synthesis considering direct and indirect environmental impacts
3. Automatic flowsheet synthesizer, e.g. MIPSYN

Gives rise to economical, environmentally conscious and socially integrated solutions

Sustainable Systems Synthesis Applied to (Bio)-chemical Supply Chain

NEW Products:
Environmentaly benign



NEW Feedstock:
- Recycled
- Waste
- Renewable

Fig. 3: Simplified (bio)-chemical supply chain.

Sustainable Systems Synthesis Applied to Energy Supply-Chain

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Energy:
Environmentaly benign

Resources:
- Cascaded
- Waste
- Renewable

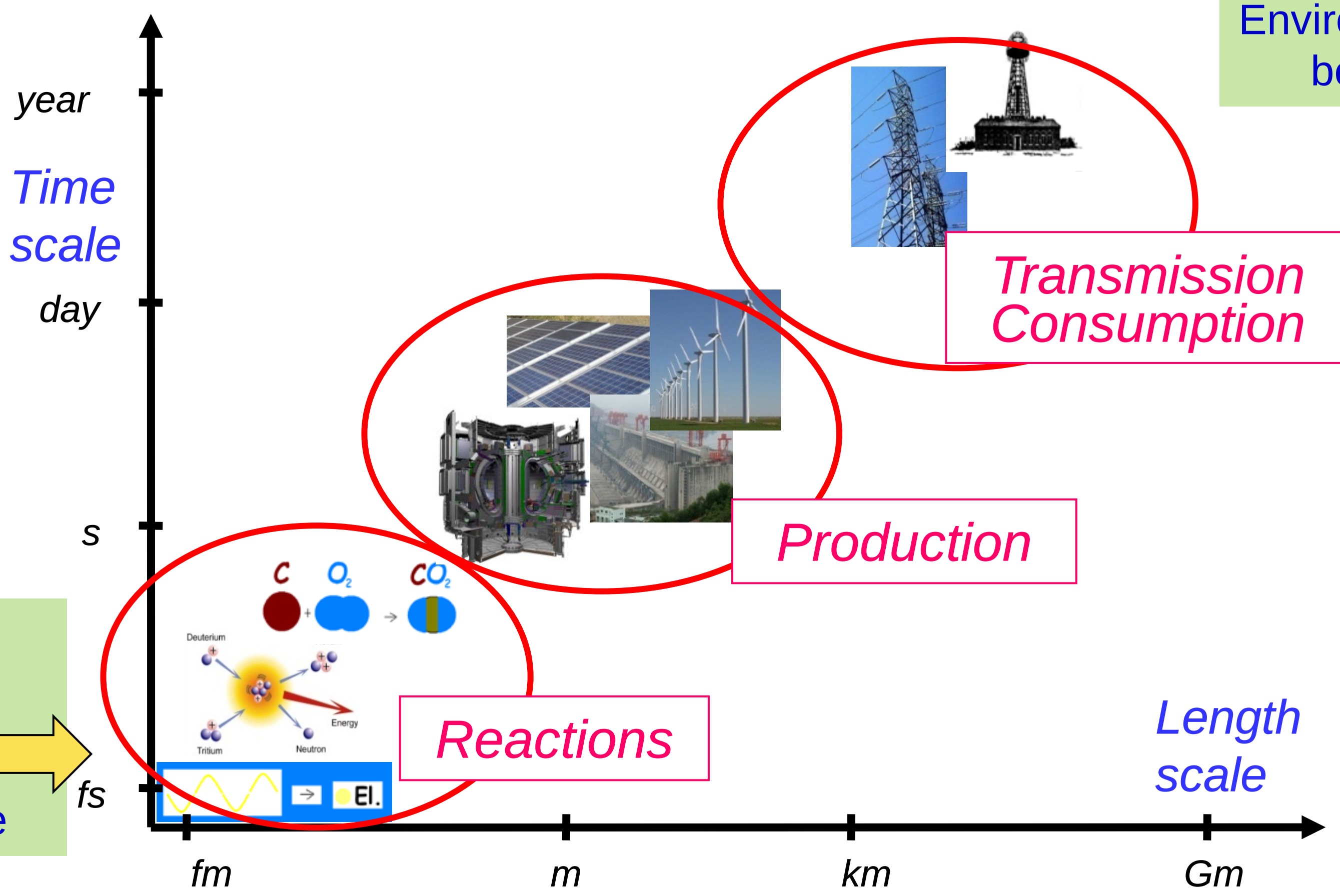
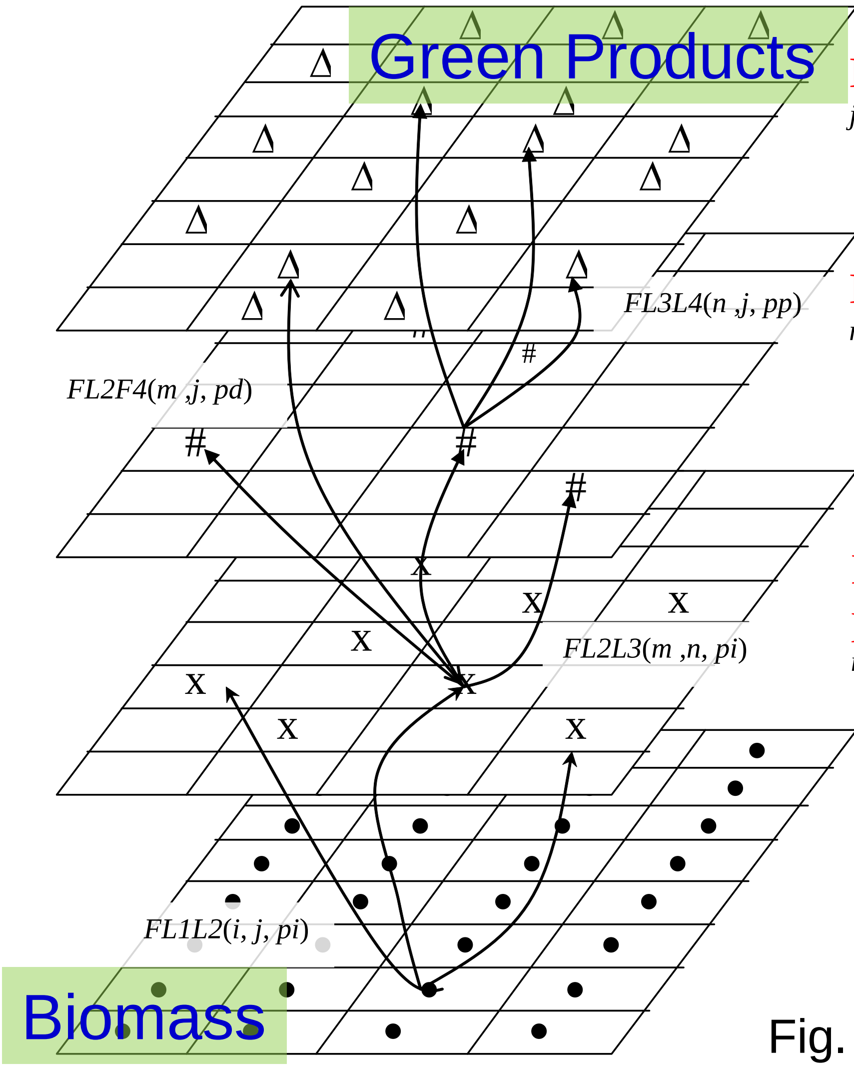


Fig. 4: Achieving global solutions through the integrated energy supply chain

Sustainable Systems Synthesis Applied to Supply/Demand Renewable Networks

Čuček, Lam, Klemeš, Varbanov, Kravanja, 2010



Layer 4: Demand/ End users

j = demands

Layer 3: Production plants

n = plants

*y*L3 (n) = To determine the location of plants
*y*L3pt (*n*, *pp*, *t*) = for technologies selection

Layer 2: Collection and pretreatment processes

m = intermediate points

*y*L2 (*m*) = To determine the location of collection points and also the pretreatment processes : drying/ compaction/ densification

Layer 1: Agricultural supply

i = zones

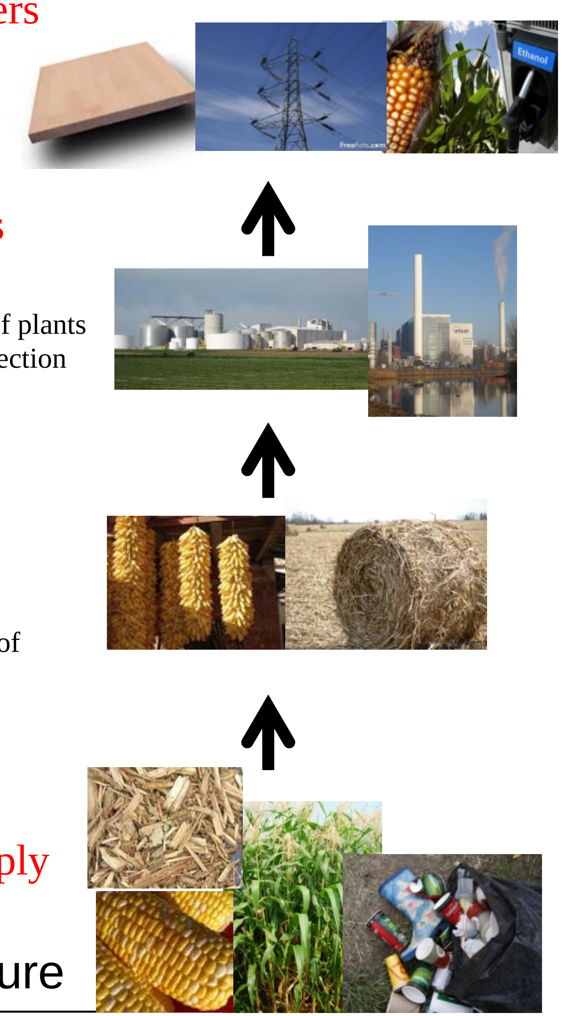


Fig. 5: SDRN superstructure

Direct and Indirect Effects

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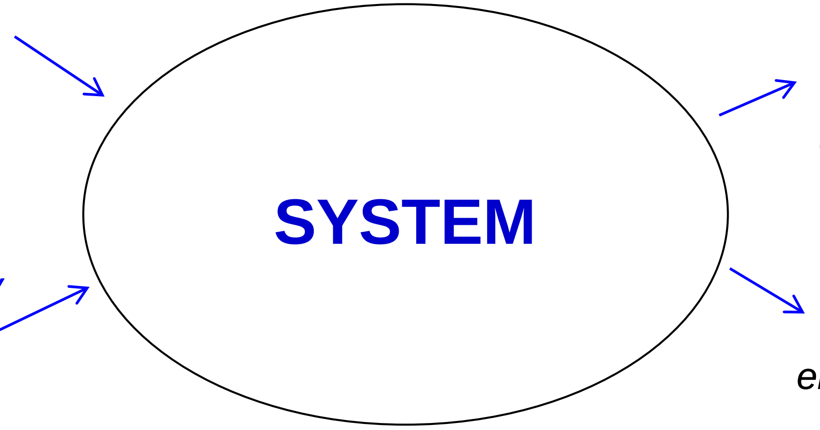
Raw materials, *which only burden the environment if they are processed*

DIRECT impacts

Raw materials, *which mainly unburden or benefit the environment, e.g. utilization of waste rather than deposit*

DIRECT and INDIRECT impacts



Products, *which only burden the environment related to processing, disposal, and transportation*

DIRECT impacts

Products, *which also unburden or benefit the environment due to products' substitution*

DIRECT and INDIRECT impacts

The DIRECT effects *of systems on the environment represent direct burden of the systems due to the extraction of resources, materials production, use, maintenance, recycling and/or disposal including all transportation steps.*

The INDIRECT effects *are those sets of impacts that indirectly unburden or benefit the environment when waste is utilized instead of being deposited or environmentally benign raw-materials, products or services are used instead of harmful ones.*

TOTAL effects = DIRECT + INDIRECT effects

LCA-Based Synthesis Approach
Direct vs. Total Environmental Effects

Direct Effects:

1. LCA Index
2. Footprints
3. Eco-cost

+ Indirect eff. →

Total Effects:

1. Total LCA Index
2. Total Footprints
3. Eco-profit

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Sustainable Bioenergy System Synthesis II.

New Concept

Upgraded Methods?

Upgraded Tools

More Sustainable Applications

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Sustainable Synthesis by Mathematical Programming Approach

- Powerful creative principles of Mathematical programming approach:
  - Optimality - > competitive advantage
  - Feasibility -> fulfilling constraints
  - Integrality -> economically, environmentally and socially integrated solutions
- Important challenges:
  - How to solve complex supply-networks integraly
  - Defining suitable sustainability measures for LCA-based optimization and synthesis
  - Performing efficient multi-objective optimization and synthesis when confronted with many different and opposed criteria

LCA-Based Synthesis Approach Considering Direct Environmental Effects

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1. LCA Index multi-objective:

$$\begin{aligned} &Max \ \ z = Profit(x,y) \\ &s.t \quad h_{ls}(x,y) = 0 \\ &\qquad g_{ls}(x,y) \le 0 \\ &LCAI(x,y) \le \varepsilon \\ &x \in X = \{x \in R^n : x^{LO} \le x \le x^U\} \\ &y \in Y = \{0,1\}^m \end{aligned}$$

LCAI-MINLP

2. Footprint multi-objective:

$$\begin{aligned} &Max \ \ z = Profit(x,y) \\ &s.t \quad h_{ls}(x,y) = 0 \\ &\qquad g_{ls}(x,y) \le 0 \\ &Footprint(x,y) \le \varepsilon \\ &x \in X = \{x \in R^n : x^{LO} \le x \le x^U\} \\ &y \in Y = \{0,1\}^m \end{aligned}$$

F-MINLP

3. Ecocost single-objective:

$$\begin{aligned} &Max \ \ z = Profit(x,y) - Ecocost(x,y) \\ &s.t \quad \left. \begin{aligned} h_{ls}(x,y) &= 0 \\ g_{ls}(x,y) &\le 0 \end{aligned} \right\} \ \forall l \in Levels, \ \forall S \in Supply\ chains \\ &x \in X = \{x \in R^n : x^{LO} \le x \le x^U\} \\ &y \in Y = \{0,1\}^m \end{aligned}$$

Ecocost-MINLP

LCA-Based Synthesis Approach Considering Total Environmental Effects

1. Total LCA Index multi-objective:

$$\begin{aligned} Max \;\; z &= Profit(x,y) \\ s.t \;\; h_{ls}(x,y) &= 0 \\ g_{ls}(x,y) &\leq 0 \\ Total\ LCAI(x,y) &\leq \varepsilon \\ x \in X &= \{x \in R^n : x^{LO} \leq x \leq x^U\} \\ y \in Y &= \{0,1\}^m \end{aligned}$$

TLCAI-MINLP

2. Total footprint multi-objective:

$$\begin{aligned} Max \;\; z &= Profit(x,y) \\ s.t \;\; h_{ls}(x,y) &= 0 \\ g_{ls}(x,y) &\leq 0 \\ Total\ footprint(x,y) &\leq \varepsilon \\ x \in X &= \{x \in R^n : x^{LO} \leq x \leq x^U\} \\ y \in Y &= \{0,1\}^m \end{aligned}$$

TF-MINLP

3. Eco-profit single-objective:

$$\begin{aligned} Max \;\; z &= Profit(x,y) + Eco\text{-}profit(x,y) \\ s.t \;\; h_{ls}(x,y) &= 0 \\ g_{ls}(x,y) &\leq 0 \\ x \in X &= \{x \in R^n : x^{LO} \leq x \leq x^U\} \\ y \in Y &= \{0,1\}^m \end{aligned}$$

$\left.\right\} \forall\, l \in Levels, \;\; \forall\, S \in Supply\ chains$

Ecoprofit-MINLP

1. Relative Approach: Definition and Normalization of LCA Index

- Indicators are normalized, e.g. by the values from a given base case
- Economic indicators:
  - Yearly profit (P) or the net present worth (NPW)
  - Relative profit and relative NPW:

$$RP = P / P^0; \qquad RNPW = NPW / NPW^0$$

- Environmental and social indicators:
  - Environmental: resource usage and pollution indicators
  - Social: assessment is difficult
  - Normalized indicators are composed into:

Negative values!

LCA Index (direct effects) or Total LCA Index (direct + indirect effects)

$$LCAI = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{d}}}{I_i^{\mathrm{d},0}}$$

$$TLCAI = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{d}} + I_i^{\mathrm{ind}}}{I_i^{\mathrm{d},0}} = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{t}}}{I_i^{\mathrm{d},0}}$$

Since I_i^{ind} are negative, TLCAI < LCAI

1. LCAI-Based MINLP Synthesis

Two-step multiobjective superstructural MINLP approach:

Step I: Base case design, best available technique or MINLP I

Economic-based synthesis for **basic process superstructure** that comprises technological end economical alternatives

Base case solution

$$P^{0} \text{ or } NPW^{0},\ I_i^{\mathrm{d},0} \text{ and } I_i^{\mathrm{ind},0}\ \forall i \in I$$

Reference point

MINLP step II:

Multiobjective synthesis for **superstructure,** augmented by sustainable energy, environmental and other alternatives

Sustainable solution

$$P_k \text{ or } NPW_k,\ I_{i,k}^{\mathrm{d}} \text{ and } I_{i,k}^{\mathrm{ind}}\ \ \forall i \in I, k \in K$$

1. Direct effects
LCAI in ε-constrained MINLP II

Relative Profit before taxation

$$\max RP = (c^{\mathrm{T}} y + f(x)) / P^0$$

s.t.

$$\left.\begin{aligned} & h_l(x, y_{ls}) = 0 \\ & g_l(x, y_{ls}) \le 0 \\ & LCAI(x, y_{ls}) \le \varepsilon_k \end{aligned}\right\} \quad \forall l \in L, s \in S$$

$$x \in X = \left\{ x \mid x \in \mathrm{R}^n;\ x^{LO} \le x \le x^{UP} \right\} \qquad (\text{LCAI-MINLP})_k$$

$$y_l = Y_l,\ \forall l \in L;\ Y_1 \cup Y_2 \ldots \cup Y_L = Y = \{0,1\}^m$$

$$\varepsilon_k = \varepsilon_{k-1} - \Delta\varepsilon$$

Loop around Solve statement in GAMS

1. Direct effects
LCAI-Based Pareto Solutions, MINLP II

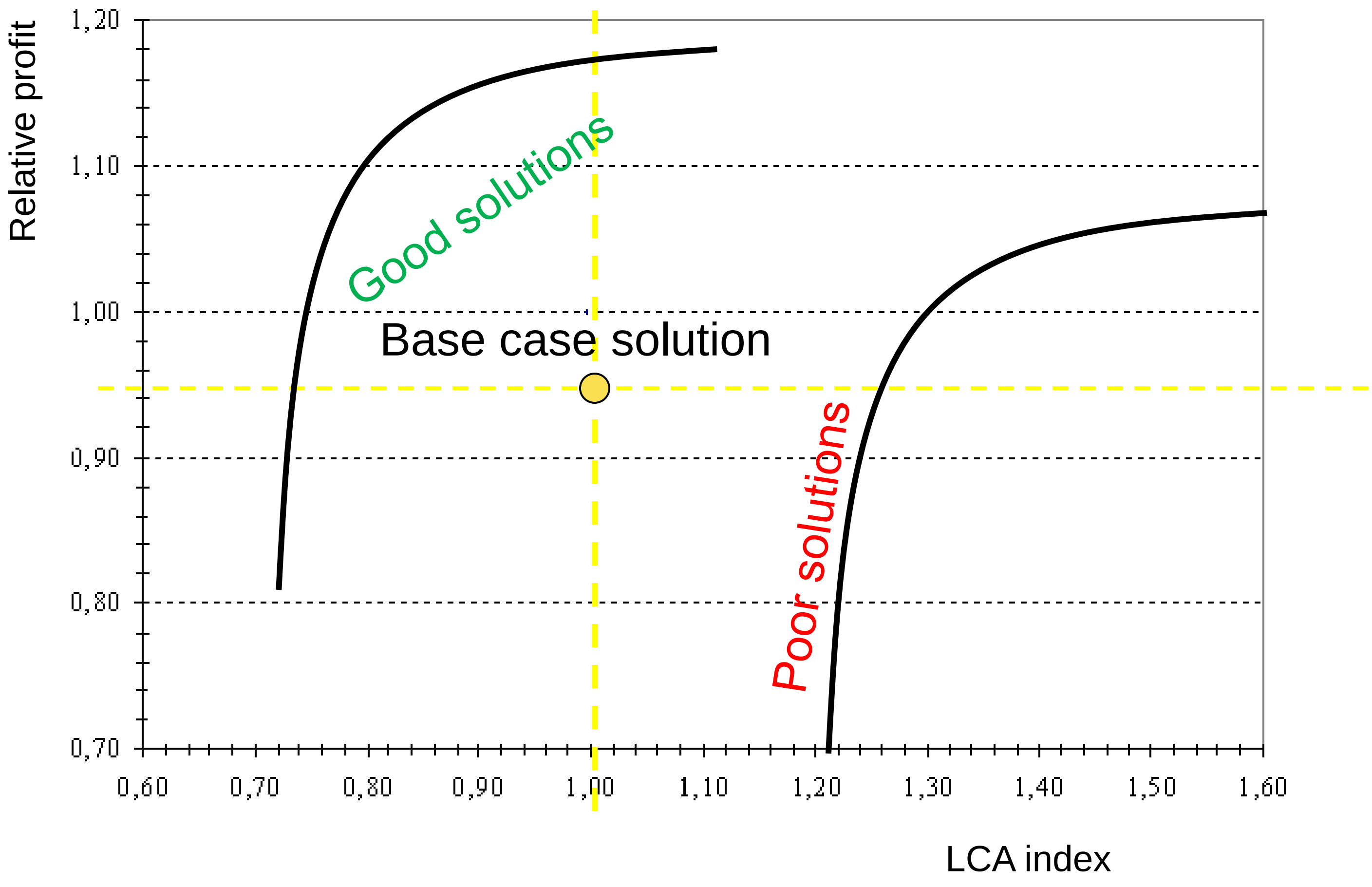

Fig. 6: Good and poor Pareto solutions

1. Total effects
TLCAI in ε-constrained MINLP II

$$\max RP = (c^{\mathrm{T}} y + f(x)) / P^0$$

$$\text{s.t.} \quad \left.\begin{aligned} & h_l(x, y_{ls}) = 0 \\ & g_l(x, y_{ls}) \le 0 \\ & TLCAI(x, y_{ls}) \le \varepsilon_k \end{aligned}\right\} \quad \forall l \in L, s \in S$$

$$x \in X = \left\{ x \mid x \in \mathrm{R}^n;\ x^{LO} \le x \le x^{UP} \right\} \qquad \text{(TLCAI-MINLP)}_k$$

$$y_l = Y_l,\ \forall l \in L;\ Y_1 \cup Y_2 ... \cup Y_L = Y = \{0,1\}^m$$

$$\varepsilon_k = \varepsilon_{k-1} - \Delta\varepsilon$$

$$TLCAI = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{d}} + I_i^{\mathrm{ind}}}{I_i^{\mathrm{d},0}} = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{t}}}{I_i^{\mathrm{d},0}}$$

1. Total Effects
TLCAI-Based Pareto Solutions, MINLP II

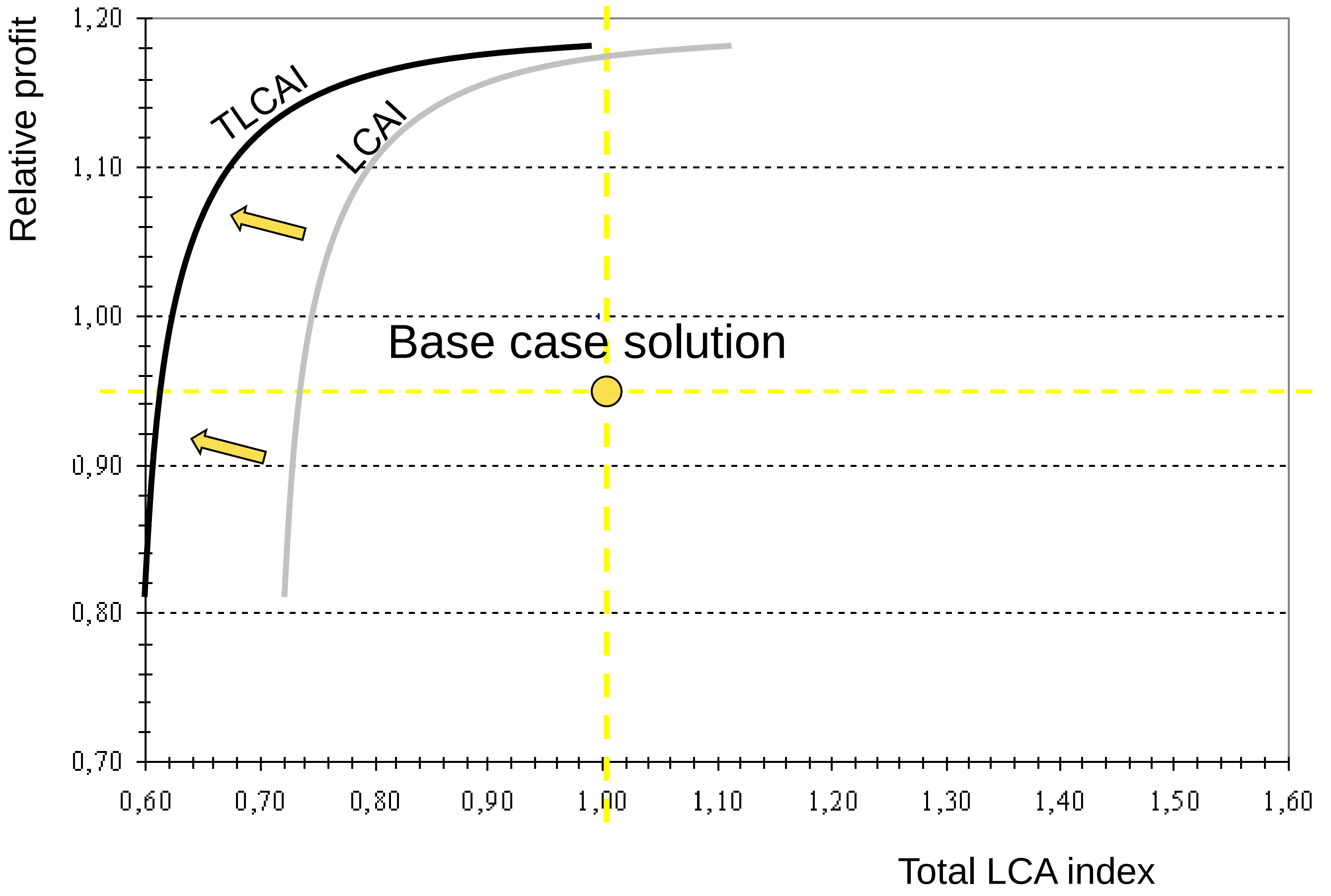

Fig. 7: Total LCAI Pareto solutions

2. Relative Approach: Definition and Normalization of Footprints

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- Footprints cannot be easily compared since they can have different measures, units, and qualities

- Footprints of studied alternatives are normalized, e.g. by the values obtained at the maximal profit or from some base-case design:

Direct relative footprint

$$RFP = \frac{FP^{\mathrm{d}}}{FP^{\mathrm{d0}}}$$

Total relative footprint

$$TRFP = \frac{FP^{\mathrm{d}} + FP^{ind}}{FP^{\mathrm{d0}}} = \frac{FP^{\mathrm{t}}}{FP^{\mathrm{d0}}}$$

Direct Footprint at the maximal profit

2. Relative Approach: Footprint-Based MINLP Synthesis

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Two-step multiobjective superstructural MINLP approach:

MINLP step I:

At the first level (MINLP-1) different footprints are obtained by the maximization of profit from a given base-case design :

$$P^0 \text{ and } FP_f^{\mathrm{d},0}, \quad \forall f \in F$$

Reference point

MINLP step II:

At the second level (MINLP-2), the superstructure can be augmented by sustainable alternatives and the ε-constraint method is applied for each relative footprint *f* ϵ *F*.

$$P_k, \; FP_{f,k}^{\mathrm{d}} \text{ and } FP_{f,k}^{\mathrm{ind}}, \forall f \in F, \, k \in F$$

Multiobjective Pareto solutions

2. Direct Effects Footprint–Based MINLP II

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Small- and medium-sized supply-networks

Lam, et al., 2011, Energy

Footprints: carbon, water, non-renewable energy, emission (water, air, soil), food vs. fuel

Direct relative footprint

$$RFP = \frac{FP^{\mathrm{d}}}{FP^{\mathrm{d},0}}$$

Direct footprint at the maximal profit

$$\max_{x,y} P = (c^{\mathrm{T}} y + f(x))$$

s.t.

$$h_{l,s}(x,y) = 0 \qquad \forall l \in L, s \in S$$

$$y_{l,s}(x,y) \le 0 \qquad (\text{F-MINLP}_i)_f$$

$$RFP_f(x,y)_{P_{\max}} \le \varepsilon_{if}, \qquad \forall i \in I, f \in F$$

$$(x^{LO} x \le x^{UP}) \in X \subset \mathrm{R}^n, \quad y = \{0,1\}^m$$

$$\varepsilon_{if} = \varepsilon_{i-1,f} + \Delta\varepsilon_f$$

Loop around Solve statement in GAMS

2. Direct effects
Footprint-Based Pareto Solutions, MINLP II

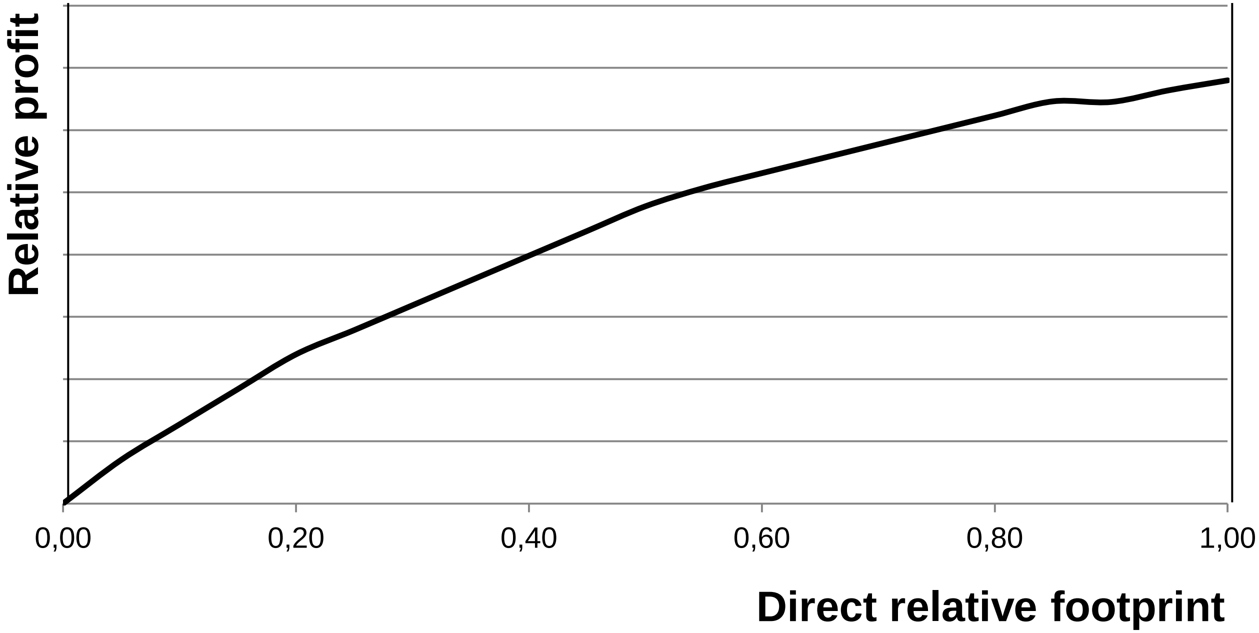


Fig. 8: Profit vs. Direct footprint

2. Total Effects
Total Footprint–Based MINLP II

$$\max_{x,y} P = (c^{\mathrm{T}} y + f(x))$$

$$\begin{aligned}
\text{s.t.} \quad & h_{l,s}(x,y) = 0 && \forall l \in L, s \in S \\
& y_{l,s}(x,y) \le 0 && (\text{F-MINLP}_i) \\
& \text{TRFP}_f(x,y)_{P_{\max}} \le \varepsilon_{if} && \forall i \in I, \; f \in F \\
& (x^{LO} x \le x^{UP}) \in X \subset \mathrm{R}^n, \quad y = \{0,1\}^m \\
& \varepsilon_{if} = \varepsilon_{i-1,f} + \Delta\varepsilon_f
\end{aligned}$$

$$TRFP = \frac{FP^{\mathrm{d}} + FP^{ind}}{FP^{\mathrm{d}0}} = \frac{FP^{\mathrm{t}}}{FP^{\mathrm{d}0}}$$

2. Total Effects: Total Footprint-Based Pareto Solutions, MINLP II

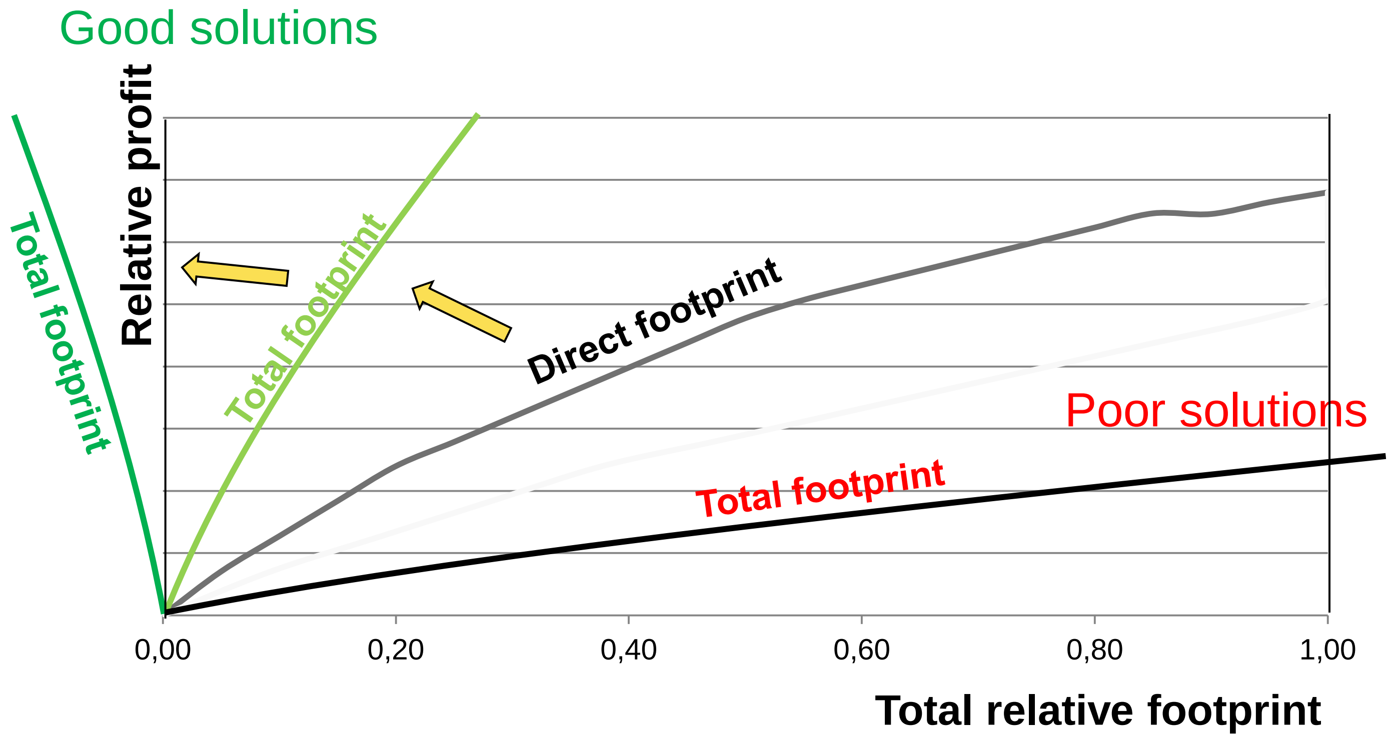
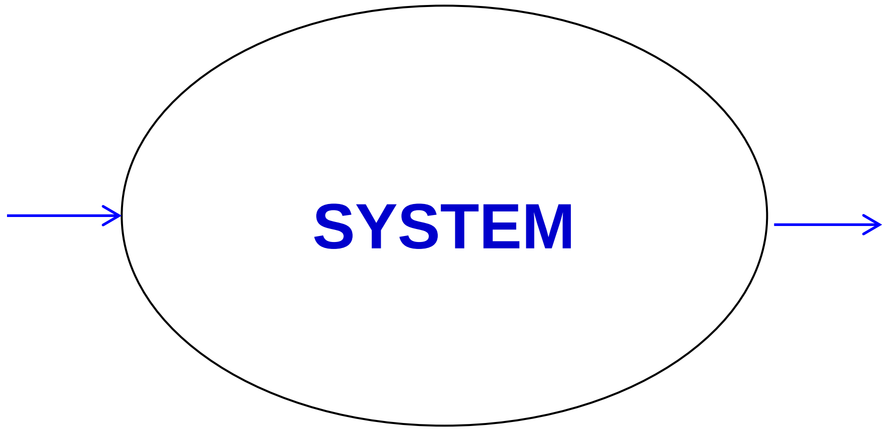


Fig. 9: Profit vs. Total footprint

3. Direct Effects in Composite-Criterion : Profit-Eco-cost

R *– raw materials, which* *directly burden the environment due to:*

- *Extraction of resources,*
- *Recycling and*
- *Transportation*



P *– set of products, which* *directly burden the environment due to:*

- *Processing,*
- *Transportation,*
- *Use and*
- *Disposal*

Eco-cost (€/yr) :

$$EC = \sum_{i \in R} q_{m_i}^{\mathrm{R}} \cdot c_i^{\mathrm{d,R}} + \sum_{k \in P} q_{m_k}^{\mathrm{P}} \cdot c_k^{\mathrm{d,P}}$$

Total profit (€/yr) = Economic profit - Eco-cost

$$TP = (R - E - D) - EC$$

Eco-cost coefficients: Delft University of Technology, <www.ecocostsvalue.com>

3. Total Effects in Composite-Criterion: Profit + ECO-PROFIT

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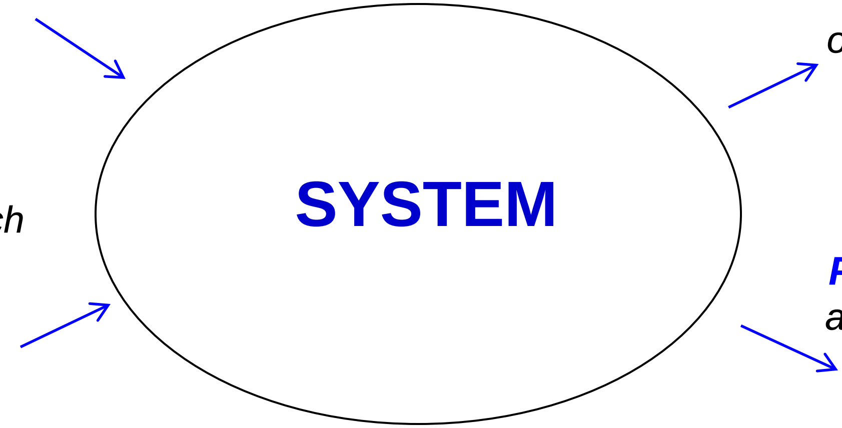
R_B *– raw materials, which only burden the environment if they are processed (direct effects)*

R_{UNB} *– raw materials, which mainly unburden or benefit the environment when they are used , e.g. utilization of waste (direct +indirect effects)*



P_B *– set of products, which only burden the environment related to processing, disposal, and transportation (direct effects)*

P_{UNB} *– set of products which alco unburden or benefit the environment (direct +indirect effects)*

Eco-profit(€/yr) = Eco-benefit - Eco-cost

Eco-benefit (€/yr): $$EB = \sum_{i \in R_{UNB}} q_{m_i}^{R_{UNB}} \cdot c_i^{R_{UNB},t} + \sum_{j \in P_{UNB}} q_{m_j}^{P_{UNB}} \cdot f_j^{S/P_{UNB}} \cdot c_j^{S,t}$$

Eco-cost (€/yr) : $$EC = \sum_{i \in R_B} q_{m_i}^{R_B} \cdot c_i^{d,R_B} + \sum_{j \in P_B} q_{m_j}^{P_B} \cdot c_j^{d,P_B} + \sum_{k \in R_{UNB}} q_{m_k}^{R_{UNB}} \cdot c_k^{d,R_{UNB}} + \sum_{l \in P_{UNB}} q_{m_l}^{P_{UNB}} \cdot c_l^{d,P_{UNB}}$$

Total profit (€/yr) = Economic profit + Eco-profit

$$TP = (R - E - D) + (EB - EC)$$

Čuček, Drobež, Pahor, Kravanja, 2011

Sustainable Bioenergy System Synthesis III.

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New Concept

Upgraded Methods

Upgraded Tools?

More Sustainable Applications

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General MP-Based Tools for System Synthesis:

- Several general MINLP solvers, e.g. DICOPT
www.gamsworld.org/minlp/solvers.html

- Logic-based solver LOGMIP
(Vecchietti and Grossmann, 1997)

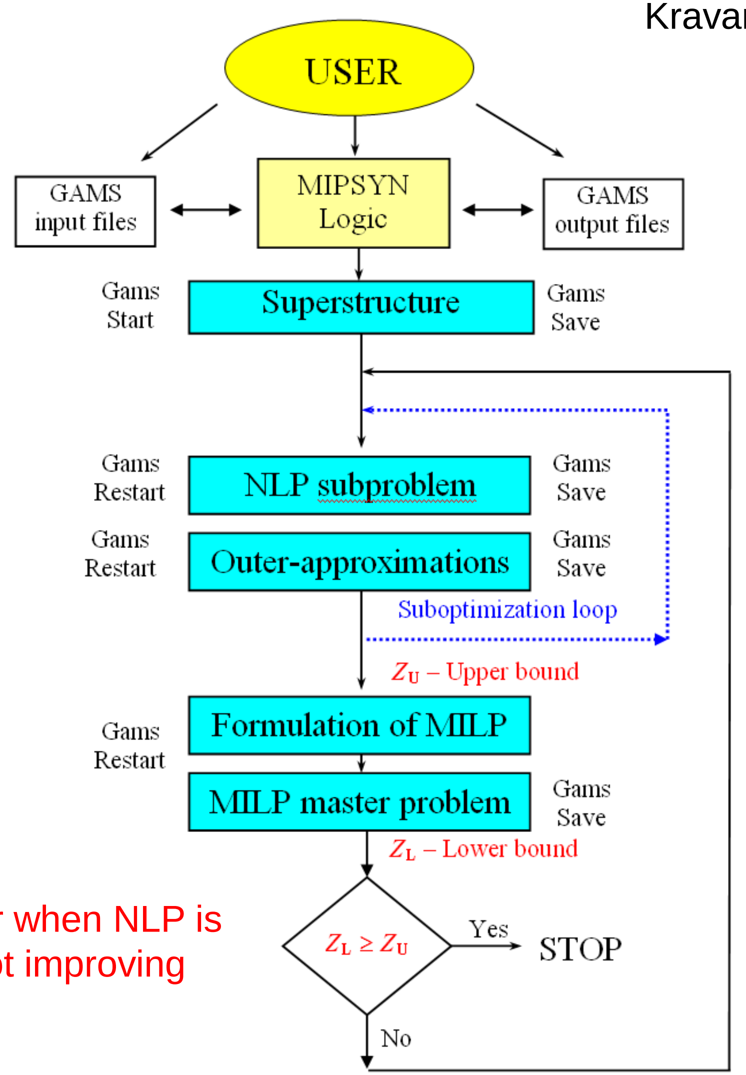
- Global MINLP Optimizer BARON
(Sahinidis, 2000)

- Almost no tool specialized in MINLP synthesis or multiobjective optimization and synthesis

MIPSYN and Logic Based OA

Kravanja and Grossmann, 1990, 1994

Kravanja, 2010



Or when NLP is not improving

Fig. 10: MIPSYN OA

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PROSYN and MIPSYN MINLP Versions

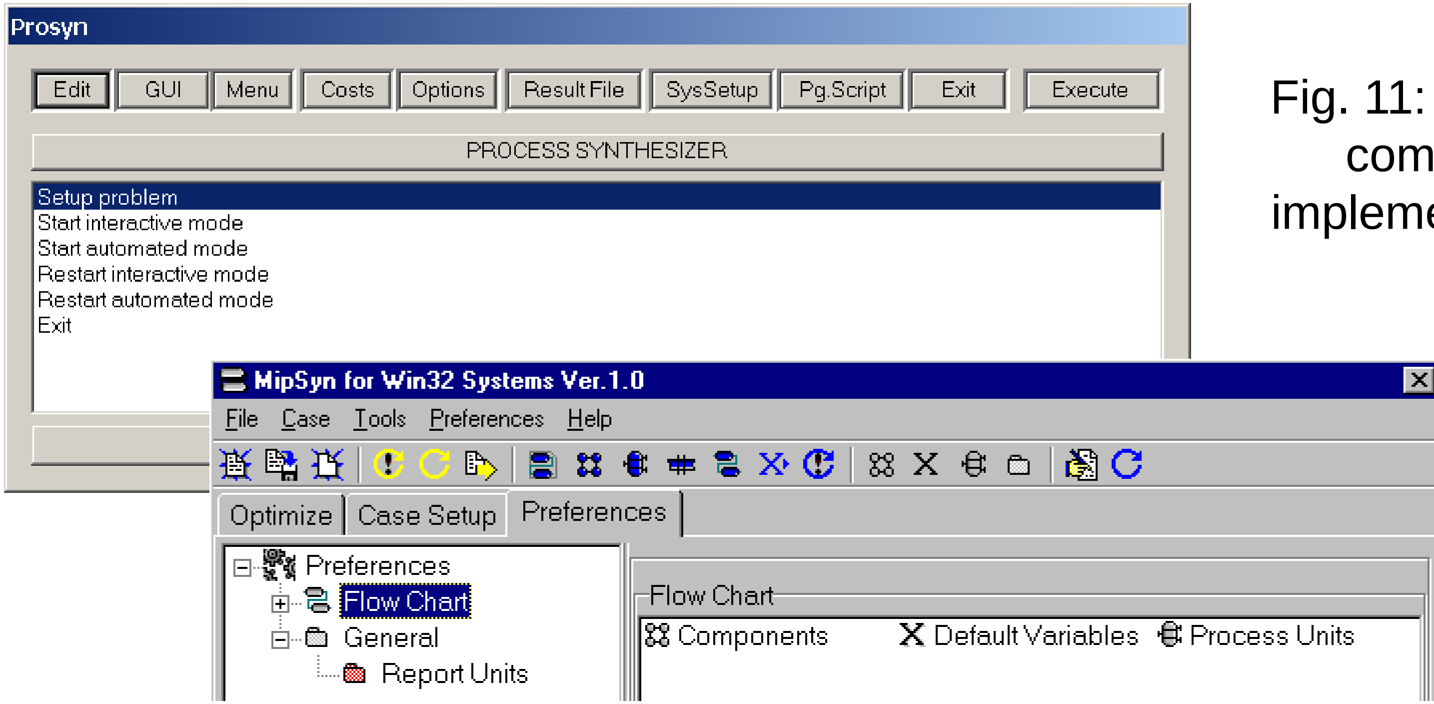


Fig. 11: Different computer implementations

MINLP synthesizer shell:

- Chemical processes
- Biochemical processes
- Mechanics

MIPSYN for Environmental Studies

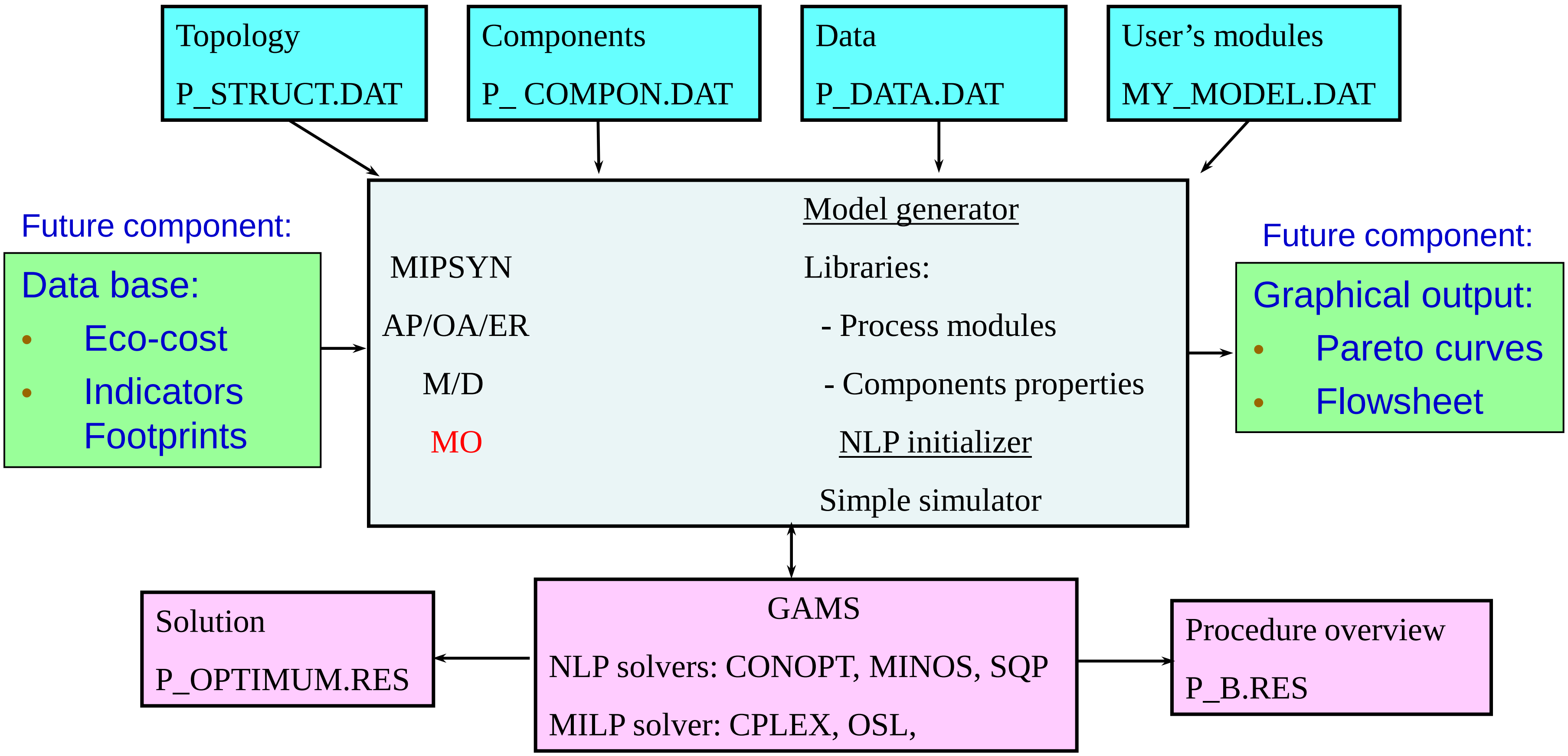
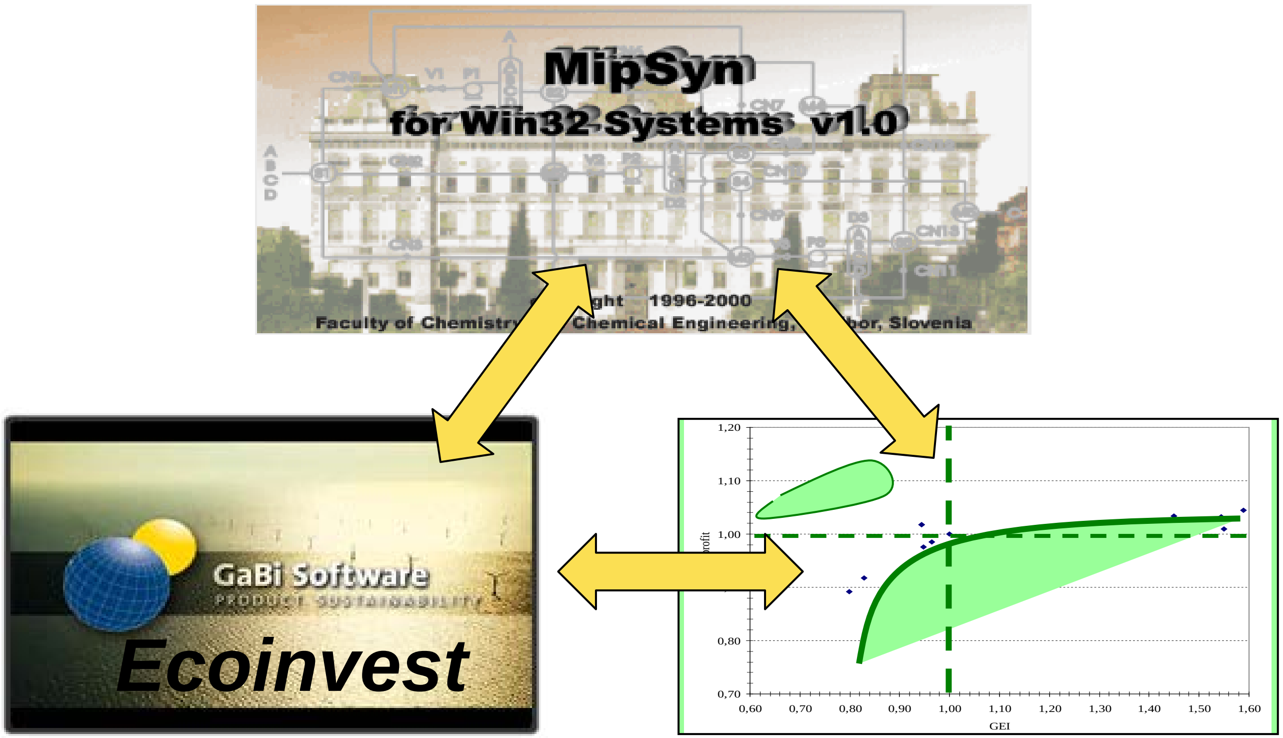


Fig. 12: Future MIPSYN flowchart

Future Tools Integration: LCA-Based Synthesizer

Synthesizer



LCA, Database | *Graphical output*

Fig. 13 LCA-based synthesizer MIPSYN

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Sustainable Bioenergy System Synthesis IV.

New Concept

Upgraded Methods

Upgraded Tools

More Sustainable Applications

EXAMPLE PROBLEM 1

Bioethanol and Total LCAI

Biomass SC and Total Footprints

Biogas and Eco-profit

Total LCA Index =
Σ (direct + indirect) effects

$$TLCAI = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{d}} + I_i^{\mathrm{ind}}}{I_i^{\mathrm{d},0}} = \sum_{i=1}^{N} w_i \cdot \frac{I_i^{\mathrm{t}}}{I_i^{\mathrm{d},0}}$$

Main Motivation

European Union targets are by 2020 to achieve at least

- a 20 % share of energy from renewable sources
- a 20 % improvement in energy efficiency
- reduction in greenhouse gas emissions
- a 10 % share of energy from renewable sources in transport

Main goal to reach or exceed 10 % of the need for gasoline in one European Country

Simultaneous integration of different technologies for converting starchy and lignocellulosic raw materials to bioethanol

Synthesis of Multi-Technologies Process

Variable raw materials input from the area of 50 000 ha and
Variable total production of ethanol

Optimization variables

Footpints based MINLP synthesis with:

- **MINLP-1:** Corn based ethanol production 2 kg/s (10 % share of bioenergy)
- **MINLP-2:** **Uncompetitive energy and food production (≤ 50 000 ha)**

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Bioethanol Process Synthesis Economic-based MINLP Step I

Karrupiah et al., 2008

Kravanja and Čuček, 2010

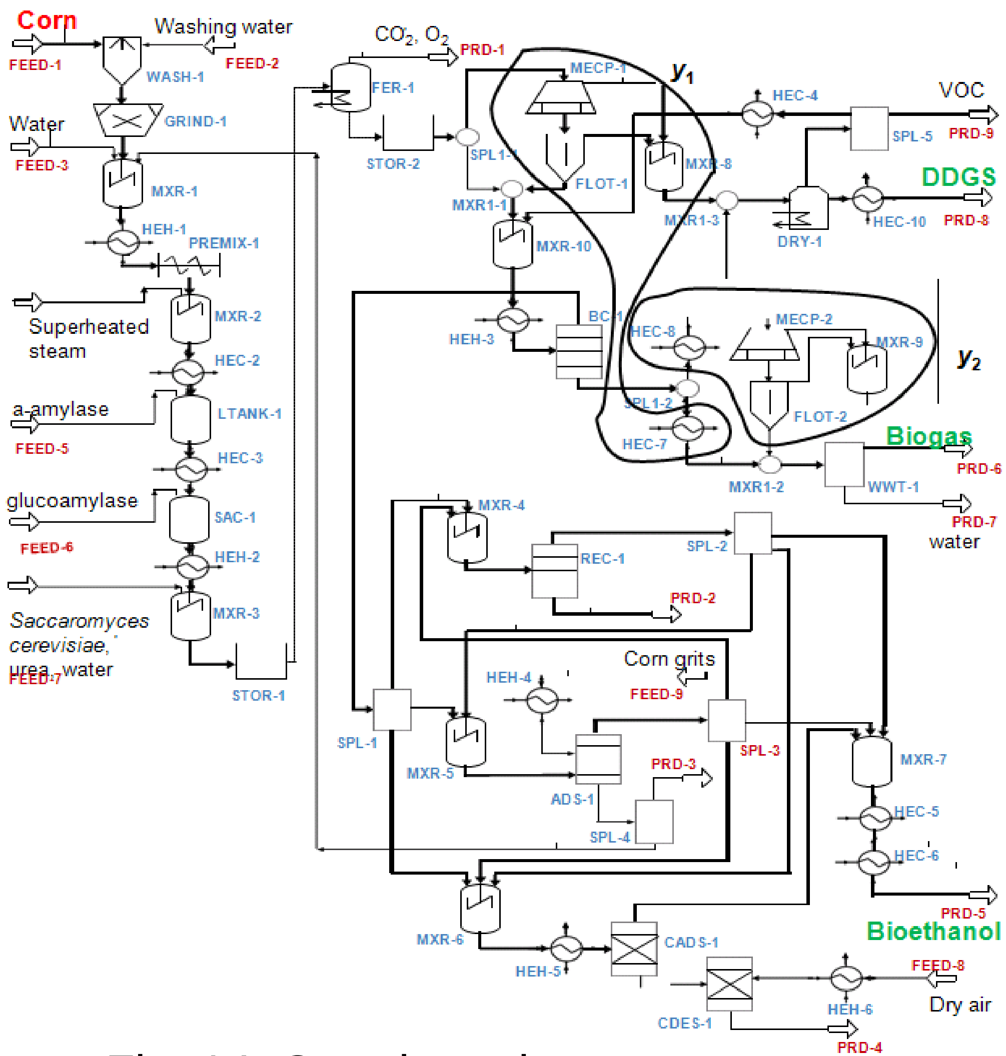


Fig. 14: Corn-based process superstructure (1st generation)

Solution:

P=22.786 M$/yr

Bioethanol Process Network
Multiobjective Sustainable MINLP Step II

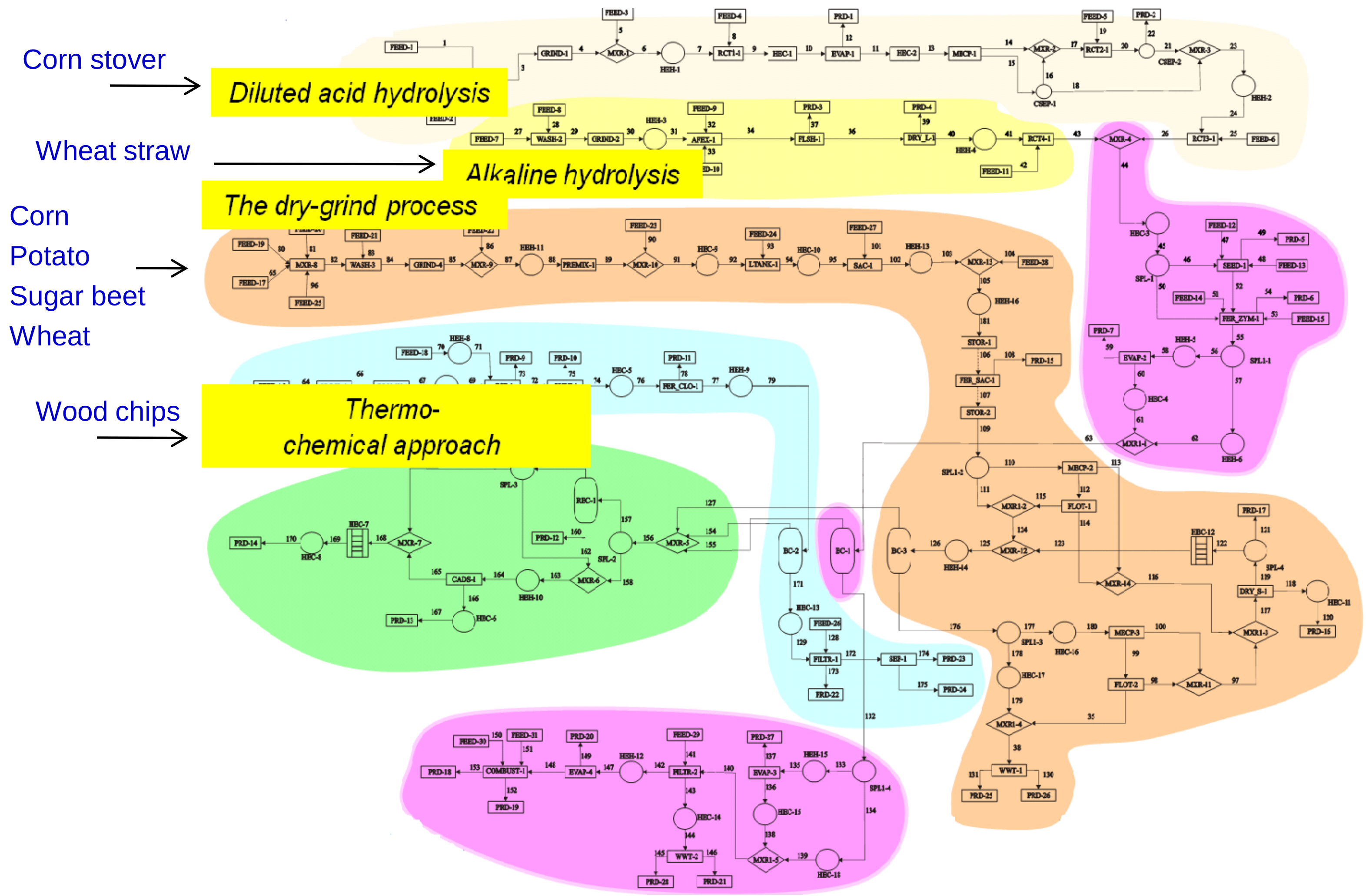


Fig. 15: Superstructure, enlarged by sustainable alternatives (2nd generation)

LCAI-Based Bioethanol Synthesis Multiobjective Sustainable MINLP Step II

University of Maribor

Economic indicator:

$$RP = \frac{P}{P^0}, \; where \; P^0 = 22.786 \; M\$/yr$$

LCA index:

Intention is to obtain solutions with smaller CO2 equivalent emissions and to produce ethanol from raw materials, not part of the food chain. Weights:

- ⅓ CO_2 emissions to the air
- ⅓ social indicator (food to energy)
- ⅓ all other indicators

$$LCAI = \frac{1}{3}\cdot\frac{q_{m,ea}}{q^0_{m,ea}} + \frac{1}{3}\cdot\frac{q_{m,fe}}{q^0_{m,fe}} + \frac{1}{3}\cdot\frac{1}{9}\cdot\left(\frac{q_{m,su}}{q^0_{m,su}} + \frac{q_{m,fu}}{q^0_{m,fu}} + \frac{q_{m,pu}}{q^0_{m,pu}} + \frac{q_{m,wu}}{q^0_{m,wu}} + \frac{(A/q_m)_{land}}{(A/q^0_m)_{land}} + \frac{q_{m,fc}}{q^0_{m,fc}} + \frac{q_{m,eu}}{q^0_{m,eu}} + \frac{q_{m,es}}{q^0_{m,es}} + \frac{q_{m,ew}}{q^0_{m,ew}}\right)$$

Total LCAI-Based Bioethanol Synthesis Multiobjective Sustainable MINLP Step II

Total LCA index:

Direct and Indirect CO2 equivalent emissions
Indirect effects due to products‘ substitution (gasoline by bioethanol)
The same weights as before:

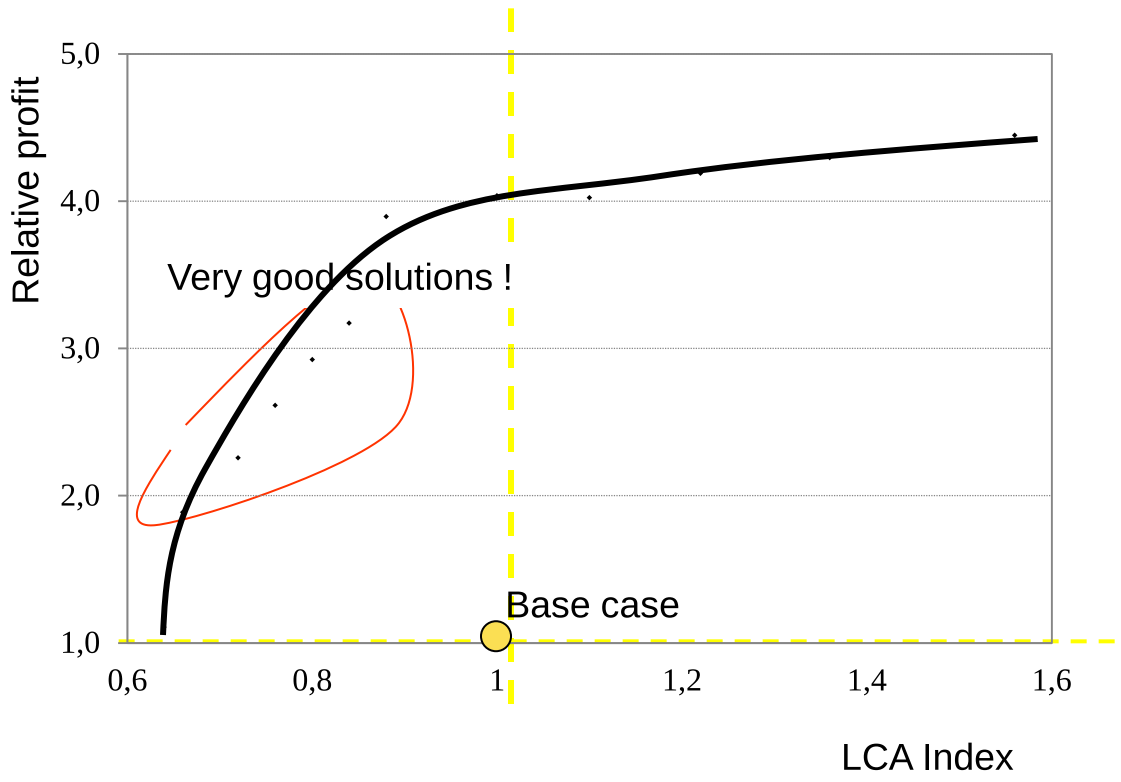
- ⅓ CO2 emissions to the air
- ⅓ social indicator (food to energy)
- ⅓ all other indicators

$$Total\ LCAI = \frac{1}{3}\cdot\left(\frac{q_{m,ea}}{q_{m,ea}^{0}} - \frac{q_{m,ea}^{\text{Ethanol}}}{q_{m,ea}^{\text{Ethanol},0}}\cdot f_{\text{Gasoline/Ethanol}}^{\text{Sub}}\right) + \frac{1}{3}\cdot\frac{q_{m,fe}}{q_{m,fe}^{0}} +$$

$$\frac{1}{3}\cdot\frac{1}{9}\cdot\left(\frac{q_{m,su}}{q_{m,su}^{0}} + \frac{q_{m,fu}}{q_{m,fu}^{0}} + \frac{q_{m,pu}}{q_{m,pu}^{0}} + \frac{q_{m,wu}}{q_{m,wu}^{0}} + \frac{(A/q_m)_{land}}{(A/q_m^{0})_{land}} + \frac{q_{m,fc}}{q_{m,fc}^{0}} + \frac{q_{m,eu}}{q_{m,eu}^{0}} + \frac{q_{m,es}}{q_{m,es}^{0}} + \frac{q_{m,ew}}{q_{m,ew}^{0}}\right)$$

LCAI-Based Solution from Multiobjective MINLP Step II

Scalar parametric optimization:



Variable raw materials input from the area of 50 000 ha

Variable total production of ethanol

Fig. 16: "Pareto curve" for Bioethanol problem obtained by LCA Index

Total LCAI-Based Solution from Multiobjective MINLP Step II

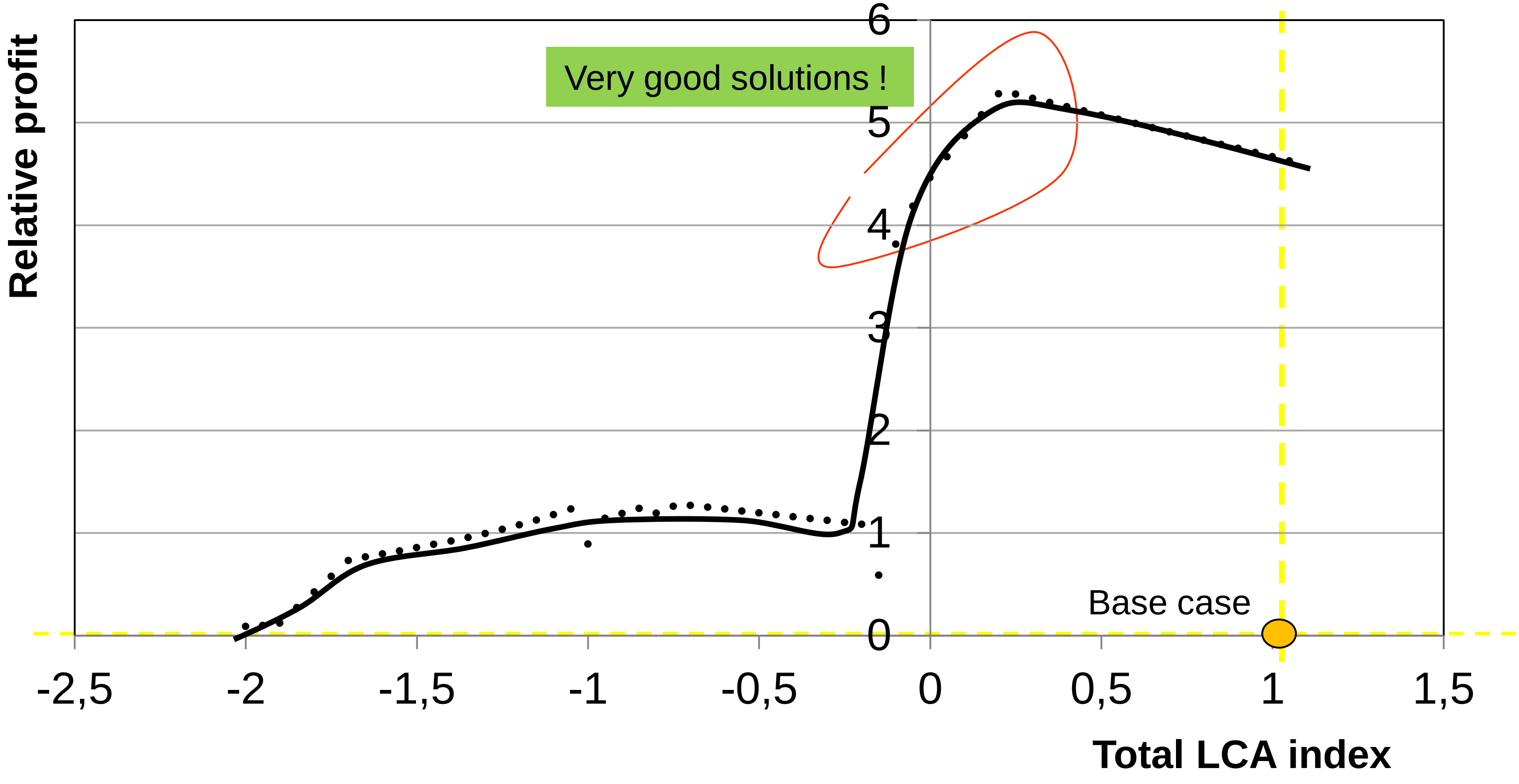


Fig. 17: “Pareto curve” for Bioethanol problem obtained by Total LCA Index

LCAI-Based Bioethanol Synthesis Solution: Energy and Food Production

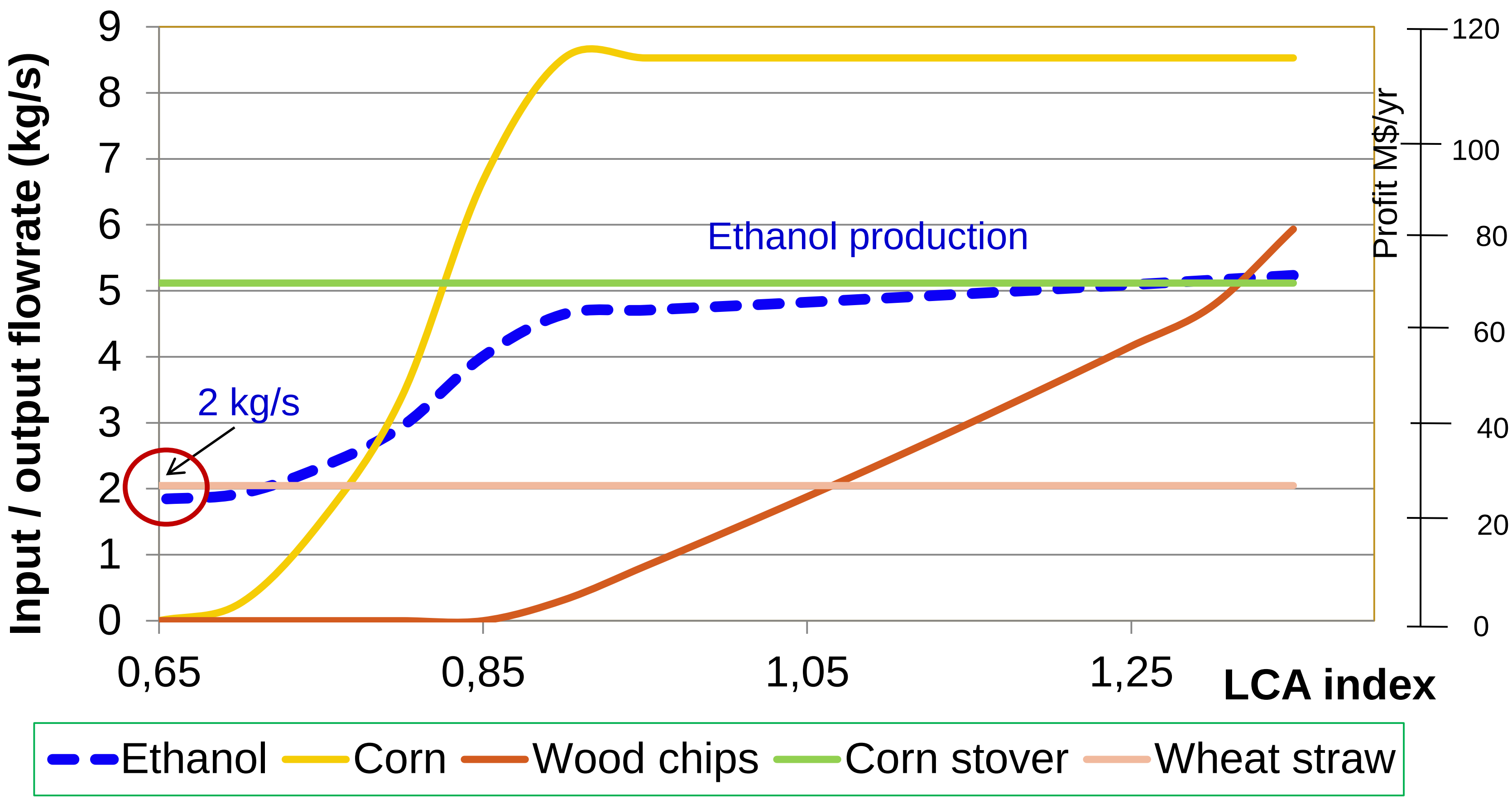


Fig. 18: Raw material and bioethanol production by LCA Index

Total LCAI-Based Bioethanol Synthesis Solution: Energy and Food Production

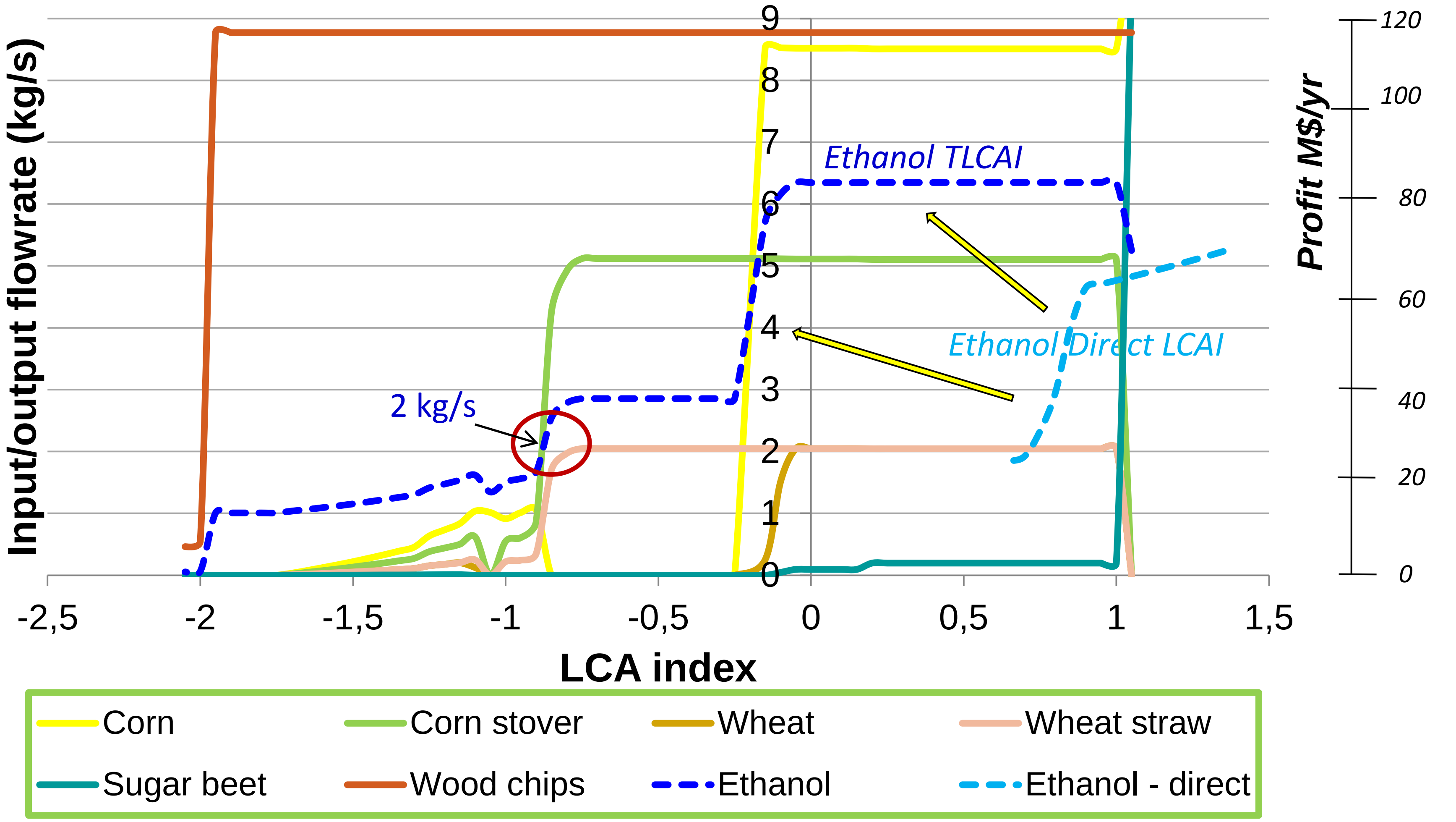


Fig. 19: Raw material and bioethanol production by Total LCA Index

Direct LCA Index vs. Total LCA Index

- Significantly different solutions can be obtained with Direct LCA Index and Total LCA Index
- Indirect effects by products' substitution can even cause the Total LCA Index to become negative.
- Total LCAI < Direct LCA Index:

  The target of 2 kg/s bioethanol was achieved at very negative Total LCA Index although the corresponding weight is 1/3.

- When using Direct LCA Index alternatives with smaller environmental impact are preferred, while with Total LCA Index those that unburden environment the most (different perception).

EXAMPLE PROBLEM 2

Bioethanol and Total LCAI

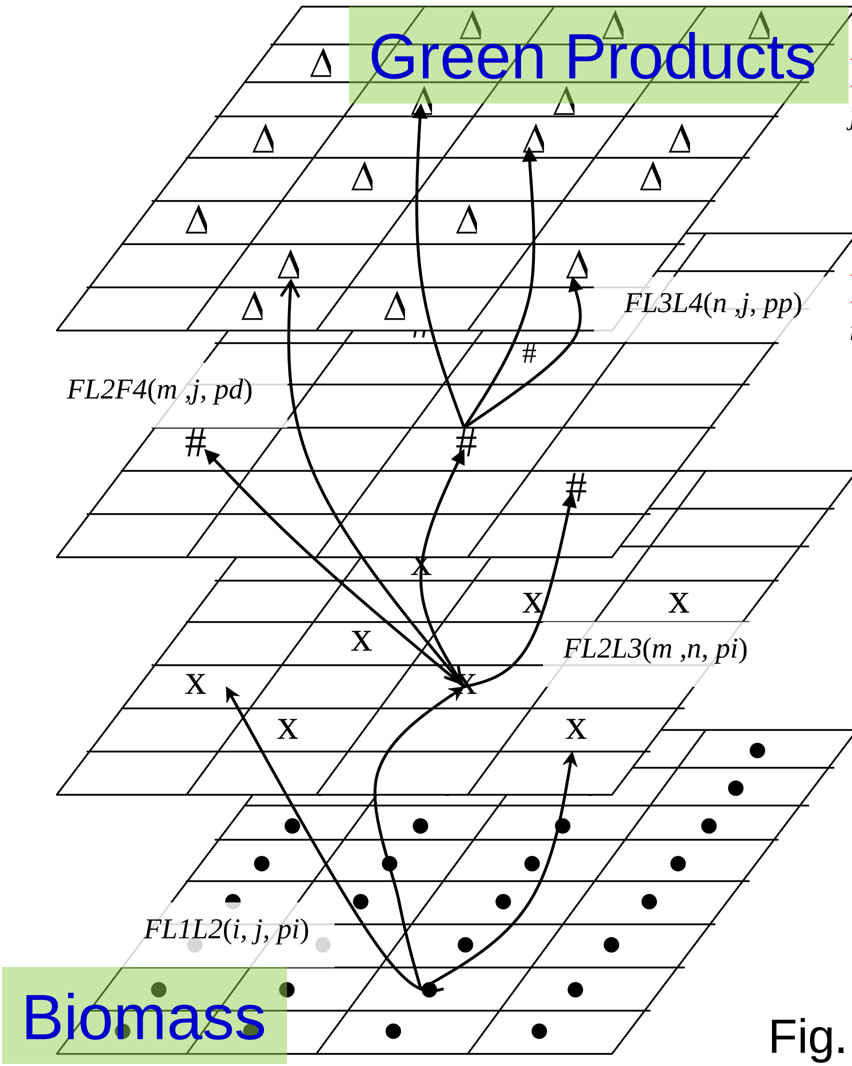
Biomass SC and Total Footprints

Biogas and Eco-profit

$$TRFP = \frac{FP^{\mathrm{d}} + FP^{ind}}{FP^{\mathrm{d0}}} = \frac{FP^{\mathrm{t}}}{FP^{\mathrm{d0}}}$$

Synthesis of Regional Biomass Supply Chain by Total Footprints

Čuček, Klemeš, Varbanov, Kravanja, submitted to Energy



Layer 4: Demand/ End users

j = demands

Layer 3: Production plants

n = plants

*y*L3 (n) = To determine the location of plants
*y*L3pt (*n*, *pp*, *t*) = for technologies selection

Layer 2: Collection and pretreatment processes

m = intermediate points

*y*L2 (*m*) = To determine the location of collection points and also the pretreatment processes : drying/ compaction/ densification

Layer 1: Agricultural supply

i = zones

Fig. 5: SDRN superstructure

Biomass Supply Chain – Mathematical Model (1)

Čuček, Lam, Klemeš, Varbanov, Kravanja, *Clean technol. environ. policy* 2010

Lam, Klemeš, Kravanja, Energy, 2011

Layer: L1 – L2

Production rates of products *pi* at zone *i*:

$$PR(i, pi) = HY(i) \times AP(i, pi) \ \forall pi, i$$

$$\sum_{pi} AP(i, pi) \le AT(i) \quad \forall i$$

Collection and transportation to L2

$$PR(i, pi) = \sum_{m} FL1L2(i, m, pi) \ \forall pi, i, m$$

Layer: L2

Determine the location of collection and pre-treatment centres CC(*m*)

$$\sum_{i, pi} FL1L2(i, m, pi) \le MAXTFCC \times yL2(m) \ \square m$$

$$\sum_{i} FL1L2(i, m, pi) \le MAXPFCC \times yL2(m) \ \square m, pi$$

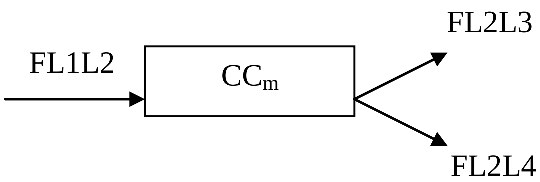
$$MINTFCC \times yL2(m) \le \sum_{i} FL1L2(i, m, pi) \ \square m$$

$$MINPFCC \times yL2(m) \le \sum_{i} FL1L2(i, m, pi) \ \square m, pi$$

Biomass Supply Chain – Mathematical Model (2)

Layer L2-L3 and L2-L4

Product *pi* can be transported from CC (*m*) to Plant (*n*) or directly to the customer (*j*)



$$\sum_i FL1L2(i,m,pi) \times CONFCC(pi) = \sum_n FL2L3(m,n,pi) + \sum_j FL2L4(m,j,pd) \quad \forall pi,m$$

Layer L3, and L3-L4

Determine the location of process plants PL(*n*)

$$\sum_{m,pi} FL2L3(m,n,pi) \le MAXTFPL \times yL3(n) \quad \forall n$$

$$\sum_{m} FL2L3(m,n,pi) \le MAXPFPL \times yL3(n) \quad \forall n,pi$$

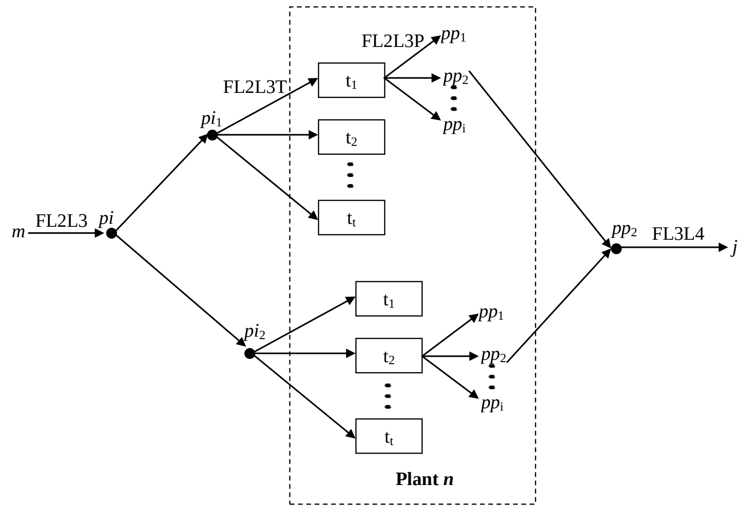
$$MINTFPL \times yL3(n) \le \sum_{m,pi} FL2L3(m,n,pi) \quad \forall n$$

$$MINPFPL \times yL3(n) \le \sum_{m} FL2L3(m,n,pi) \quad \forall n,pi$$

Biomass Supply Chain – Mathematical Model (3)

Layer L3, and L3-L4 (cont.)

Select Technology *t* that convert intermediate product *pi* to product *pp*.



For each selected Plant *n* only one type of technology *t* is selected for each type of *pi*.

$$\sum_{pt(pi,t)} yL3T(n,pi,t) \le yL3(n) \quad \forall n, pi$$

$$\sum_{m} FL2L3(m,n,pi) = \sum_{pt_{pi}} FL2L3(n,pi,t) \quad \forall n, pi$$

$$FL2L3T(n,pi,t) \le MAXFT(t) \times yL3T(n,pi,t) \quad \forall n, pi, t, pt$$

$$FL2L3T(n,pi,t) \times CONFPL(pi,pp,t) = FL2L3P(n,pi,pp,t) \quad \forall n, pi, pp, t$$

$$\sum_{pip(pi,pp),pt(p,t)} FL2L3P(n,pi,pp,t) = \sum_{j} FL3L4(n,j,pp) \quad \forall n, pp$$

Demand for products *pp*:

$$D(j^{o},pp) \ge \sum_{n} FL3L4(n,j^{o},pp) + \sum_{m} FL2L4(m,j^{o},pd) \quad \forall j^{o}, pp, pd$$

Biomass Supply Chain – Mathematical Model (4)

Max P = Incomes – Outcomes
= Sale incomes –
(Raw material cost + Transportation + Operation + Annualized investments)

Sales incomes:

$$\sum_{n,j,pp} FL3L4(n,j,pp)\times price(pp) + \sum_{m,j,pd} FL2L4(m,j,pd)\times price(pd)$$

Outcomes:

Feedstock cost:

$$\sum_{i,pi} PR(i,pi)\times pcost(pi) +$$

Transportation:

$$+\ TCL1L2 + TCL2L3 + TCL2L4 + TCL3L4 +$$

Operational costs for Collecting Centers:

$$+\sum_{i,m,pi} COCC(pi)\times FL1L2(i,m,pi) +$$

Operational costs for Plants and Technologies:

$$+\sum_{n,pt(pi,t)} COPLT(pi,t)\times FL2L3T(n,pi,t) +$$

Annualized investment for Collecting Centers:

$$+\sum_{i,m,pi} CFCC\times yL2(m) + CVCC\times FL1L2(i,m,pi) +$$

Annualized investment for Plants and Technologies:

$$+\sum_{n,pt(pi,t)} \left(CFPLT(pi,t)\times yL2T(n,pi,t) + CVPLT(pi,t)\times FL2L3T(n,pi,t)\right)$$

Biomass Supply Chain – Mathematical Model (5)

❑ Implementation of footprints

Environmental footprints *f* ε *F*:

- CFP (Carbon footprint) – amount of CO_2 and other greenhouse gases emitted over the full life-cycle of a process or product
- EFP (Energy footprint) – the demand for non-renewable energy resources
- WFP (Water footprint) – the total volume of direct and indirect freshwater used
- LFP (Agricultural land footprint) – the agricultural land area used for growing biomass
- WPFP (Water pollution footprint) – the amount of substances emitted to water

Social footprint

- FEFP (Food-to-energy footprint) – relates the usage of food intended biomass for the production of energy

Biomass Supply Chain – Mathematical Model (6)

E.g.: Environmental footprint – supply layer L1

All environmental are defined annually, and per unit of the supply-chain network's total area (A, km^2).

For supply layer, $ENVB_f^{\mathrm{L1}}$: as the production rate of biomass *pi*, $q_{i,pi}^{m,\mathrm{L1}}$, multiplied by Specific Environmental Footprint for that biomass, $ei_{pi,f}^{\mathrm{L1}}$, caused by growing biomass:

$$ENVB_f^{\mathrm{L1}} = (\sum_{i \in I} \sum_{pi \in PI} q_{i,pi}^{m,\mathrm{L1}} \cdot ei_{pi,f}^{\mathrm{L1}})/\mathrm{A} \quad \forall f \in F$$

Biomass Supply Chain – Mathematical Model (7)

❑ Environmental and social footprint

The **total environmental footprint *f* ε *F*** of the supply chain network is defined:

$$ENVB_f = ENVB_f^{\mathrm{L1}} + ENVB_f^{\mathrm{L2}} + ENVB_f^{\mathrm{L3}} + ENVB_f^{\mathrm{L4}} + ENVB_f^{\mathrm{tr}}$$

The social footprint – food-to-energy footprint is defined only for multi-functional (multi-product) crops which can result in a supply of food, fodder, and/or energy. The food-to-energy footprint is defined as a fraction of food-intended crops used for energy production:

$$FEFP = \Big(\sum_{n \in N} \sum_{pi \in PI} \sum_{pp \in PP} \sum_{t \in T^e} \sum_{(pi,pp) \in PIP} q_{n,pi,pp,t}^{m,\mathrm{T,L2,L3}} \Big/ \sum_{i \in I} \sum_{m \in M} \sum_{pi \in PI} q_{i,m,pi}^{m,\mathrm{L1,L2}}$$

$$T^e = \{\text{energy production plants}\}$$

Demonstration Case Study

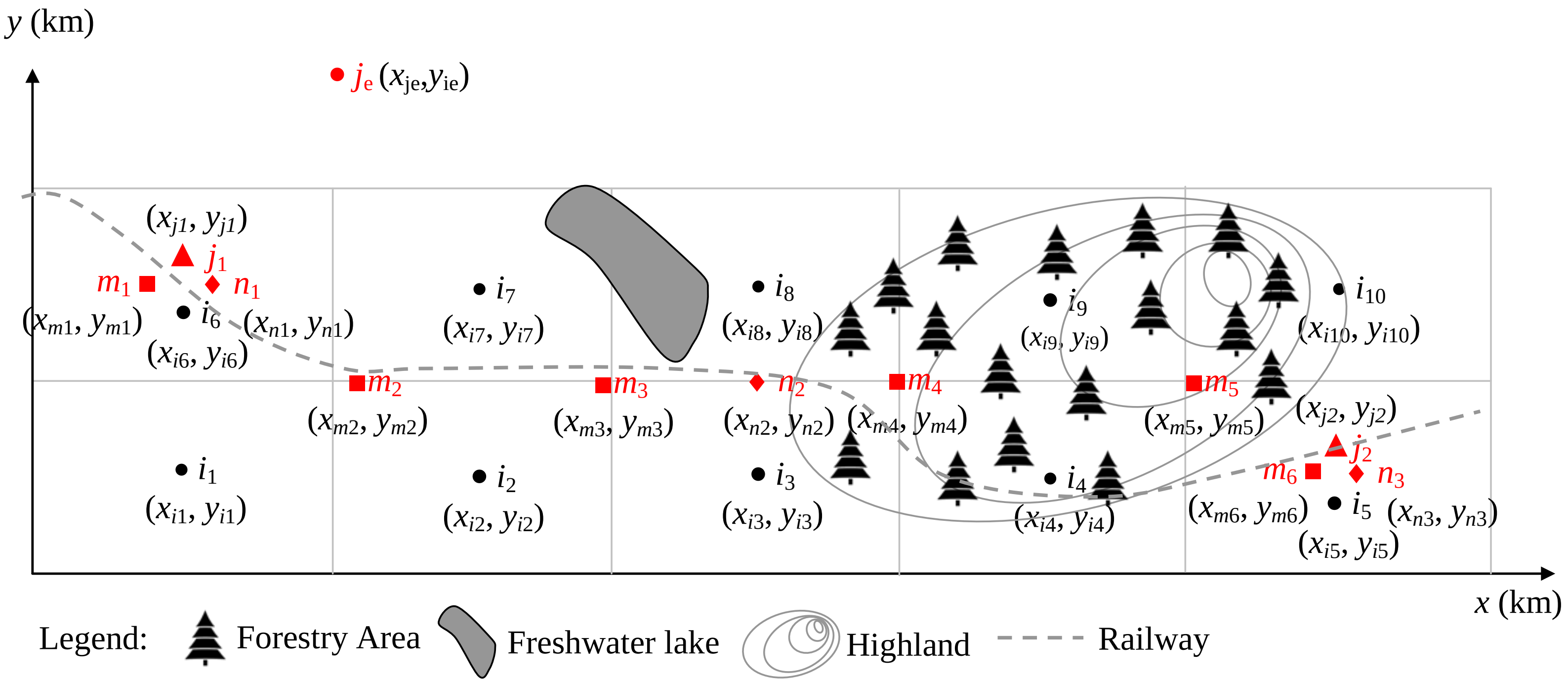


Fig.20: The supply-network structure of the demonstrated case study

Biomass Supply/Demand Renewable Networks

Raw materials included on the given area:
corn, corn stover, MSW, wood chips, manure and timber

Considered **technological options**:

- The dry-grind process (corn)
- Diluted acid pre-treatment (corn stover)
- Gasification/fermentation (wood chips)
- Anaerobic co-digestion (biomass waste)
- Incineration (MSW and lignocellulosic raw materials)
- Sawing (timber)

Products:
electricity, heat, bioethanol, boards, digestate, DDGS

Footprints Obtained at MINLP-1

Table 1: Direct, Indirect and Total footprints for Biomas supply chain

	Direct footprints	Indirect footprints	Total footprints
CFP (t/(km^2·y))	117.65	-311.95	-194.3
WFP (t/(km^2·y))	376,500.75	-39,210.75	337,290
EFP (GJ/(km^2·y))	1,440.65	-4,906.72	-3,466.07
WPFP (t/(km^2·y))	12.02	-6.47	5.55
LFP (km^2/(km^2·y))	0.32	0	0.32
FEFP (-)	0.38	0	0.38

Direct Footprints

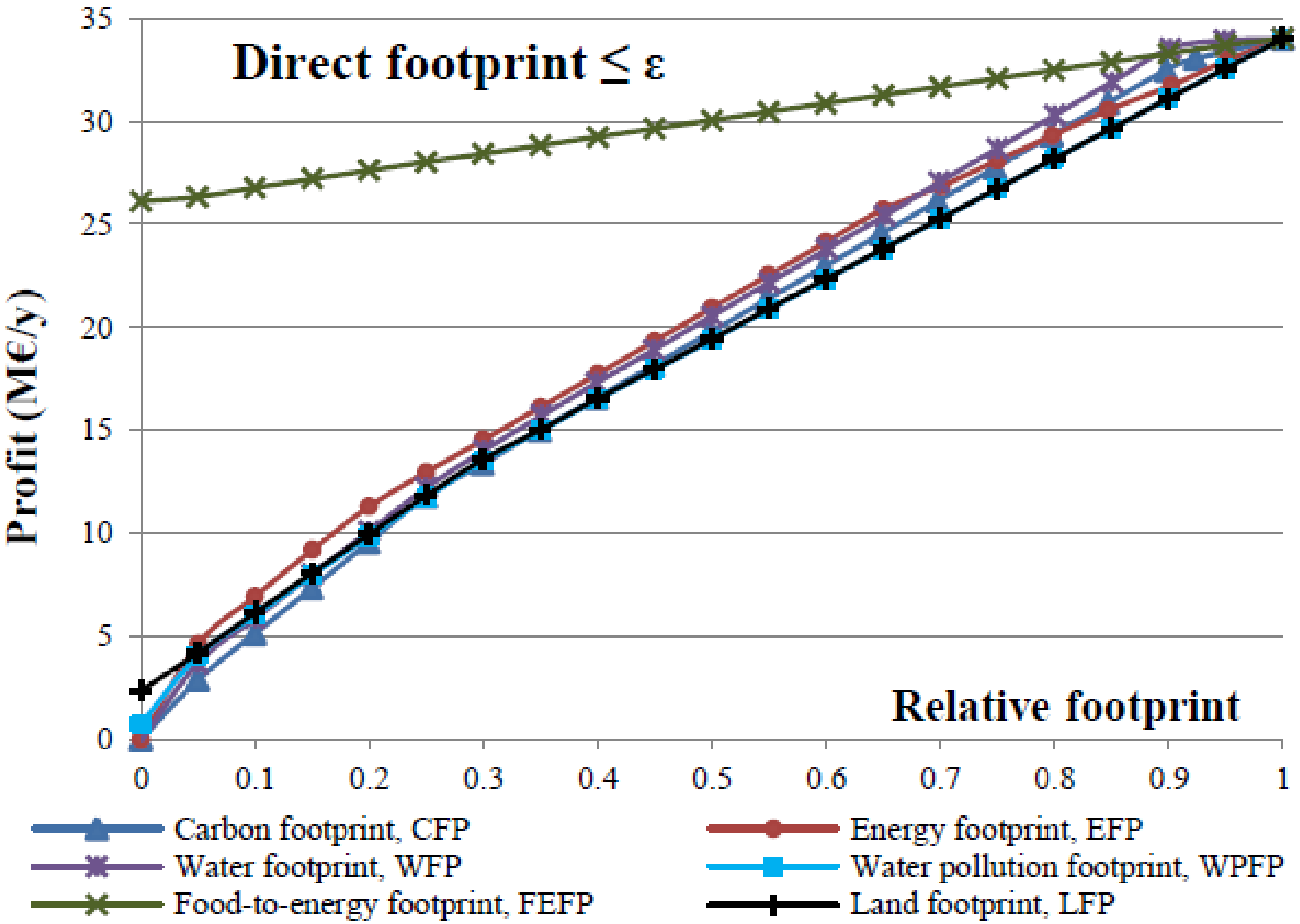


Fig. 21: Direct footprints for Biomass supply chain

Total/Direct Footprints

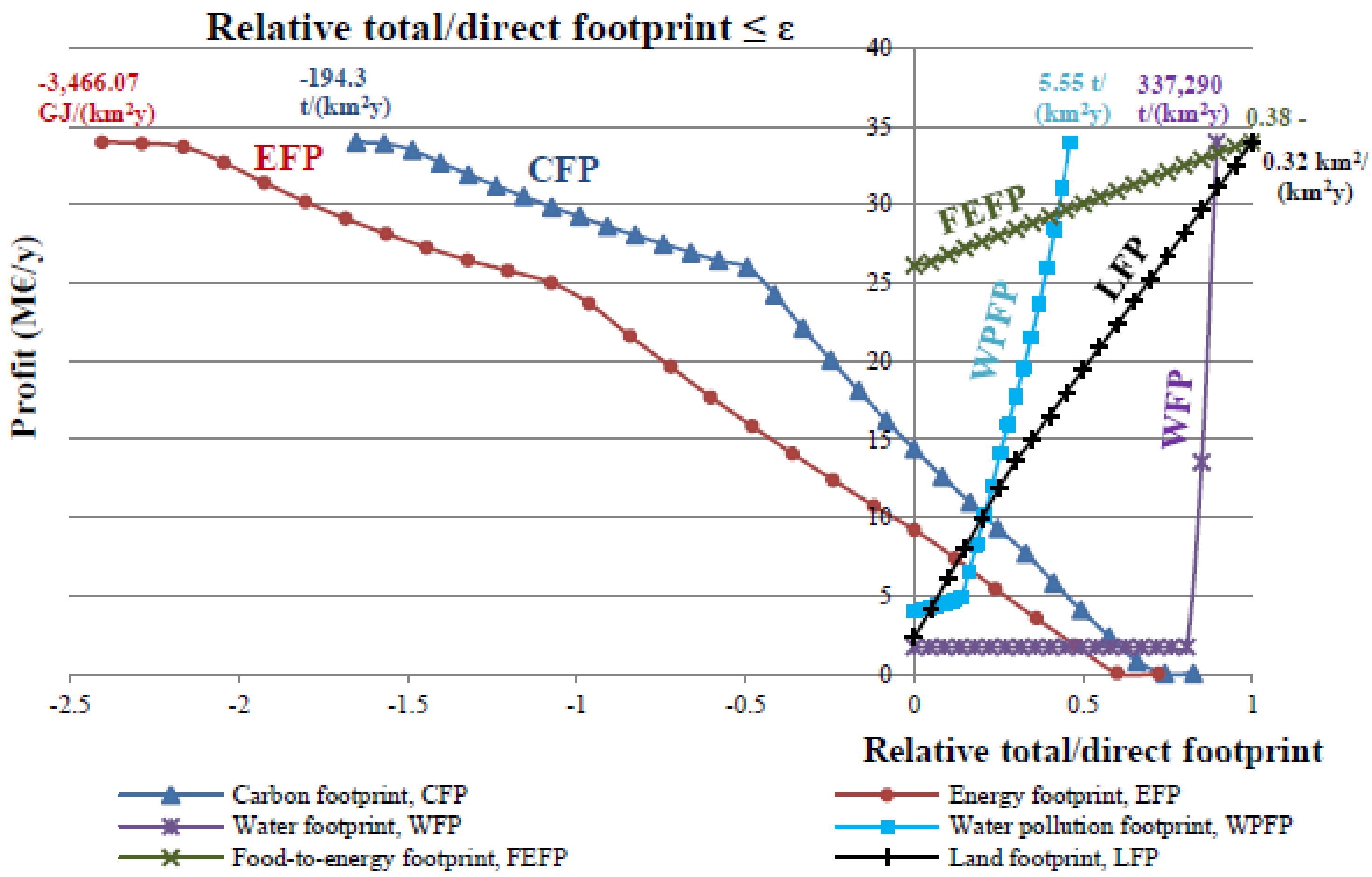


Fig. 22: Total/direct footprints for Biomass supply chain

Product Flowrates by Direct Footprints

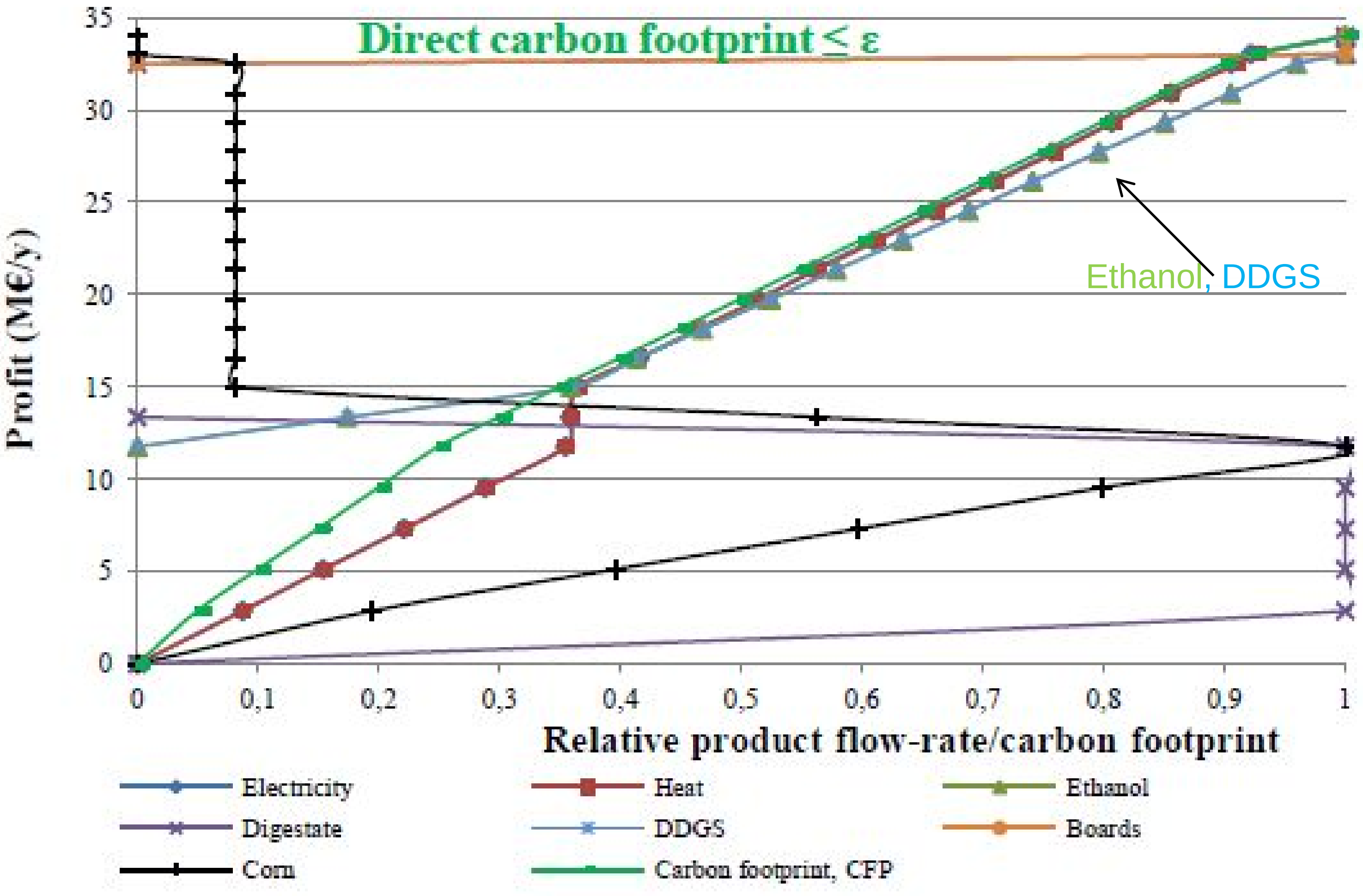


Fig. 23: Relative products flow-rates by Direct footprints

Product Flowrates by Total/Direct Footprints

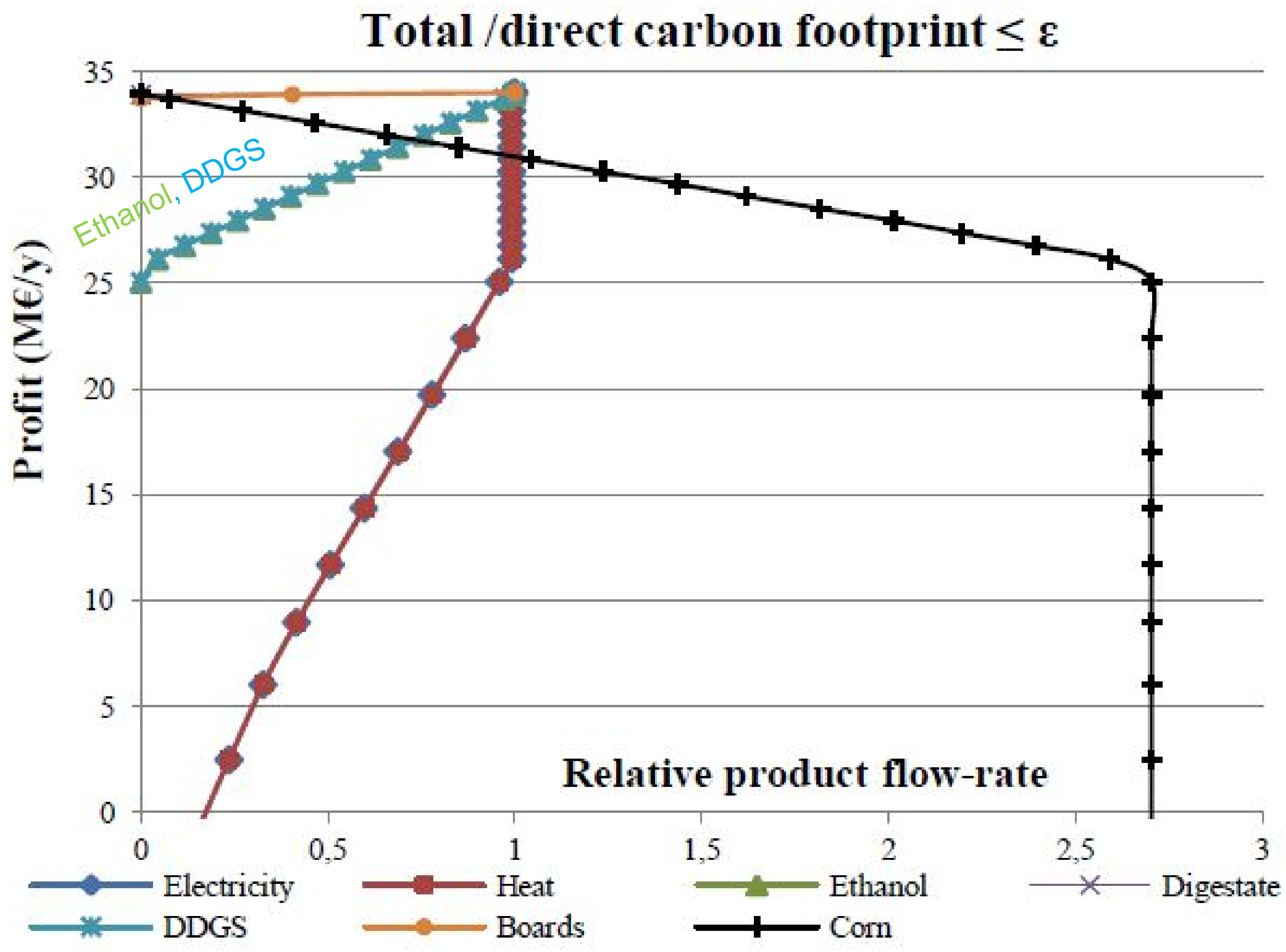


Fig. 24: Relative total/direct products flow-rates

Direct Footprints vs. Total Footprints

- Significantly different solutions can be obtained with direct and total footprints
- Indirect effects by products‘ substitution can cause some footprints to become negative.
- Total Footprints ≤ Direct Footprints:

  Biomass supply chains have negative total CFP and EFP, reduced but still positive total WPFP and WFP, and unchanged LFP and FEFP, when compared to the corresponding direct footprints.

- When using direct footprints alternatives with smaller environmental impact are preferred, while with total footprints those that unburden environment the most (different perception).

EXAMPLE PROBLEM 3

Bioethanol and Total LCAI

Biomass SC and Total Footprints

Biogas and Eco-profit

Eco-profit(€/yr) = Eco-benefit - Eco-cost

Eco-benefit (€/yr): $EB = \sum_{i \in R_{UNB}} q_{m_i}^{\mathrm{R_{UNB}}} \cdot c_i^{\mathrm{R_{UNB},t}} + \sum_{j \in P_{UNB}} q_{m_j}^{\mathrm{P_{UNB}}} \cdot f_j^{\mathrm{S/P_{UNB}}} \cdot c_j^{\mathrm{S,t}}$

Eco-cost (€/yr) : $EC = \sum_{i \in R_{\mathrm{B}}} q_{m_i}^{\mathrm{R_B}} \cdot c_i^{\mathrm{d,R_B}} + \sum_{j \in P_{\mathrm{B}}} q_{m_j}^{\mathrm{P_B}} \cdot c_j^{\mathrm{d,P_B}} + \sum_{k \in R_{\mathrm{UNB}}} q_{m_k}^{\mathrm{R_{UNB}}} \cdot c_k^{\mathrm{d,R_{UNB}}} + \sum_{l \in P_{\mathrm{UNB}}} q_{m_l}^{\mathrm{P_{UNB}}} \cdot c_l^{\mathrm{d,P_{UNB}}}$

Total profit (€/yr) = Economic profit + Eco-profit

$$TP = (R - E - D) + (EB - EC)$$

Eco-profit Based MINLP Synthesis of Biogas Process

University of Maribor

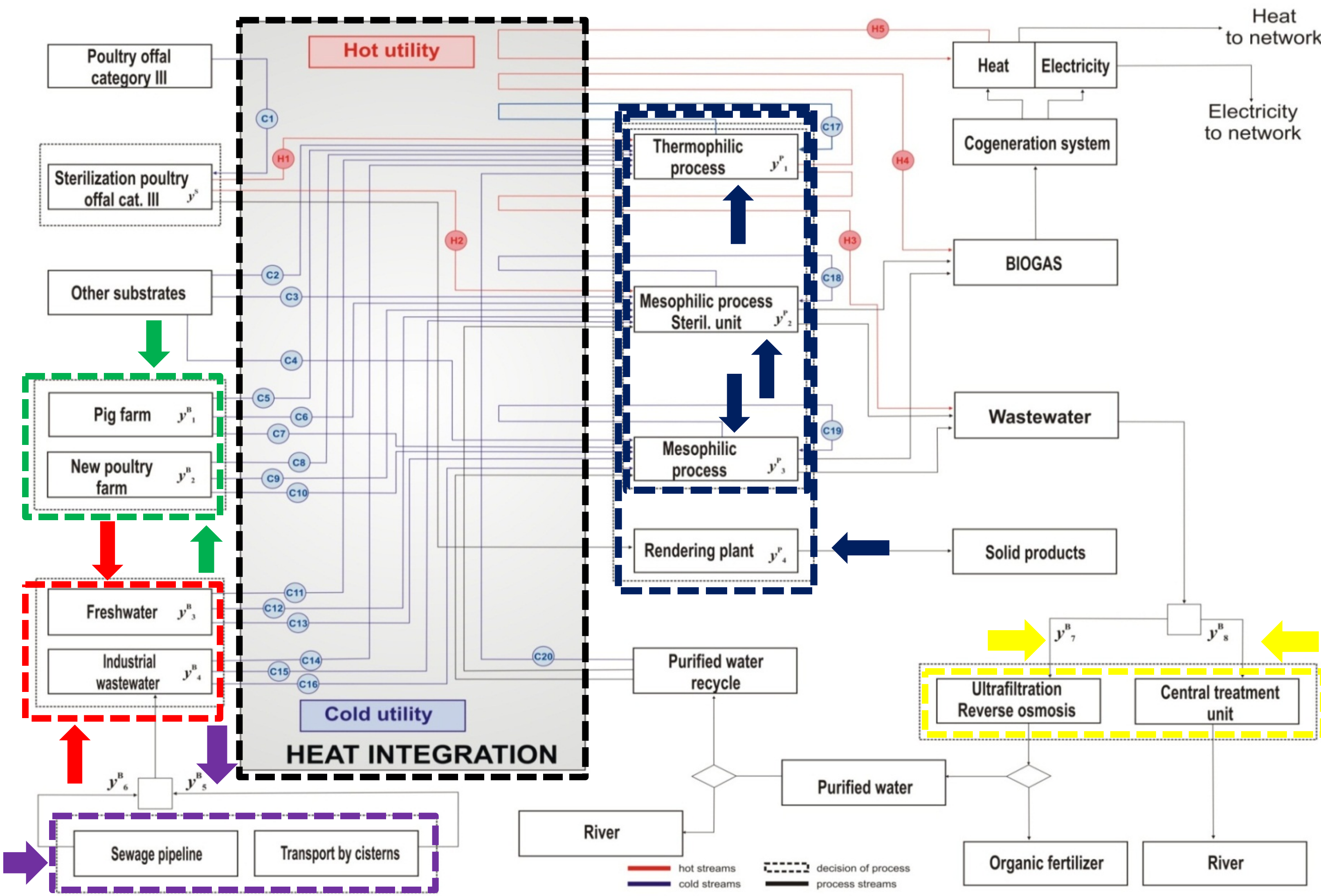


Fig. 25: Biogas from Organic and Animal Waste study

Results

Eco-cost:

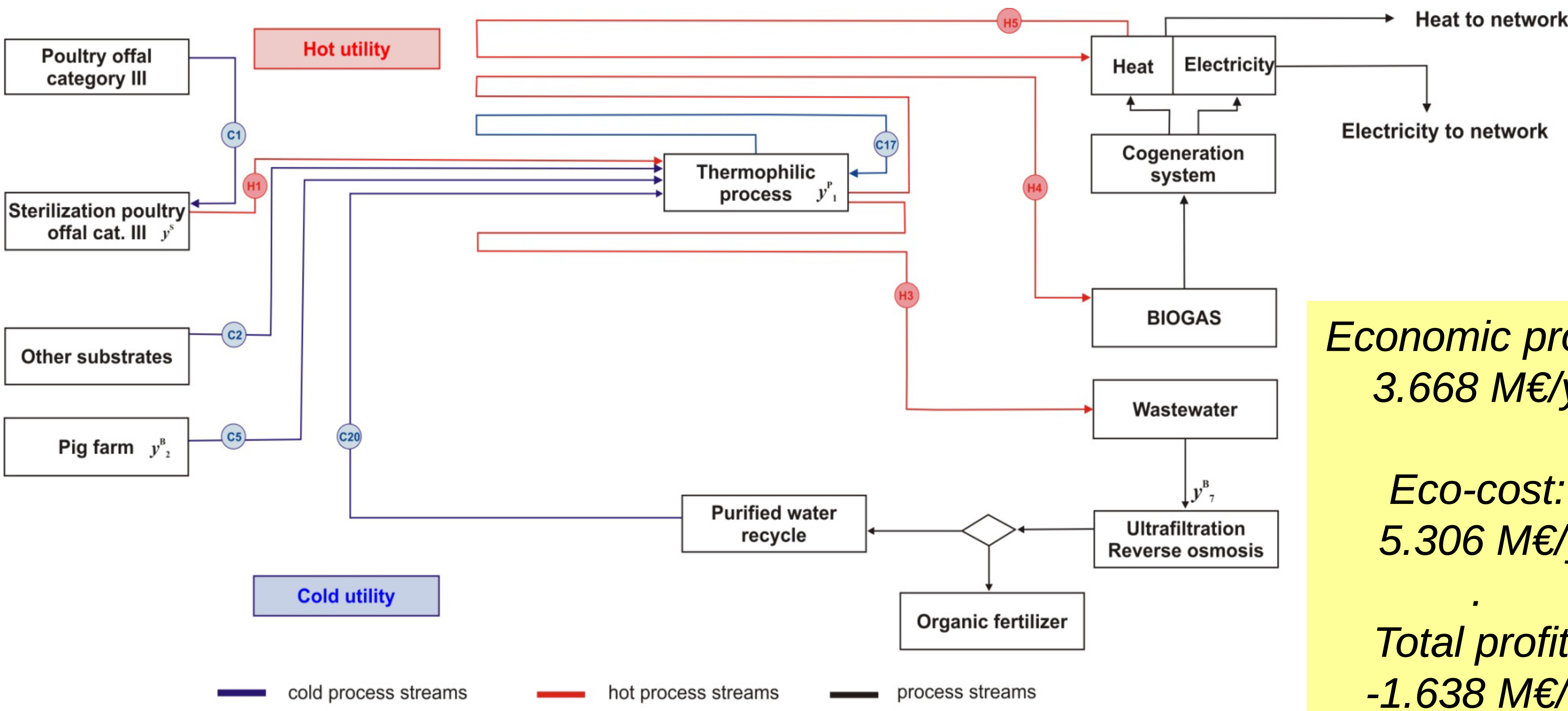
- Economical profit maximization
- Eco-cost minimization
- Total-profit maximization

Total profit (€/yr) = Economic profit - Eco-cost

Single-objective Optimization

Drobež, Novak-Pintarič, Pahor, Kravanja, 2010 Čuček, Drobež, Pahor, Kravanja, 2011

Maximization of the **economic profit**



Economic profit:
3.668 M€/y

Eco-cost:
5.306 M€/y

.

Total profit:
-1.638 M€/y

Fig. 26: Optimal Biogas production flowsheet

Single-objective Optimization

Table 2: Different optimization schemes with Eco-cost for Biogas problem

	Maximized economic profit (*P*)	**Minimized eco-cost (*EC*)**	**Maximized total profit (*TP*)**
Economic profit (M€/y)	3.308	0	0
Eco-cost (M€/y)	5.301	0	0
Total profit (M€/y)	-1.992	0	0
Income (M€/y)	7.546	0	0
Depreciation (M€/y)	2.943	0	0
Investment (M€)	20.727	0	0
Operating costs (M€/y)	4.238	0	0
Biogas production (m^3/d)	43,281	0	0
The amount of used wastes (t/y)	122,861	0	0

Multi-criteria Optimization: Economical Profit vs. Eco-cost

Profit before taxes

$$\max_{x,y} P = (R(x,y) - E(x,y) - D(x,y))$$

$$\text{s.t.} \quad h(x,y) = 0$$

$$y(x,y) \leq 0$$

$$EC(x,y) \geq \varepsilon_i$$

$$(x^{LO} x \leq x^{UP}) \in X \subset \mathrm{R}^n, \quad y = \{0,1\}^m$$

$$\varepsilon_i = \varepsilon_{i-1} + \Delta\varepsilon$$

Multi-criteria Optimization: Economic Profit vs. Eco-cost

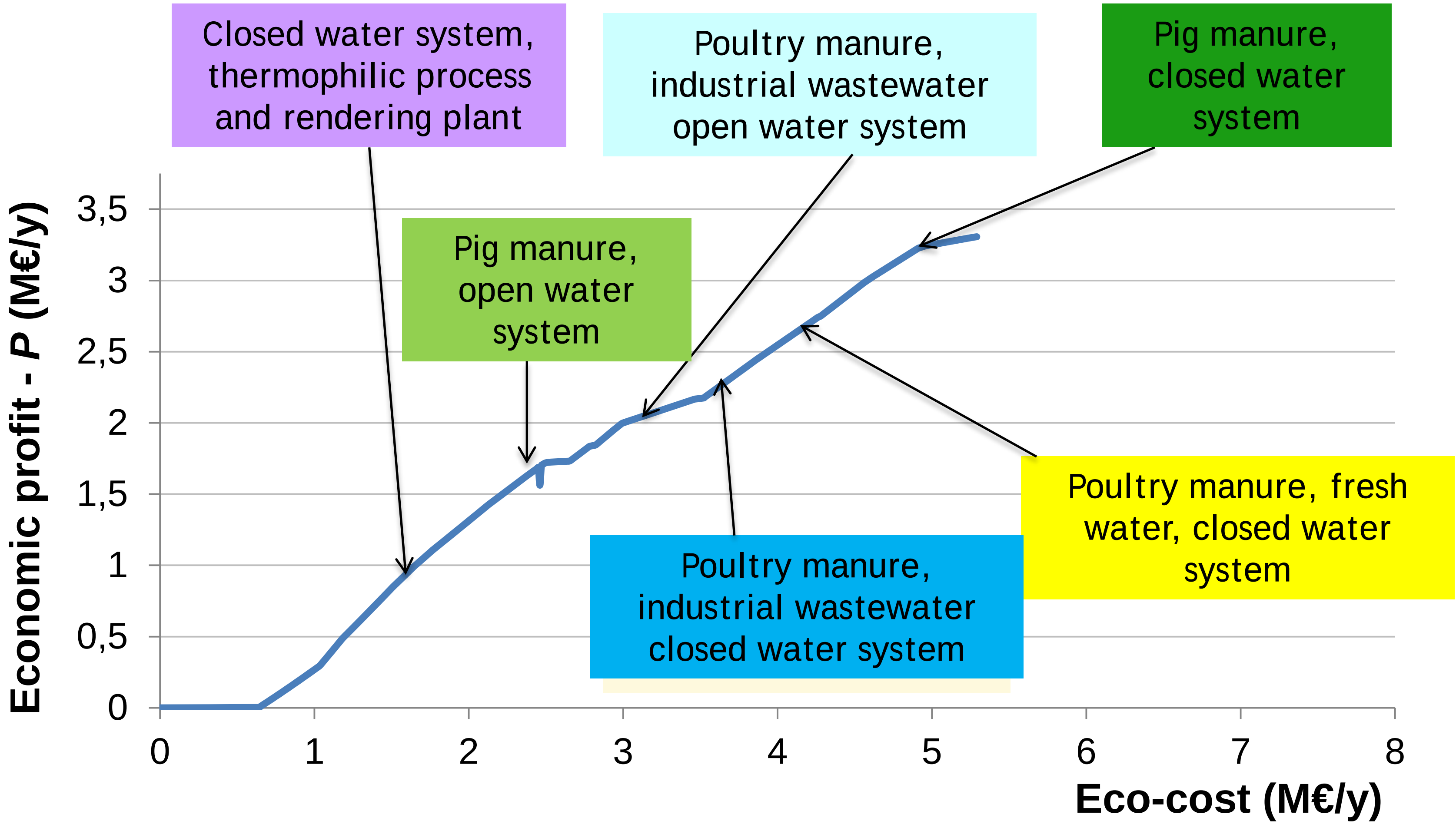


Fig. 27: Pareto curve which shows trade-offs between Economic profit and Eco-cost

Results

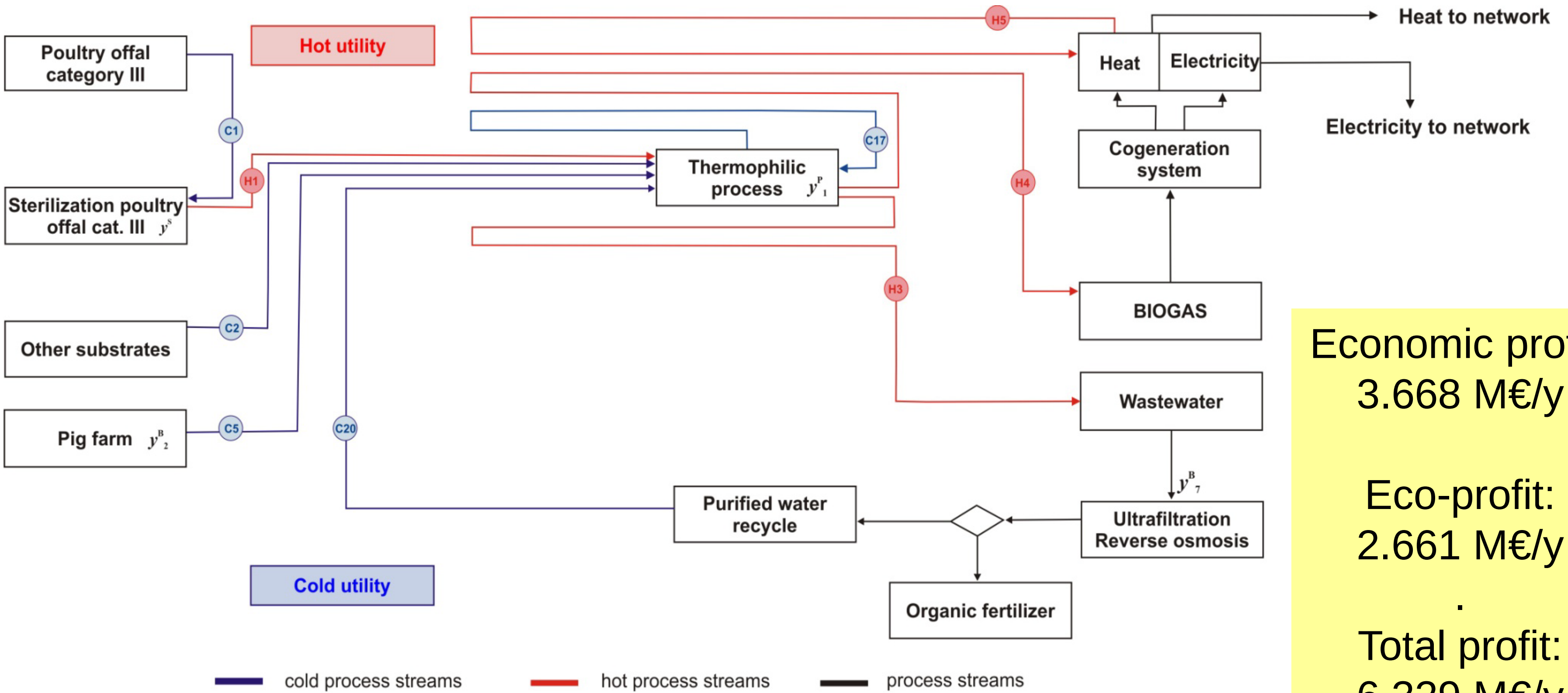
Eco-profit:

- Economical profit maximization
- Eco-profit maximization
- Total-profit maximization

Total profit (€/yr) = Economic profit + Eco-profit

Single-objective Optimization

Maximization of the **economic profit**



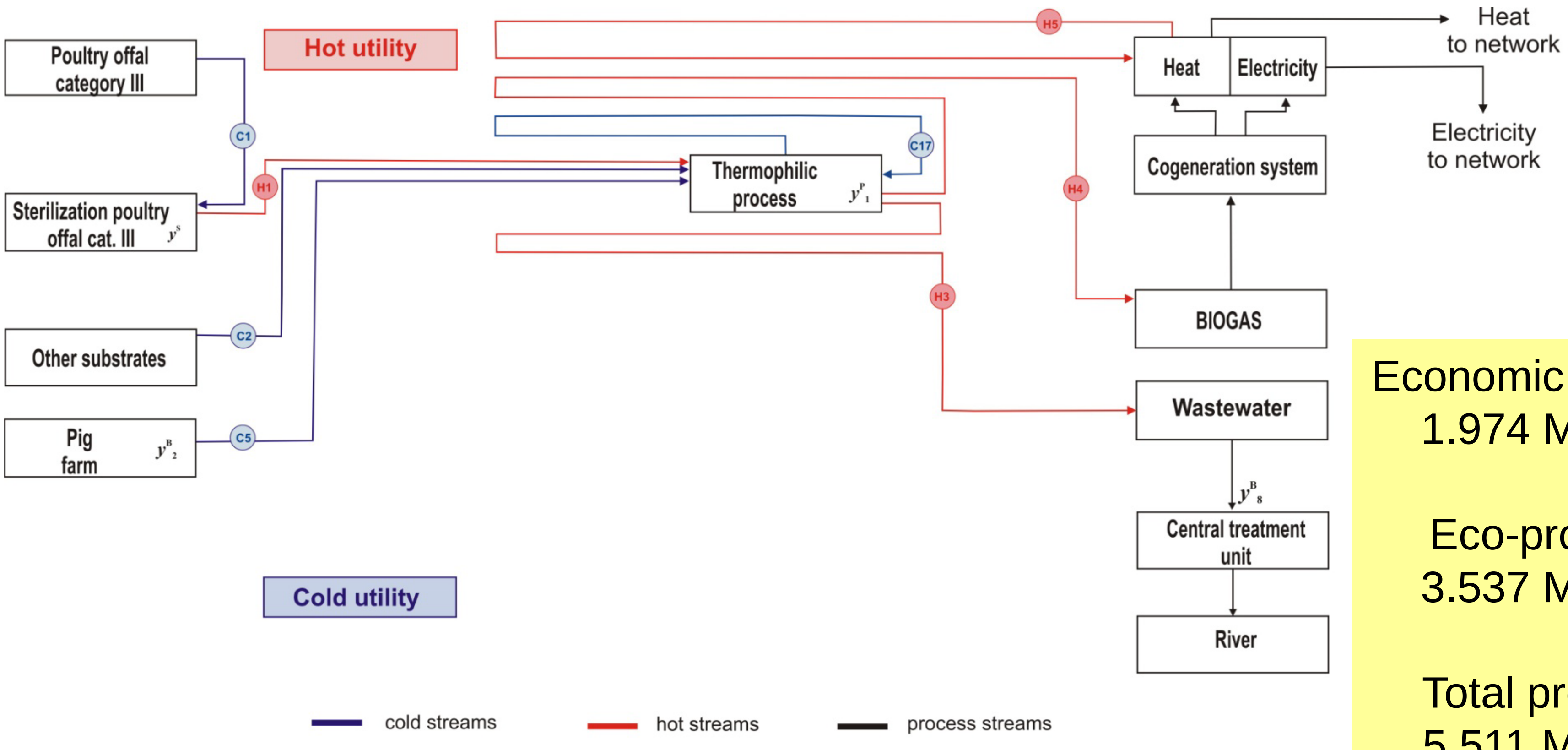
Economic profit:
3.668 M€/y

Eco-profit:
2.661 M€/y
.
Total profit:
6.329 M€/y

Fig. 28: Optimal Biogas production flowsheet

Single-objective Optimization

Maximization of the **eco-profit**



Economic profit:
1.974 M€/y

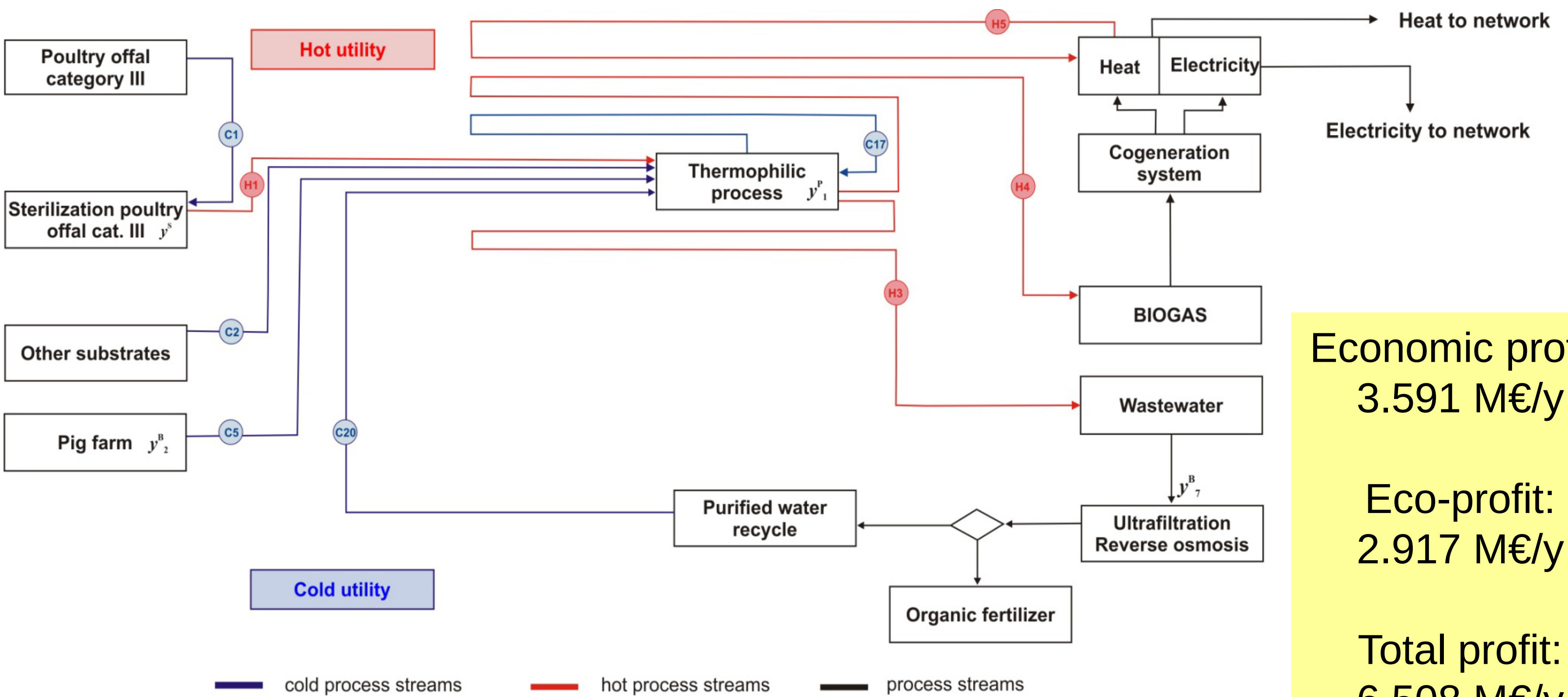
Eco-profit:
3.537 M€/y

Total profit:
5.511 M€/y

Fig. 29: Optimal Biogas production flowsheet

Single-objective Optimization

Maximization of the **total profit**



Economic profit:
3.591 M€/y

Eco-profit:
2.917 M€/y

Total profit:
6.508 M€/y

Fig. 30: Optimal Biogas production flowsheet

Single-objective Optimization

Table 3: Different optimization schemes with Eco-profit for Biogas problem

	Maximized economic profit (*P*)	**Maximized eco-profit (*EP*)**	**Maximized total profit (*TP*)**
Economic profit (M€/y)	3.668	1.974	3.591
Eco-profit (M€/y)	2.661	3.537	2.917
Total profit (M€/y)	6.329	5.511	6.508
Income (M€/y)	7.354	5.217	7.249
Depreciation (M€/y)	2.943	2.394	2.925
Investment (M€)	20.727	16.858	20.600
Operating costs (M€/y)	3.686	3.243	3.658
Biogas production (m^3/d)	43,281	33,106	42,623
The amount of used wastes (t/y)	122,861	112,821	121,180

Multi-criteria Optimization: Economical Profit vs. Eco-profit

University of Maribor

Profit before taxes

$$\max_{x,y} P = (R(x,y) - E(x,y) - D(x,y))$$

$$\text{s.t.} \quad h(x,y) = 0$$

$$y(x,y) \le 0$$

$$EP(x,y) \ge \varepsilon_i$$

$$(x^{LO} x \le x^{UP}) \in X \subset \mathrm{R}^n, \quad y = \{0,1\}^m$$

$$\varepsilon_i = \varepsilon_{i-1} + \Delta\varepsilon$$

Multi-objective Optimization

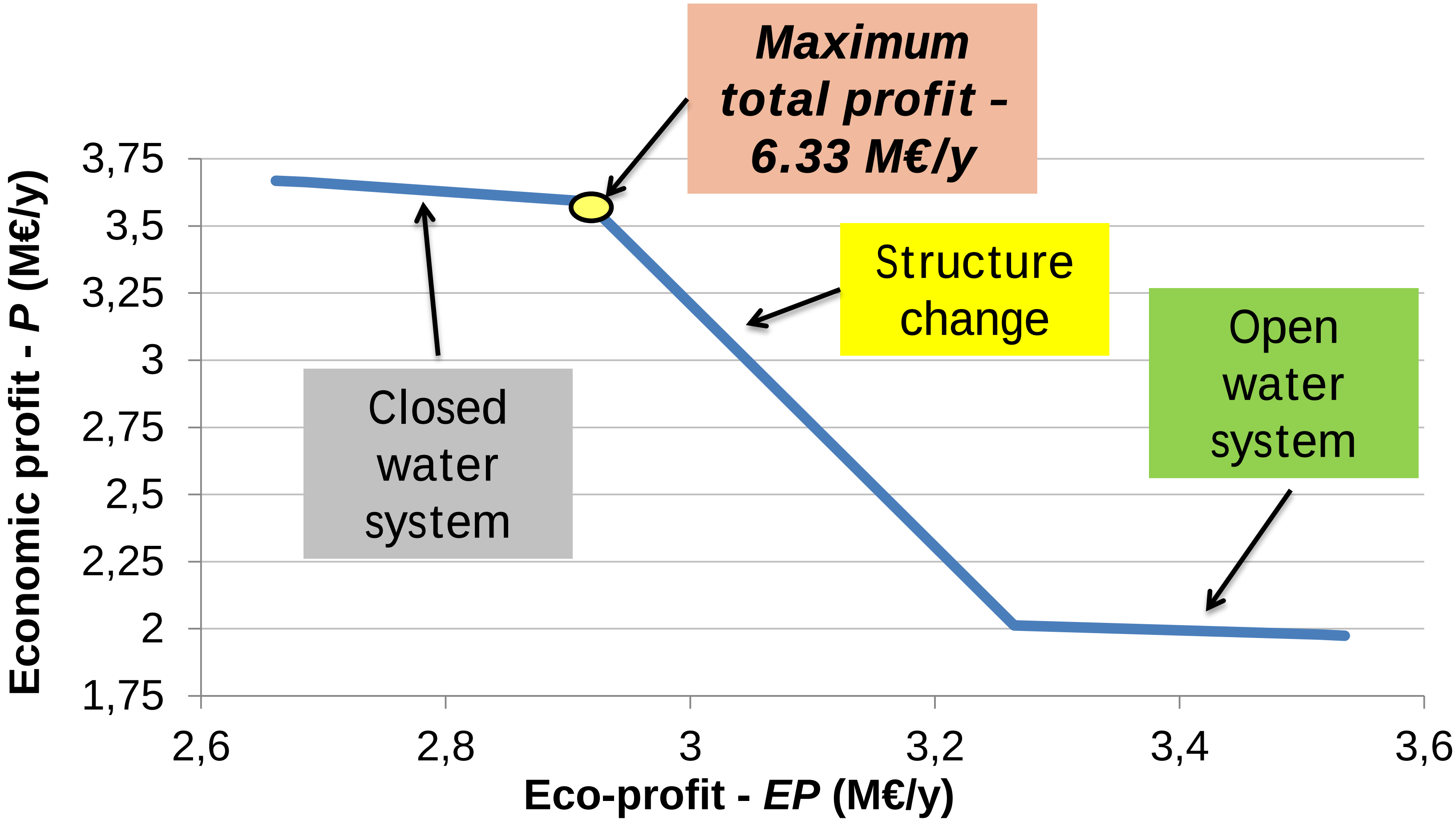


Fig. 31: Economic profit decreases with the increase of eco-profit

Economic Profit vs. Eco-cost and Eco-profit

University of Maribor

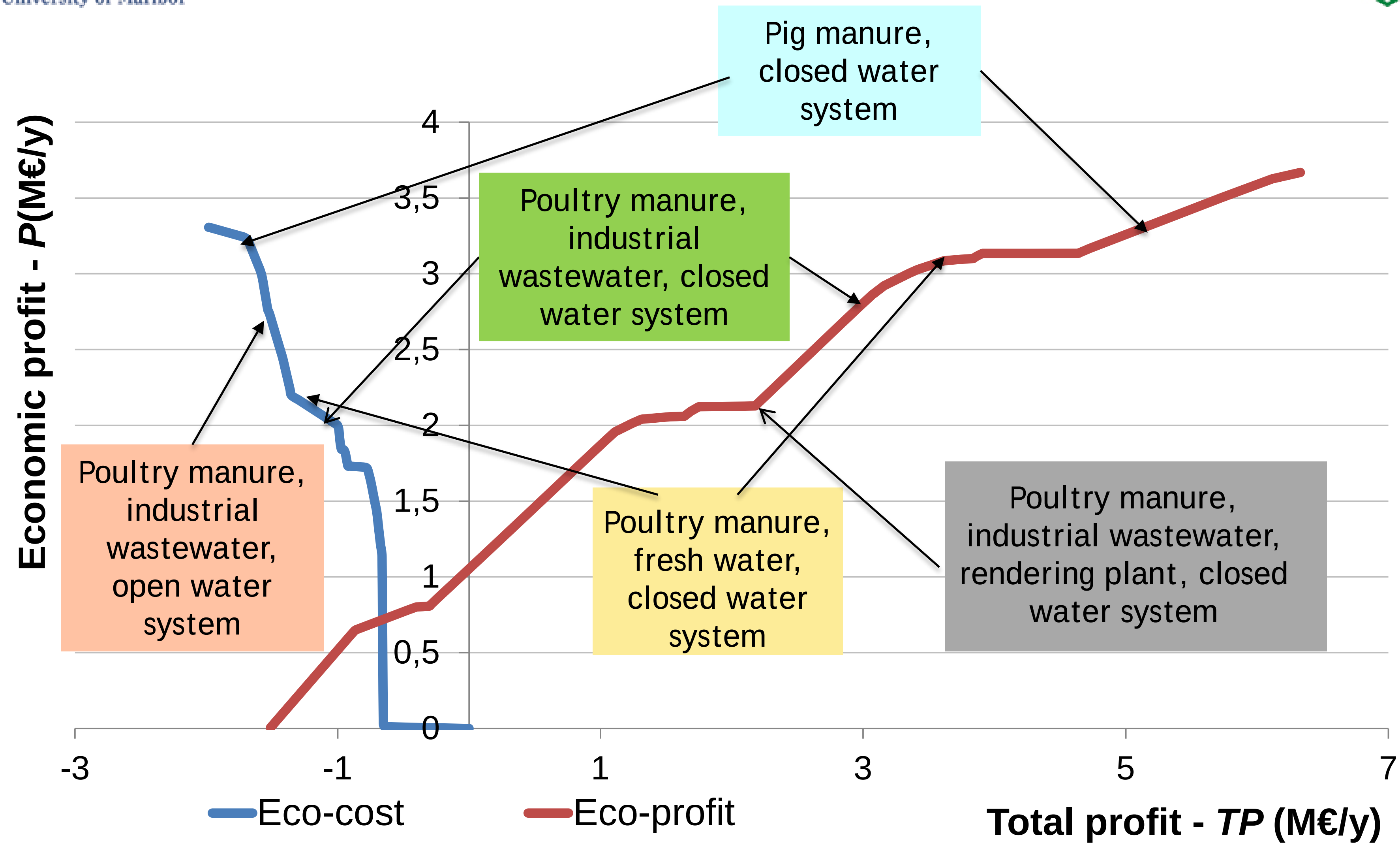


Fig. 32: Trade-offs between Economic profit vs. Eco-cost and Eco-profit

Eco-cost vs. Eco-profit

- Significantly different solutions can be obtained with eco-cost and eco-profit.
- Total profit based on eco-cost can be negative (no production).
- Total profit based on eco-cost << Total profit based on eco-profit:

  When eco-cost is used, biogas production from animal and organic waste seems to be unsustainable. However, it is sustainable with significant economical and eco-profit.

Assessments based on direct eco-costs can be wrong!

- When using eco-cost alternatives with smaller environmental impact are preferred, while with eco-profit those that unburden environment the most (different perception).

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Conclusion

- Indirect effects caused by products‘ substitution should be considered, besides direct effects.
- New concepts of Total LCA index, Total Footprints, and Total profit based on Eco-profit have been introduced.
- By considering both effects, alternatives that unburden the environment the most have higher priority than those with only smaller impacts.
- Considering total effects on the environment enables one to obtain more profitable and yet environmentally less harmful solutions.

Thank you!