KES Transactions on Sustainable Design and Manufacturing II
Sustainable Design and Manufacturing 2015 : pp.74-81 : Paper sdm15-061

Non-parametric benchmarking of Life Cycle Impact Assessment results

Sebastián Lozano[1], Mª Teresa Moreira[2] and Gumersindo Feijoo[2]

[1]Escuela Superior de Ingeniería. Universidad de Sevilla. Camino de los
Descubrimientos s/n. 41092 Sevilla, Spain
slozano@us.es
[2]Dept. of Chemical Engineering, University of Santiago de Compostela, Spain
Maite.moreira@usc.es, Gumersindo.feijoo@usc.es

Abstract In this paper, the Data Envelopment Analysis (DEA) is proposed for benchmarking Life Cycle Impact Assessment (LCIA) results of a sample of Wastewater Treatment Plants (WWTP) is presented. DEA inputs are the normalized values of seven impact categories. A constant unit output is the functional unit of the LCIA analysis. Several DEA models have been applied. The results of the different DEA models were very consistent, with three of the WWTP labelled as efficient and one of them especially super-efficient. The proposed approach allows the identification and ranking of the inefficient units.

1. Introduction

Life Cycle Assessment (LCA) is a useful tool for evaluating the environmental performance of products, including not only goods, but also processes and services. ISO 14040:2006 establishes four steps within LCA: goal and scope definition, inventory analysis, impact assessment and interpretation. In the second step, Life Cycle Inventory (LCI), a systematic and exhaustive process of data collection is carried out while the third step, Life Cycle Impact Assessment (LCIA), consists in the assessment and evaluation of the environmental impact associated with the LCI. For comparative LCA studies, the interpretation of results is quite complex, since there is no clearly dominant impact category. We propose to use Data Envelopment Analysis (DEA) which is a non-parametric technique aimed at assessing the relative efficiency of a number of comparable units (Cooper et al 2000). DEA has been used previously for environmental performance assessment (e.g. Lozano and Gutiérrez 2008, Barba-Gutiérrez et al. 2009, Lozano et al. 2009, 2010, etc).

In this paper, a DEA approach is proposed for benchmarking LCIA results of WWTP. The structure of this paper is the following. Section 2 presents some DEA models that can be used to benchmark LCIA results. In Section 3, the proposed approach is applied to a real-world dataset and the results obtained are presented and discussed. Section 4 summarizes and concludes.

InImpact: The Journal of Innovation Impact | ISSN 2051-6002 | http://www.inimpact.org

2. Proposed DEA models for benchmarking LCIA results

This section reviews some existing DEA models that can be used for benchmarking LCIA results. Table 1 introduces the notation required for the formulation of the DEA models.

Data and variables	*Description*
N	number of units (products or facilities) to benchmark
j=1,2,…, N	index on the units to benchmark
M	number of impact categories from the LCIA
i=1,2, …, M	index on impact categories
x_{ij}	normalized value of the contribution of unit j to impact category i
$(\lambda_{10}, \lambda_{20}, ..., \lambda_{N0})$	vector of coefficients of linear combination for assessing unit 0
ρ_0	radial contraction of environmental impacts of unit 0
s_{i0}	slack of impact category i for unit 0
ρ_{i0}	reduction factor of environmental impact i of unit 0
$\tilde{\theta}_0$	Non Radial Efficiency Score (NRES) of unit 0
$R_i = \max_j x_{ij} - \min_j x_{ij}$	range of values of environmental impact i
σ_0	Range-Adjusted Measure (RAM) of efficiency of unit 0
t_0	auxiliary variable for linearization of SBM model of unit 0
$(\hat{\lambda}_{10}, \hat{\lambda}_{20}, ..., \hat{\lambda}_{N0})$	transformed coefficients of linear combination for assessing unit 0
$\hat{s}_{i0}$	transformed slack of impact category i for unit 0
μ_0	Slacks-based measure of efficiency (SBM) of unit 0
$\hat{x}_{i0}$	hypothetical SuperSBM target value of impact category i for unit 0

Table 1. DEA notation

The proposed DEA models are shown, in compact form, in Tables 2 and 3 (see next page). Note that in DEA, a different Linear Program (LP) is solved for each unit under assessment (UUA) in turn and the projection computed for that UUA is used as its target operation point. In this application an input orientation is assumed. This means that the direction in which the target is sought corresponds to minimizing inputs consumption (i.e. minimizing environmental impacts) for the given output functional unit.In thus type of DEA models, the efficiency score is computed as a function of the distance (i.e. the separation) between the UUA and its computed target. There are, however, different ways of measuring that distance, e.g. radial, non-radial, additive, etc. When all inputs (i.e. all environmental impacts) are decreased equi-proportionally (so that the environmental impact mix is maintained), a radial input contraction is said to be carried out. This type of DEA models provides a Radial Efficiency Score (RES) (Banker et al. 1984) and its two phases, for our case of a single, constant output, are shown in Table 2.

Another possibility is to compute the Russell non-radial measure of technical efficiency (Färe and Lovell 1978). In this case, each environmental impact may be decreased in a different proportion and the corresponding Non-Radial Efficiency Score (NRES) is the average of the different reduction factors. Efficient units have NRES equal to unity.

Model	RES	NRES
Constraints	Phase 1 $\sum_{j=1}^{N} \lambda_{j0} x_{ij} = \theta_0 x_{i0} - s_{i0} \quad \forall i$ $\sum_{j=1}^{N} \lambda_{j0} = 1$ $\lambda_{j0} \geq 0 \ \forall j \quad s_{i0} \geq 0 \ \forall i$	$\sum_{j=1}^{N} \lambda_{j0} x_{ij} \leq \rho_{i0} x_{i0} \quad \forall i$ $\sum_{j=1}^{N} \lambda_{j0} = 1$ $\rho_{i0} \leq 1 \quad \forall i$ $\lambda_{j0} \geq 0 \ \forall j$
Objective function	Phase 1: $\theta_0 = \text{Min } \rho_0$ Phase 2 $a_0 = \text{Max } \sum_{i=1}^{M} s_{i0}$	$\tilde{\theta}_0 = \text{Min } \frac{1}{M} \sum_{i=1}^{M} \rho_{i0}$

Table 2. RES and NRES DEA models

A third possibility is to use the Range-Adjusted Measure (RAM) of efficiency (Cooper et al 1999). In this model, the reductions in each environmental impact are measured as input slacks and scaled by the range of values of each input prior to their sum. As in the previous model, in order to be assessed as efficient a unit must have a RAM equal to unity.

Finally, another DEA model that can be used to benchmark LCIA results is the Slacks-Based Measure of efficiency (SBM) (Tone 2001). Table 3 shows the corresponding SBM linear programming formulation. An interesting feature of these efficiency measures (RES, NRES, SBM and RAM) is their units-invariance. In our LCIA application, this translates in that if a different set of normalization factors were used for the results of the LCIA characterization, the DEA assessment would not change at all, i.e. the units would have the same RES, NRES, SBM and RAM.

Model	RAM	SBM
Constraints	$\sum_{j=1}^{N} \lambda_{j0} x_{ij} = \theta_0 x_{i0} - s_{i0} \quad \forall i$ $\sum_{j=1}^{N} \lambda_{j0} = 1$ $\lambda_{j0} \geq 0 \; \forall j \quad s_{i0} \geq 0 \; \forall i$	$\sum_{j=1}^{N} \hat{\lambda}_{j0} x_{ij} = t_0 x_{i0} - \hat{s}_{i0} \quad \forall i$ $\sum_{j=1}^{N} \hat{\lambda}_{j0} = 1$ $\hat{\lambda}_{j0} \geq 0 \quad \forall j \quad \hat{s}_{i0} \geq 0 \quad \forall i$ $t_0 > 0$
Objective function	$\sigma_0 = \mathrm{Max} \sum_{i=1}^{M} \frac{s_{i0}}{R_i}$	$\mu_0 = \mathrm{Min} \quad t_0 - \frac{1}{M} \sum_{i=1}^{M} \frac{\hat{s}_{i0}}{x_{i0}}$

Table 3. RAM and SBM DEA models

3. Application to a real-world dataset

Gallego et al (2008) have carried out an LCA study of 13 WWTP corresponding to small populations (less than 20000 p.e.) in Galicia (NW of Spain). The assumptions, methodology and quantitative results of the LCA study are described in that paper. Table 4 (see next page) shows the normalized LCIA results obtained using CML 2 baseline 2000 (Guinée et al 2001) for seven impact categories, namely: Abiotic Depletion (AD), Global Warming (GW), Acidification (AC), Eutrophication (EU), Ozone Layer Depletion (OLD), Terrestrial Ecotoxicity (TET) and Photochemical Oxidation (PO).

The proposed DEA approach was applied to this dataset. First of all we solved the Phase 1 of the RES model and computed the RES (θ_0) of the units. These are shown in table 5. Since this radial measure of efficiency does not take into account remaining input slacks after the radial contraction it is not surprising that many units (actually all except WWTP 13) have a value of unity. Solving the Phase 2 RES model, however, allows us to identify only three efficient units, namely WWTP

3, WWTP 5 and WWTP 10. The rest have non zero slacks along the environmental impact dimensions, i.e. $a_0>0$. These units are shown in table 7 in increasing order of a_0 since the higher a_0, the larger their inefficiency.

UUA	**AC**	**GW**	**OLD**	**TET**	**EU**	**PO**	**AD**
WWTP 1	0.19	0.09	0.001	0.37	0.90	0.011	0.17
WWTP 2	0.17	0.07	0.001	0.44	2.25	0.008	0.11
WWTP 3	0.17	0.06	0.001	0.47	0.65	0.007	0.09
WWTP 4	0.10	0.05	0.001	0.19	1.32	0.006	0.08
WWTP 5	0.09	0.05	0.001	0.09	0.85	0.005	0.07
WWTP 6	0.18	0.16	0.001	0.28	2.56	0.017	0.27
WWTP 7	0.14	0.13	0.001	0.11	4.07	0.015	0.27
WWTP 8	0.12	0.05	0.001	0.14	2.58	0.005	0.08
WWTP 9	0.12	0.06	0.001	0.17	1.65	0.007	0.11
WWTP 10	0.27	0.10	0.002	0.36	0.66	0.012	0.17
WWTP 11	0.29	0.10	0.001	0.32	1.56	0.012	0.17
WWTP 12	0.19	0.16	0.001	0.22	3.17	0.017	0.28
WWTP 13	0.25	0.15	0.002	0.65	2.14	0.019	0.32
Max	0.29	0.16	0.002	0.65	4.07	0.019	0.32
Min	0.09	0.05	0.001	0.09	0.65	0.005	0.07
Range	0.20	0.11	0.001	0.56	3.42	0.014	0.25

Table 4. Normalized LCIA results (10^{-10} p.e./year)

	RES model		
Rank	θ_0	a_0	**Unit**
1	1.000	0	**WWTP 3**
2	1.000	0	**WWTP 5**
3	1.000	0	**WWTP 10**
4	1.000	0.576	**WWTP 1**
5	1.000	0.591	**WWTP 4**
6	1.000	0.962	**WWTP 9**
7	1.000	1.297	**WWTP 11**
8	1.000	1.820	**WWTP 8**
9	1.000	1.893	**WWTP 2**
10	1.000	2.312	**WWTP 6**
11	1.000	2.882	**WWTP 12**
12	1.000	3.580	**WWTP 7**
13	0.500	0.610	**WWTP 13**

Table 5. Results and ranking provided by RES DEA model

Table 6 shows the Russell NRES ($\tilde{\theta}_0$). This model, as expected, also identifies WWTP 3, WWTP 5 and WWTP 10 as efficient. Table 6 also shows the RAM efficiency (σ_0) which is unity if and only if a unit is efficient. Although the Russell NRES are usually lower than RAM scores, the NRES ranking of inefficient units coincides almost exactly with that of RAM. Moreover, as it can be also seen in table 6, the Russell NRES coincide exactly with the SBM efficiency values. This occurs because this application considers a single, constant output.

	NRES and SBM models		**RAM model**	
Rank	$\tilde{\theta}_0$	**Unit**	σ_0	**Unit**
1	1	**WWTP 3**	1	**WWTP 3**
2	1	**WWTP 5**	1	**WWTP 5**
3	1	**WWTP 10**	1	**WWTP 10**
4	0.818	**WWTP 4**	0.932	**WWTP 4**
5	0.800	**WWTP 8**	0.888	**WWTP 8**
6	0.711	**WWTP 9**	0.868	**WWTP 9**
7	0.584	**WWTP 2**	0.716	**WWTP 2**
8	0.583	**WWTP 1**	0.685	**WWTP 1**
9	0.521	**WWTP 7**	0.575	**WWTP 11**
10	0.495	**WWTP 11**	0.504	**WWTP 7**
11	0.431	**WWTP 6**	0.436	**WWTP 6**
12	0.430	**WWTP 12**	0.413	**WWTP 12**
13	0.316	**WWTP 13**	0.131	**WWTP 13**

Table 6. Results and ranking provided by NRES, SBM and RAM models

Finally, Table 7 (see next page) shows the targets and inputs reductions computed by all four DEA models solved. Note that the potential improvements are zero for the efficient units and for some units in some environmental impact categories but they can be significant for other units, especially for the most inefficient units like WWTP 6, WWTP 11, WWTP 12 and WWTP 13.

4. Conclusions

In this paper a DEA is proposed the efficiency assessment and ranking of the units and the calculation of the environmental impacts that can be achieved once inefficiencies are removed and best practices adopted. Different DEA models can be used, e.g. radial, non-radial, RAM, etc.

The proposed approach was tested on a real-world dataset of WWWTP. The dataset considered seven impact categories. The results of the different DEA models were reported and shown to be very consistent in the identification and ranking of inefficient units.

Unit	AC	GW	OLD	TET	EU	PO	AD
WWTP 1	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	53%	44%	0%	76%	6%	55%	59%
WWTP 2	9%	0.06	0.001	0.47	0.65	0.007	0.09
	47%	0%	0%	0%	0%	0%	0%
WWTP 3	0.17	0.06	0.001	0.47	0.65	0.007	0.09
	0%	0%	0%	0%	0%	0%	0%
WWTP 4	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	10%	0%	0%	53%	36%	17%	13%
WWTP 5	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	0%	0%	0%	0%	0%	0%	0%
WWTP 6	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	50%	69%	0%	68%	67%	71%	74%
WWTP 7	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	36%	62%	0%	18%	79%	67%	74%
WWTP 8	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	25%	0%	0%	36%	67%	0%	13%
WWTP 9	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	25%	17%	0%	47%	48%	29%	36%
WWTP 10	0.27	0.1	0.002	0.36	0.66	0.012	0.17
	0%	0%	0%	0%	0%	0%	0%
WWTP 11	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	69%	50%	0%	72%	46%	58%	59%
WWTP 12	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	53%	69%	0%	59%	73%	71%	75%
WWTP 13	0.09	0.05	0.001	0.09	0.85	0.005	0.07
	64%	67%	50%	86%	60%	74%	78%

Table 7. Target environmental impact values and potential improvements

Acknowledgements

This research is funded by Andalusia Government through grants P10-TEP-6332.

References

[1] Banker, R.D., Charnes, A. and Cooper, W.W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. Management Science, 30, 1078-1092.

[2] Barba-Gutiérrez, Y., Adenso-Díaz, B. and Lozano, S. (2009). Eco-Efficiency of Electric and Electronic Appliances: A Data Envelopment Analysis (DEA)., Environmental Modeling and Assessment, 14 (4) 439-447.

[3] Cooper, W.W., Park, K.S. and Pastor, J.T. (1999). RAM: A Range Adjusted Measure of Inefficiency for Use with Additive Models and Relations to Other Models and Measures in DEA. Journal of Productivity Analysis, 11, 5-42.

[4] Cooper WW, Seiford, L.M. and Tone, K., Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References and DEA-Solver Software. Kluwer Academic Publishers, Boston, 2000

[5] Färe, R. and Lovell, C.A.K. (1978). Measuring the Technical Efficiency of Production. Journal of Economic Theory, 19, 150-162.

[6] Gallego, A., Hospido, A., Moreira, M.T. and Feijoo, G. (2008). Comprehensive analysis of the environmental performance of wastewater treatment plants for small populations. Resources, Conservation & Recycling, 52 (6) 931-940.

[7] Guineé, J., Gorreé, M., Heijungs, R., Huppes, G., Kleijn, R., de Konnig, A., van Oers, L. Weneger, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin R. and Huibregts, M., Life Cycle Assessment: An operational guide to the ISO standards. Ministry of Housing, Spatial Planning and Environment, Netherlands, 2001

[8] Lozano, S. and Gutiérrez, E. (2008). Non-parametric frontier approach to modelling the relationships among population, GDP, energy consumption and CO2 emissions. Ecological Economics, 66 (4) 687-699.

[9] Lozano, S. Iribarren, D., Morerira, M.T. and Feijoo, G. (2009). The link between operational efficiency and environmental impacts. A joint application of Life Cycle Assessment and Data Envelopment Analysis. Science of the Total Environment, 407 (5) 1744-1754.

[10]Lozano, S. Iribarren, D., Morerira, M.T. and Feijoo, G. (2010). Environmental impact efficiency in mussel cultivation. Resources, Conservation & Recycling, 54 (12) 1269-1277.

[11]Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. European Journal of Operational Research, 130, 498-509.