“A resource efficiency assessment of the industrial mushroom production chain”
Key messages

- **Exergy analysis** is growing and will become an important tool in the sustainability assessment of food production chains.

- The main **Critical Exergy loss Points (CEP)** identified for the base case scenario are the **cooking-out process** of the spent mushroom substrate and the **phase I composting process** which are related to chemical and physical exergy losses, respectively.

- The **largest exergy losses** are due to **unclosed material balances**. Therefore, only after utilizing maximally all mass streams that translate into chemical exergy flows, it makes sense to reduce any avoidable physical exergy losses.

- The **variations** in the assumed **electricity consumption** values for the **ventilation in phase I composting** and for the **ammonia scrubbing process** affect greatly the exergetic indicators and the number of critical exergy loss points. Therefore, any further improvement on the exergetic performance should focus on these two process variables.

- **Variability in data** can influence both **quantitatively** and **qualitatively** the outcome of exergetic analyses of food production chains since it can lead to the calculation of different values for the selected indicators as well as to the identification of completely different critical exergy loss points.
Why is exergy relevant for the food industry?

- Annual global food wastage
  1.3 billion tons\(^1\)

- Considerable use of “embodied” resources
  e.g. 1 kg of meat ~ 15 m\(^3\) water\(^2\)

- Fast production = high driving forces
  e.g. spray drying of milk

- Reasons that hinder sustainability assessments\(^3\)
  - Vast product diversity
  - Specific and limited production times
  - Large distribution areas

- A lot of different indicators
  Consumption of natural resources is not yet related with the generated services\(^4\)

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Exergy analysis in the food industry
Still small ... But growing!

Zisopoulos et al. (2015). The use of exergetic indicators in the food industry – A review
Critical Reviews in Food Science and Nutrition
Exergy is the quality of energy
Example – Thermal exergy

\[ Q = 10 \text{ MJ} \]

\[ B = Q \cdot \left( \frac{T_{\text{source}} - T_{\text{sink}}}{T_{\text{source}}} \right) \]

\[ T_{\text{source}} = 1000 \, ^\circ\text{C} \]

\[ T_{\text{source}} = 60 \, ^\circ\text{C} \]

\[ T_{\text{sink}} = 25 \, ^\circ\text{C} \]
Exergy analysis

- Is an objective assessment of the performance of a system
- Shows the wasted potential or the lost opportunity to do work
- Can simultaneously assess (quantity and quality!) materials, water, energy and emission streams
- Can be applied from a global scale to a single unit operation
- Can be used to evaluate alternative processes
General description of the mushroom chain

**Compost production**
- Straw pre-treatment
- Straw moisture
- Horse manure moisture
- Destoning
- Mixing
- Ammonia scrubber

**Casing soil production**
- Fresh peat
- Frozen peat
- Marl
- Spent lime
- Water
- Transport
- Mixing
- Moisturization
- Casing soil
- Transport

**Mushroom production**
- Growing and harvesting
- Cooking out
- Mushrooms
- Champost

- Straw
- Horse manure
- Chicken manure
- Gypsum
- Ammonium sulphate
- Water

- Electricity
- Fuels
Industrial mushroom production
Description of the chain – Mass flow analysis
Industrial mushroom production
Exergy analysis – Identifying Critical Exergy loss Points (CEPs)

Exergetic indicators

<table>
<thead>
<tr>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cum. exergy losses (GJ/3 flushes)</td>
</tr>
<tr>
<td>Specific exergy losses (MJ/kg mushrooms)</td>
</tr>
<tr>
<td>Exergetic efficiency (%)</td>
</tr>
</tbody>
</table>
Industrial mushroom production

The nature of exergy loss will determine the type of chain improvement

Chemical losses 69%

Physical losses 31%

- COOKING OUT 80%
- TRANSPORT COMPOST TO GROWER 1%
- TRANSPORT CHICKEN MANURE 1%
- TRANSPORT HORSE MANURE 1%
- TRANSPORT COMPOST 3%
- MIXING COMPOST 4%
- PASTEURISATION AND COMPOSTING PHASE I 1%
- MIXING CASING SOIL 8%
- GROWTH AND HARVEST 1%
- PASTEURISATION AND COMPOSTING PHASE II 7%

- SCRUBBER 14%
- SPAWNING 1%
- GROWTH AND HARVEST 0%

TI FOOD NUTRITION
Industrial mushroom production

By how much will the chain improve if part of the spent compost is recycled?

<table>
<thead>
<tr>
<th>Exergetic indicators</th>
<th>Current</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cum. exergy losses (GJ/3 flushes)</td>
<td>24.9</td>
<td>17.3</td>
</tr>
<tr>
<td>Specific exergy losses (MJ/kg mushrooms)</td>
<td>36.3</td>
<td>25.2</td>
</tr>
<tr>
<td>Exergetic efficiency (%)</td>
<td>4.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Industrial mushroom production

Chemical losses 69%
Physical losses 31%

Chemical losses 56%
Physical losses 44%

Input exergy (GJ/3 flushes)

Current chain
Recycling chain

Diesel
Natural gas
Electricity
Spawn
Spent Lime
Marl
Peat Frozen
Peat Fresh
Amm. Sulphate
Chicken Manure
Gypsum
Horse Manure
Water
Straw
Industrial mushroom production
Identifying the process variables that influence the outcome the most

The variability of the values related to the model process variables can influence considerably the overall assessment.
Summary

Case specific conclusions:

- The **Critical Exergy loss Points (CEPs)** identified were the **Phase I** and the **cooking-out** process
- The chemical exergy flows are **much larger** than physical exergy flows
- **Recycling** of the spent compost could theoretically improve the exergetic indicators of the industrial mushroom production chain

Conclusions of broader interest:

- The **nature of exergy losses** (e.g. chemical or physical) at the CEPs can determine the type of improvement to be assessed
- CEPs can be assessed further with **“what if” scenarios** to see what is the impact of the potential “modification” of the configuration of the food chain on its overall thermodynamic performance
- **Variability in data** can **influence the outcome of the analysis** both quantitatively (i.e. the values of the indicators) and qualitatively (i.e. the identification of CEPs)
Thank you for your attention!

Questions?

Special thanks to:
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Argyris Kanellopoulos, Operations Research & Logistics, Wageningen University
Frits Claassen, Operations Research & Logistics, Wageningen University
Jacqueline Bloemhof, Operations Research & Logistics, Wageningen University
Jack van der Vorst, Operations Research & Logistics, Wageningen University
Multi-Criteria Decision Making in Eco-Efficient Food Supply Chains

Aleksander Banasik
Argyris Kanellopoulos
Frits Claassen
Jacqueline Bloemhof
Jack van der Vorst

Operations Research & Logistics
Wageningen University

18.05.2016
Multi-Criteria Decision Making for Eco-Efficient Food Supply Chains

Objectives:
- to develop tools for decision support that can be used to re-design the logistical structure of food supply chains such that raw materials are used to their full potential,
- to optimize food chains with respect to costs and efficient use of resources.

Environment: waste generated, fuel consumed, energy consumed, water consumed

Case studies considered:
- bread supply chain
- mushroom supply chain

Exergy analysis
Mushroom supply chain

Raw Material
1
2
...
R

Processing facilities
Phase 1 → Phase 2 → Phase 3

Factory 1
Waste processing
Casing soil

Producers
1
2
...
J

Demand for fresh mushrooms

Recover waste
Dispose waste
Mushroom supply chain
Research questions

- What are the optimal production planning decisions to achieve specific feasible economic and environmental goals?
- How much, when, and where to produce substrate? (substrate production facilities)
- On which day to start cultivating substrate, and for how many days should substrate be cultivated? (mushroom producers)
- What are the consequences of alternative production options?
- What is the cost for improving sustainability? Quantification of trade-off between exergy losses (MJ) and profit (€)
Mushroom supply chain
Assumptions

- Two substrate production facilities
- Seven zones of mushroom producers
- Deterministic price, cost, productivity and demand
- The “age” of substrate determines productivity
- We optimize a year production plan with time step of a day
- Optimization at supply chain level NOT individual links of the chain
Best environmental solution

Processing facilities

Phase 1 → Phase 2 → Phase 3
Moerdijk

Phase 2 → Phase 3
Casing soil
Milsbeek

Producers

1 → 2 → 3 → 4 → 5 → 6 → 7
Demand for fresh mushrooms

Dispose waste

Raw Material

1 → 2 → ... → R

Waste processing

Recover waste

1st flush
2nd flush
3rd flush
Best economic solution

Raw Material

Processing facilities

Producers

1st flush
2nd flush
3rd flush

Phase 1
Phase 2
Phase 3

Moerdijk
Milsbeek

Casing soil
Forward flow
Reverse flow

Phase 1
Phase 2
Phase 3

Casing soil

Mushrooms

Waste processing
Recover waste

Demand for fresh mushrooms
Dispose waste

Producers

1
2
3
4
5
6
7

1
2
7
6
5
4
3

R
Eco-efficient solutions

![Graph showing the relationship between profit (%) and exergy loss (%).]
Eco-efficient solutions

- scenario 1: base case
- scenario 2: full logistical structure
- scenario 3: reusing
- scenario 4: recycling
- scenario 5: reusing and recycling
Conclusions

• Recycling and reusing materials brings substantial economic and environmental benefits

• Trade-off curve allows quantifying monetary costs for environmental improvement

• Mathematical models can be used to quantify the potential benefits of alternative logistical structures and to test what-if scenarios

Thank you for your attention!

Questions?

Aleksander Banasik
e-mail: olek.banasik@wur.nl
Industry perspective of C4C

Specific for C4C:

- The project enabled us to link all the steps in the entire production chain; these were considered separately in the past
- Project gave insight in mass and energy flows of our production chain
- The model was used as a tool to evaluate the best export strategy to Asia
- Reusing scenario of champost as peat replacer will be further investigated
Industry perspective of C4C

General:

- The model gives insight in (the processes of) the entire chain and pinpoints the links that have highest potential for improvement.
- The model shows the effect of any changes in the entire chain.
- Strong that the model considers both resource efficiency as well as economic aspects.
- The model might bring together different partners of the chain to improve the entire chain.
- The model is a valuable support tool to evaluate different scenario’s and helps to prioritize or choose best options for research and development. => The model helps in making strategic choices.
Questions?
From land to meat to body: Including protein bioavailability in the exergy analysis of meat and meat replacer chains

18.05.2016

Marta Rodriguez-Illera
Atze Jan van der Goot
Remko M. Boom
Food Process Engineering
Wageningen University
Current sustainability assessment in Food

Carbon footprint
Per kg of product

Land use
Per kg of protein


Need for consumer integration

*consumer*

If you care about the planet, care for the people first.

Consumer choices
Current nutritional scoring methods

Overall nutrition

- Nutritional footprint (or “foodprint”)

- Overall Nutritional Quality Index (ONQI)

\[
ONQI = \frac{\text{protein quality} \cdot \text{fat quality} \cdot \sum_{n=1}^{15} (W_n \cdot \log_{10} TS_n)}{\text{Glycemic Load} \cdot \text{Energy Density} \cdot \sum_{d=1}^{5} (W_d \cdot \log_{10} TS_d)}
\]

- Remains subjective
- Health is diet and individual dependent
- Bioavailability?
Why including nutrition in Exergy Analysis?

- Exergy gives an “objective” overall indicator
- How to include the degree of processing?

Problem in waste valorisation

\[ B_{\text{chem, flour}} \approx 13 \text{ MJ/kg of bread} \]

Bioavailability
Nutrient bioaccessibility

\[ B_{\text{chem, bread}} \approx 13 \text{ MJ/kg of bread} \]

- Processing vs nutrition (different scenarios)
Research aim

Include nutritional quality within exergy analysis of FSCs.

Context
Lack of resources
→ search for resource efficiency.

**Integrated** exergy analysis
(part of sustainability assessment)
How to couple nutrition to Exergy?

Food Nutrients

• Macro:
  - Carbohydrates → Glucose → ATP
  - Fat
  - Proteins

• Micro: minerals, vitamins, antioxidants, carotenoids

Amino acid metabolism and demand adapted from (WHO/FAO/UNU, 2007)
Approach

Solvents

Processing

Preparation

System boundaries

Nutrients bioavailable

ATP

Losses

Losses
Focus

Efficiency of Carb-rich chains

Meat vs Plant based Meat-replacers

Lycopene delivery efficiency in tomato chains

Sustainability vs protein quality and nutrition in two pasta chains (collaboration with Filippos)
Meat vs meat replacers case study

Meat vs Plant based Meat-replacers

What is more sustainable & nutritious; Meat or plants based proteins?
Model system

Oil extraction and feed production
- Soybeans
  - Oil extraction
  - Marc
  - Miscella
  - Hexane
- Soybean meal production
- Hexane recovery
- Pig growing
- Meat production
- Home preparation
- 1000 kg Ready-to-eat pork meat
- Corn, Supplements, Water
- Electricity
- Frying oil
- Oil waste, Vapour
- 1000 kg Ready-to-eat Textured soy protein (TSP)

Oil extraction and flake production
- Soybeans
  - Oil extraction
  - Marc
  - Miscella
  - Hexane
- White flake production
- Hexane recovery
- Aqueous ethanol extraction
- SPC manufacturing
- TSP production
- Home preparation
- 1000 kg Ready-to-eat Textured soy protein (TSP)
- Electricity
- Frying oil
- Oil waste, Vapour
- Oil
- Soy molasses

Ingredients
- Frying oil
- Marc
- Miscella
- Electricity
- Oil
- Soy molasses
- Vapour
Chains exergy analysis (summary)

For 1000kg of product prepared...

Pork meat

Textured soy protein
Resource conversion

### Protein conversion ratio 6:1

![Image showing protein conversion ratio](image)

### Mass efficiency ratio (kg/kg)

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork meat</td>
<td>5:1</td>
<td>4:1</td>
</tr>
<tr>
<td>Textured soy protein</td>
<td>0.6:1</td>
<td>1:1</td>
</tr>
</tbody>
</table>

### Exergy efficiency (%)

\[ \eta = \frac{B_{\text{out}}}{B_{\text{in}}} \]

<table>
<thead>
<tr>
<th></th>
<th>Base case</th>
<th>Case including sidestream valorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork meat</td>
<td>9</td>
<td>46</td>
</tr>
<tr>
<td>Textured soy protein</td>
<td>32</td>
<td>54</td>
</tr>
</tbody>
</table>

### Exergy (MJ)

<table>
<thead>
<tr>
<th>Exergy (MJ)</th>
<th>Base case</th>
<th>Case including waste valorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total input</td>
<td>(1.3 \times 10^5)</td>
<td>(1.3 \times 10^5)</td>
</tr>
<tr>
<td>Prepared product</td>
<td>(3.0 \times 10^4)</td>
<td>(3.0 \times 10^4)</td>
</tr>
<tr>
<td>Hulls</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soy oil</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Manure</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pig by-products</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soy molasses</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Still positive result for meat replacers.

Protein quality scores

Recommended by FAO (2012) as quality scores

* True digestibility (TPD)  
  \[ TPD = \frac{N_{\text{intake}} - N_{\text{feces}}}{N_{\text{intake}}} \]

  Ileal digestibility (IPD)  
  \[ IPD = \frac{N_{\text{intake}} - N_{\text{ileum}}}{N_{\text{intake}}} \]

  In vitro digestibility (IVPD)  
  In vitro model systems (example: TIM (TNO))

Composition (qualitative)  
Amino acid score (AAS)  
mg IAA/g test protein  
mg same IAA/g reference pattern

Integrated measures (quantitative and qualitative)  
PDCAAS*  
AAS + TPD

DIAAS*  
AAS + IPDAA
Methods - Including nutrition

Cumulative exergy losses (CEL) = process (PEL) + metabolic (MEL)

Specific exergy losses:

\[
SEL = \frac{CEL}{m_{\text{cooked product}} \cdot \chi_{\text{protein}} \cdot \phi_{\text{nutrition}}} \quad (MJ/kg \text{ useful protein bioav.})
\]

\[\phi_{\text{nutrition}}\] (kg of useful protein bioavailable/kg protein)

**Analysis**
- Quantitative
- Semi-qualitative
- Qualitative
  (AA composition referred to reference pattern)
Chains exergy indicators
Including Nutritional data

<table>
<thead>
<tr>
<th></th>
<th>Protein composition (%)</th>
<th>Ileum digestibility (%)</th>
<th>Essential AAs &quot;bioavailable&quot; (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork meat</td>
<td>26.68</td>
<td>91.6</td>
<td>471.8</td>
</tr>
<tr>
<td>Soy meat replacer</td>
<td>21.4</td>
<td>97</td>
<td>412.3</td>
</tr>
</tbody>
</table>

Quantitative  
Semi-qualitative

Qualitative (AA composition referred to reference pattern)

<table>
<thead>
<tr>
<th></th>
<th>His</th>
<th>Ile</th>
<th>Leu</th>
<th>Lys</th>
<th>SAA</th>
<th>AAA</th>
<th>Thr</th>
<th>Trp</th>
<th>Val</th>
<th>Quality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork meat</td>
<td>0.12</td>
<td>0.14</td>
<td>0.25</td>
<td>0.26</td>
<td>0.11</td>
<td>0.23</td>
<td>0.12</td>
<td>0.03</td>
<td>0.15</td>
<td>1.4</td>
</tr>
<tr>
<td>Textured soy protein</td>
<td>0.07</td>
<td>0.13</td>
<td>0.22</td>
<td>0.18</td>
<td>0.07</td>
<td>0.26</td>
<td>0.11</td>
<td>0.04</td>
<td>0.14</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Chains exergy indicators
Including Nutritional data

<table>
<thead>
<tr>
<th></th>
<th>MJ/kg cooked product</th>
<th>MJ/kg protein</th>
<th>Specific Exergy losses</th>
<th>MJ/kg ileum digested protein</th>
<th>MJ/g EAAs bioavailable</th>
<th>MJ/g EAAs bioavailable following reference pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC</td>
<td>CIWV</td>
<td>BC</td>
<td>CIWV</td>
<td>BC</td>
<td>CIWV</td>
</tr>
<tr>
<td>Pork meat</td>
<td>120.1</td>
<td>71.7</td>
<td>450.1</td>
<td>268.8</td>
<td>491.4</td>
<td>293.4</td>
</tr>
<tr>
<td>Textured soy protein</td>
<td>20.1</td>
<td>14.0</td>
<td>93.9</td>
<td>65.4</td>
<td>96.8</td>
<td>67.4</td>
</tr>
<tr>
<td>Products comparison</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5-6</td>
<td>4-5</td>
<td>4-5</td>
<td>3.5-4</td>
<td>3-4</td>
<td>3.5-4</td>
</tr>
</tbody>
</table>

**Process analysis**

**Process analysis including nutrition**

**Quantitative**  | **Semi-qualitative**  | **Qualitative**

BC: Base case
CIWV: Case including side stream valorisation

This meat replacer is 3-4 times more efficient than meat delivering the required nutrition.
In a nutshell...

*If you care about the planet, care for the people.*

- Exergy analysis of food chains can be extended to **human metabolism**.
- Including **consumer processing** and **bioavailability** should be included for integral analysis of food chains.
- **Plant-based** protein chains can be **more efficient** (up to 4 times at the moment) due to:
  - More efficient **protein conversion** (1:1 instead of 4:1)
  - Possible to obtain **similar protein quality** in meat replacers
Thank you for your attention

Questions?

Special thanks to:

Lisa Overmars, MSc student
Friso van Assema, TIFN