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# Applying Data Envelopment Analysis to aggregate Life Cycle Impacts for Eco-Efficiency

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# Sustainable economy and eco-efficiency

- Integrating (global) environmental impacts and (local) **economic decision** making
- Relative environmental cost of production
- Cost of environmental improvement
- Maybe: carrying capacity?

**Eco-efficiency** is to sustainable economy what technical efficiency is to 'economic' economy!

# LCA and eco-efficiency

Unlike in traditional LCA, where we relate the environmental impacts to the functional unit (FU), **eco-efficiency** (Huppes and Ishikawa (2005)) relates a measure of production (kg, liter, added value, etc.) to the environmental impact (**environmental productivity**). In the eco-efficiency framework, $\frac{env.impact}{FU}$ would be called *environmental intensity*

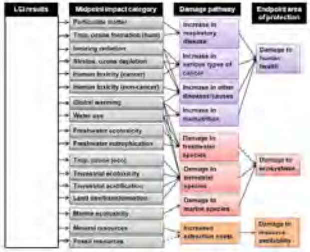
Eco-efficiency (EE):

$$EE = \frac{\sum_{i=1}^{n}(output_i)}{\sum_{j=1}^{m}(impact_j)} \tag{1}$$

- $output_i$: functional unit (e.g. product, service, income)
- $impact_j$: **environmental impacts** (e.g. GWP100y, aquat. tox)

# LCA for eco-efficiency

Eco-efficiency demands **aggregation** of all **environmental impacts**:



ReCiPe2016 mid and endpoints

- Endpoint allow some aggregation/ reduction of dimensions

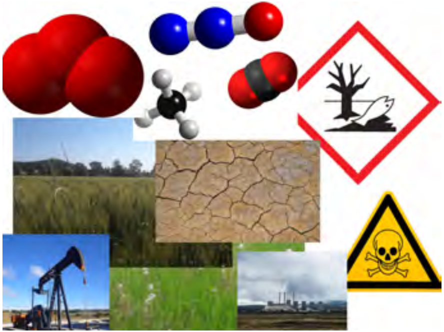
What about **weighted midpoints** ?

- **D**ata **E**nvelopment **A**nalysis for LCA (Kuosmanen and Kortelainen (2005))

# LCA for eco-efficiency

**Aggregation** of all environmental impacts:

- avoid using normative weightings based on value choices
- use information about similar observations (**peers**) in sample
- keep things simple and transparent



Environmental impacts

# LCA for eco-efficiency

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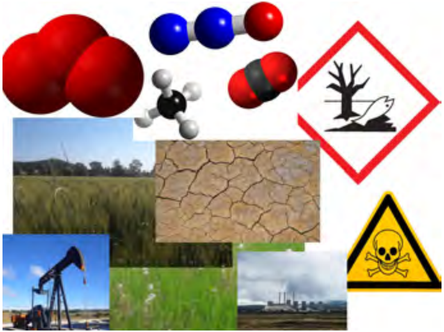
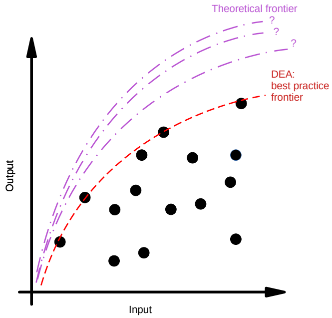


Environmental impacts

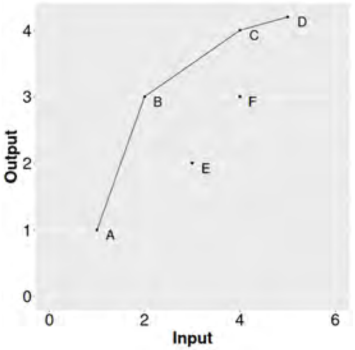
Proposition: **D**ata **E**nvelopment **A**nalysis satisfies our 'wishlist'

# Background Data Envelopment Analysis

- Originally developed in the 1970s for operation research and economics (Charnes et al. (1978))
- Used to estimate the **relative efficiency** of a set of homogeneous decision-making units (DMU) without having to specify the functional form of the production function.
- Each DMU is **compared against its peers**, more efficient units serve as benchmark for less efficient ones
- Output is **measure of efficiency** [0,1]



# Simple example

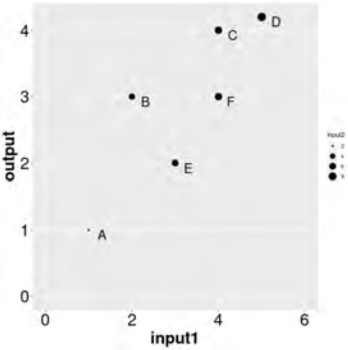



Example DEA 1 input and 1 output

- 1 input, 1 output
- We find the frontier by connecting the concave line formed by the outermost points
- DMUs below the frontier are less efficient than their peers

| | input1 | w_input1 | input2 | w_input2 | output | w_output | efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 2 | 0.5000000 | 1.0 | 0.8333333 | 0.8333333 |
| 2 | 2 | 0 | 5 | 0.2000000 | 3.0 | 0.3333333 | 1.0000000 |
| 3 | 4 | 0 | 7 | 0.1428571 | 4.0 | 0.2380952 | 0.9523810 |
| 4 | 5 | 0 | 9 | 0.1111111 | 4.2 | 0.1851852 | 0.7777778 |
| 5 | 3 | 0 | 6 | 0.1666667 | 2.0 | 0.2777778 | 0.5555556 |
| 6 | 4 | 0 | 7 | 0.1428571 | 3.0 | 0.2380952 | 0.7142857 |

# A bit more complex example




Example DEA 2 inputs and 1 output

- 2 inputs, 1 output
- It's not obvious which DMUs are more efficiently using *input*1 and *input*2 to produce *output*
- We need a **algebraic solution**

# How does DEA get the score?

DEA is a form of linear programming. The resulting maximization problem is subject to the constraints shown below.

- For each decision making unit (**DMU**):
  - Maximize $\frac{\sum_{i=1}^{I} w_i * output_i}{\sum_{j=1}^{J} w_j * input_j}$ using $w_i$ and $w_j$
  - **Constraint**: If we apply $w_i$ and $w_j$ on any other DMU the value can not be larger than 1!
- Each DMU is 'allowed' to use any weighting of its inputs to maximize $\frac{output}{input}$, as long as no other DMU achieves higher ratio with the same weightings
- The result is the 'best' set of weightings $w_i$ and $w_j$ that keep the score between (0,1] for **all** DMUs

# A bit more complex example

DEA solution for 2 input 1 output example

| DMU | input1 | input2 | output | DEA_Efficiency |
|---|---|---|---|---|
| A | 1.00 | 2.00 | 1.00 | 0.83 |
| B | 2.00 | 5.00 | 3.00 | 1.00 |
| C | 4.00 | 7.00 | 4.00 | 0.95 |
| D | 5.00 | 9.00 | 4.20 | 0.78 |
| E | 3.00 | 6.00 | 2.00 | 0.56 |
| F | 4.00 | 7.00 | 3.00 | 0.71 |

DEA gives us efficiency scores [0,1] for each DMU

To use DEA for eco-efficiency we can **treat environmental impacts as inputs**, or as **undesirable outputs** (or conduct the DEA without inventory data only )!

# DEA and LCA: Recent trends

Publication by Vásquez-Ibarra et al. (2020)


LCA + DEA articles according to the year of publication (Scopus and Web of Science)


Science of the Total Environment

The joint use of life cycle assessment and data envelopment analysis methodologies for eco-efficiency assessment: A critical review, taxonomy and future research

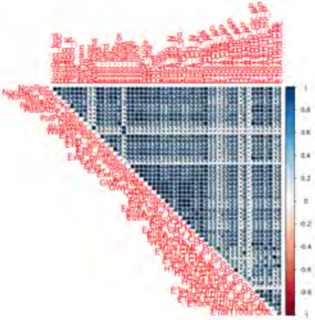
The joint use of **life cycle assessment and data envelopment analysis** methodologies for eco-efficiency assessment: A critical review, taxonomy and future research

# A **practical example**: Data

- 251 farm-year observations (113 farms over three years) of Swiss farms
- production region 'valley', 'hills' and 'mountains'
- 20% Organic farming
- Average 3 product groups per farm
- Product groups: milk, beef, wheat, beets & potatoes, pig fattening, vegetables
- Environmental impacts using Swiss Agriculture LCA (SALCA)

# A practical example: Methodology

- Reduce redundancy using principal component analysis
- Include domains (water, land, health effects on humans etc.)
- Specify constant returns to scale constraint
- All observations for the same product group are considered as peers



Correlations environmental impacts (preliminary results)

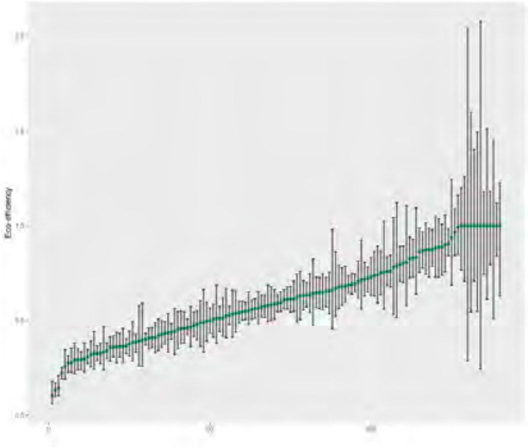
# A practical example: Impacts

Used environmental impacts

Used environmental impacts

| Impact |
|---|
| Non_renewable_fossil_and_nuclearMJ_eq |
| Land_competitionm2a |
| Deforestationm2 |
| Total_water_use_blue_waterm3 |
| IPCC_GWP_100a_2013kg_CO2_eq |
| Acidification_GLOmolc_H_eq |
| Eutrophication_norm._GLOperson.year |
| Human_tox_100a_CML_kg_14DB_eq |
| Ecotox_terr._100a_CML_kg_14DB_eq |
| Ecotox_aq._100a_CML_kg_14DB_eq |

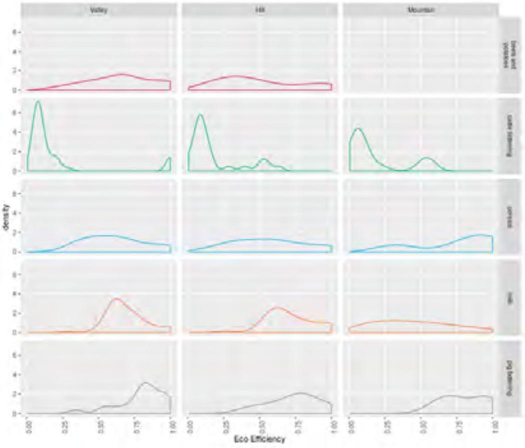
# A practical example: Eco-efficiency of cereals for selected farms



Estimates for eco-efficiency for cereal production
(preliminary results)

- Confidence intervals larger for high efficiency estimates
- Few very inefficient observations, few observations with score of 1
- Large variance **within** product group

# A practical example: Comparison eco-efficiency for multiple product groups




Estimates for eco-efficiency (preliminary results)

- Large differences distribution of eco-efficiency **between** product groups
- Effects of production region depending on product group

# Data requirements: Sample size and variable selection

- Needs peers (multiple observations of DMUs)
- Rule of thumb: 3 x as many observations as number of inputs + number of outputs
- Considered DMUs have to be homogeneous to be comparable
- Account for all important impacts
- Avoid redundancies between impacts

# Plausibility test and further analysis

- Sensitivity to input and output variables ('leave one out' analysis)
- Sensitivity to sample ('bootstrapping')
- Sensitivity to constant or variable return to scale (effects of scale)
- Super efficiency (analysis of DMUs with efficiency score of 1)
  - It would not be reasonable to claim that the efficient DMUs all perform with perfect efficiency in reality.
  - Super-efficiency implies the capability of a DMU in increasing its inputs and/or reducing its outputs without becoming inefficient Banker et al. (2015)
  - Use SE as framework for identifying outliers (e.g. Banker et al. (2015))
  - Extended methods to further rank efficient DMUs (e.g. Lin and Chen (2017))
- Stochastic DEA with Monte Carlo simulation
- ...

# Summary

- LCA and DEA **complement** each other: LCA assess impacts and DEA calculates eco-efficiency
- DEA is applicable to calculate eco-efficiency from LCA impacts with **minimal normative information**
- Using **actual observations as reference** (instead of a theoretical "best case scenario")
- **Comprehensible** methodology
- **Robust**, at least semi-quantitative interpretation of results possible, even for small sample size
- Active community, **active development**

# Relation to 74th DF LCA overarching issues

- Combining LCA with DEA allows decision-makers to jointly consider economic and environmental issues
- The LCA + DEA approach can reveal opportunities for improvements and risk (cost of avoided environmental burden)
- The LCA + DEA tool chain can be used to combine economic, environmental and social aspects for efficiency assessments

# Literature


Rajiv D. Banker, Hsihui Chang, and Zhiqiang Zheng. On the use of super-efficiency procedures for ranking efficient units and identifying outliers. *Annals of Operations Research*, 250(1):21–35, aug 2015. doi: 10.1007/s10479-015-1980-8. URL `https://doi.org/10.1007%2Fs10479-015-1980-8`.

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Leonardo Vásquez-Ibarra, Ricardo Rebolledo-Leiva, Lidia Angulo-Meza, Marcela C. González-Araya, and Alfredo Iriarte. The joint use of life cycle assessment and data envelopment analysis methodologies for eco-efficiency assessment: A critical review, taxonomy and future research. *Science of The Total Environment*, 738:139538, 2020.

## Thank you for your attention

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