Integration of Life Cycle Assessment and Data Envelopment Analysis using a Free Disposable Hull Approach to Evaluate Farms' Eco-efficiency

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Abstract: The joint use of Life Cycle Assessment and Data Envelopment Analysis, also known as LCA+DEA, appears as a suitable methodology to evaluate eco-efficiency of multiple units. This methodology has been developed mainly during the last decade, and different methodological aspects has been proposed. However, there are other such as the use of advanced DEA models that have been poorly explored. In this sense, this study seeks to integrate the Free Disposable Hull (FDH) approach into LCA+DEA methodology, applied an agricultural case study. The five-step method is employed to a sample of 37 raspberry producers considering carbon footprint as environmental category. The results indicated that 11 farmers are identified as inefficient for which operational and environmental targets are proposed. The use of FDH model is suitable for the use into the LCA+DEA methodology since it allows to determine one benchmark for inefficient farmers, unlike others models widely used in this methodology, such as BCC, SBM or CCR.

1 INTRODUCTION

Sustainable development has received great attention during the last decade. Since its proposal eco-efficiency has been coined as a quantitative management approach for studying both, environmental and economic aspects (Rybaczewska-Błażejowska & Gierulski, 2018). The World Business Council for Sustainable Development (WBCSD) defined eco-efficiency concept as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the earth's estimated carrying capacity" (Schmidheiny & Stigson, 2000).

Eco-efficiency has been evaluated using different methodologies, which can be classified into linear programming methods, statistical and econometric tests, and, accounting and indicator techniques (Nikolaou & Matrakoukas, 2016). Among these methodologies, the joint use of life cycle assessment and Data Envelopment Analysis appears as one of the most recent approaches, allowing to assess the operational and environmental performance of multiple units (Rebolledo-Leiva, Angulo-Meza, Iriarte, & González-Araya, 2017a).

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LCA is a widely used methodology to evaluate the potential environmental impacts through the whole life cycle of products or services (ISO, 2006). This methodology allows to identify opportunities to improve their environmental performance.

DEA is a non-parametric tool that uses linear programming to estimate the relative efficiency of several homogeneous units, known as Decision Making Units (DMU) (Cooper, Seiford, & Tone, 2007). These DMUs use multiple inputs (resources) to produce multiple outputs (outcomes of the processes). The relative efficiency is measured employing inputs and outputs into different mathematical DEA models. In general terms, these models, could be oriented to inputs or to outputs. The former (input-oriented models) seek to minimize the inputs while maintaining the outputs constant. On the contrary, the second (output-oriented models) aim to maximize all outputs while maintaining the inputs constant (Ten Raa & Greene, 2019). DEA models classified the DMUs into efficient if its score is 1 (or 100%) and inefficient otherwise. For the inefficient ones, DEA also provides targets and benchmarks in order to become efficient.

The joint use of LCA and DEA, also namely LCA+DEA methodology, has been developed into three different LCA+DEA methods, five-step method Vázquez-Rowe et al. (2010), three-step method Lozano et al. (2010) and four-step method Rebolledo-Leiva et al. (2017). The main differences among these methods are the number of steps and the kind of variables used into the DEA model (Vásquez-Ibarra, Rebolledo-Leiva, Angulo-Meza, González-Araya, & Iriarte, 2020). Beyond the LCA+DEA methodology, others Life Cycle approaches have been coupled with DEA, outstanding the development of the LC+DEA concept. Due to the current relevance of GHG emissions mitigation, based on the Carbon Footprint (CF), a methodological framework is based on the combined use of CF and DEA, known as CF+DEA (Rebolledo-Leiva et al., 2017a; I Vázquez-Rowe & Iribarren, 2015).

The use of LCA+DEA has increased during the last decade. Vásquez-Ibarra, Rebolledo-Leiva, Angulo-Meza, González-Araya, & Iriarte (2020) conducted a critical review, proposed a taxonomy and proposed future research related to the development of this methodology. One item developed by these authors were the widely used of three DEA models: CCR (Charnes, Cooper, & Rhodes, 1978), BCC (Banker, Charnes, & Cooper, 1984), SBM (Tone, 2001). In these models, inefficient DMUs can achieve an efficient point on the frontier reducing their inputs (in input-oriented models), adding output (in output-oriented models), or both (in non-oriented models). This efficient point is a combination of available efficient units and they not necessarily represent real units, as pointed out by Safari, Jafarzadeh, & Fathi (2020). Furthermore, these models provide many reference units (benchmarks) for inefficient DMUs, making difficult their implementation in real world, for example in agricultural sector. Particularly, small farmers could be one of the most challenge group in agricultural context, since its limit access to information and communication technologies (Otter & Theuvsen, 2014), making difficult to follow operational practices of many benchmarks.

One way to deal with these issues is the use of Free Disposable Hull (FDH) approach. FDH relaxes the convexity assumption of DEA models providing just one benchmark for each inefficient DMU as a reference unit. This implies that FDH' reference set is more consistent and corresponds with real world (Deprins, Simar, & Tulkens, 1984; Safari et al., 2020). Therefore, the use of FDH model can provide benefit from a practical point of view, since small inefficient farmers have just one benchmark.

In this context, this study seeks to evaluate the use of the FDH DEA model into the joint use of LCA and DEA methodology to evaluate eco-efficiency. To do this, we employ a case study of 37 Chilean raspberries producers using the five-step method.

2 METHODS

In this Section, methodological aspects of five-step CF+DEA method are presented. Briefly, the five-step method consists of five stages: life cycle inventory, actual environmental characterization using CF; operational efficiency performed for each DMU through DEA; environmental characterization using the target DMUs from the previous step; and, comparison of the current and target environmental impacts.

2.1 Data Collection of Multiple Units

The first step of the five-step CF method is to develop a Life Cycle Inventory (LCI), i.e. input and output data for the assessed system are collected.

2.2 Carbon Footprint Assessment

In this step, carbon footprint (CF) assessment for every DMU is performed. This step represents the actual environmental characterization of all DMUs under study. CF is an environmental indicator that estimated the overall greenhouse gas (GHG) emissions associated to a product or activity during its whole life cycle. The most common GHG emissions are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), among several others (ISO, 2018).

2.3 Data Envelopment Analysis

In this step, the DEA model is performed. As mention in the Introduction section, the FDH DEA model is employed in order to determine operational efficiency of 37 farmers. The selection of this model lies on that it provides one benchmark for inefficient DMUs, unlike CCR, BCC or SBM which provides many efficient units as references which could result difficult to implement from a practical point of view for small farmers. Furthermore, benchmarks and calculation of the target for each inefficient DMU is conducted.

The five-step CF method employs an input-oriented DEA model (I Vázquez-Rowe & Iribarren, 2015). In this sense, the FDH model is used considering operational inputs and outputs, while the CF is evaluated before and after DEA model.

The mathematical formulation of DEA model is as follow. Suppose there are n observed DMUs and assume that each one uses m inputs to produce s outputs. The FDH model that minimize the inputs of DMU_0 assuming Variable Returns to Scale (VRS) is presented from Eqs. (1) to (6).

$$\text{Min } \theta \quad (1)$$

Subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{i0} \ \forall \quad (2)$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{r0} \ \forall\, r \quad (3)$$

$$\sum_{j=1}^{n} \lambda_j = 1 \quad (4)$$

$$\lambda_j \in \{0,1\}\ \forall\, j \quad (5)$$

$$\theta \text{ is unconstrained} \quad (6)$$

Where,

j is the subindex of the set of observed DMUs,
i is the subindex of the inputs,
r is the subindex of the outputs,
θ corresponds to the proportion by which all inputs can be reduced (efficiency level),
λ_j is the intensity of the participation of the DMUj in the construction of the "compound" DMU or benchmark,
x_{ij} is the amount of input i consumed by DMUj,
y_{rj} is the amount of output r produced by DMUj,
x_{i0} is the amount of input i of DMU_0,
y_{r0} is the amount of output r of DMU_0

In the FDH model, Eq. (1) seeks to minimize the proportion of inputs used by DMU_0 and it represents the efficiency of this DMU. Eq. (2) guarantees the proportional reduction of inputs limited by the efficient frontiers. Similarly, Eq. (3) prevents that the outputs of DMU_0 are limited by the efficient frontier. Eq. (4) (4) stablishes that each DMUs evaluated is compared with DMUs in similar size and scale. Eq. (5) and (6) represent the nature of the decision variables.

2.4 Carbon Footprint using Target Values

After the target values were obtained for inefficient DMUs through the FDH model, the CF is calculated using the new LCI. This step is carried out with the aim to calculate the potential environmental targets of inefficient DMUs if they operate under efficient level. This procedure entails the environmental benchmarking of the sample.

2.5 Interpretation and Eco-efficiency Assessment

In this step, the environmental impacts calculated in step 2 are compared with those obtained in step 4 associated to the targets. In this sense, as stated I Vázquez-Rowe & Iribarren (2015), "…the environmental consequences of operational inefficiencies are revealed…" and the eco-efficiency can be verified. Furthermore, benchmark (best practice) provided by FDH model can be used as a guideline for inefficient farmers.

3 RESULTS AND DISCUSSION

This section presents the results obtained using the five-step CF+DEA method following the FDH.

3.1 Data Collection of Multiple Units

The data of raspberries producers were obtained from previous works of our research group (Fernández

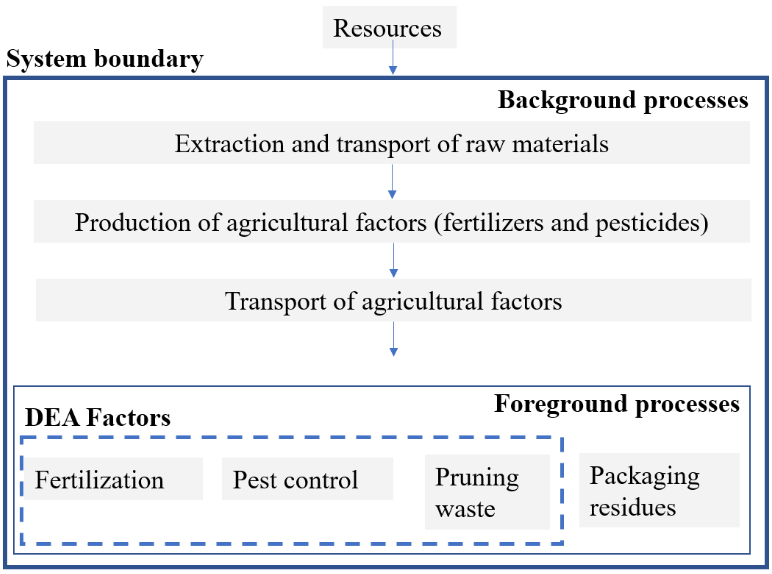

Figure 1: System boundaries and DEA factors employed.

Cáceres, 2018; Rebolledo-Leiva, Angulo-Meza, Iriarte, González-Araya, & Vásquez-Ibarra, 2019) and based on Consultora Campo Nova Ltda (2011) who obtained them through face-to-face interviews.

The study considers 37 farmers of the Maule Region in Chile, between the 35th and 36th parallel south. This is one of the main regions where raspberry is cultivated, totalizing 1216 hectares of this fruit (Larrañaga et al., 2016).

The agricultural operations are made manually and consequently, energy is not considered. Furthermore, agricultural inputs are classified considering it main function, i.e. fertilizer input represents all chemical and organics compounds that contribute to nutrition of the plants. The LCI is extracted from Rebolledo-Leiva et al. (2019) and consider as inputs the amount of fertilizers, pesticides, waste pruning and packaging residues, while the output is the raspberry production.

3.2 Carbon Footprint Assessment

In the second step, the system boundaries for CF assessment were setted from cradle-to-gate. This imply that the agricultural factors evaluated correspond to fertilizers, pesticides, waste pruning and packaging residues. Figure 1 presents LCA factors used in this study. While the functional unit (FU) is 1 kg of harvested raspberries.

The CF was obtained using the software CCalC2 v1.43 of the University of Manchester (2016) following the CML 2001 method (Guinée et al., 2002). Background processes, e.g. extraction of raw material, fertilizer production, etc., were obtained mainly from the Ecoinvent v.2.2 database (Wernet et al., 2016). While the field emissions were calculated following World Food Guide LCA Database (Nemecek et al., 2015).

The total amount of CF produced by raspberry production is on average 4409 $kgCO_{2\text{-}eq}$ (0.82 $kgCO_{2\text{-}eq}$ / kg of raspberry). Farmer 29 has the highest value per FU (5.5 $kgCO_{2\text{-}eq}$ / kg of raspberry) while farmer 9 has the lowest one (0.1 $kgCO_{2\text{-}eq}$ / kg of raspberry). The agricultural factors with the highest contribution to the total CF are widely fertilizers (93.4%) followed by pruning waste (4.2%), and pesticides (2.4%). Packaging residues contributes only 0.01%.

3.3 Data Envelopment Analysis

Considering the low contribution of packaging residues to the total CF, the inputs used in the FDH model are fertilizers, pesticides and pruning waste, while the output is raspberry production (see Figure 1). The DEA model was performed using software IBM ILOG CPLEX Optimization Studio v.12.7.1.0.

According to the input oriented FDH model, a total of 26 DMUs were classified as efficient and 11 DMUs as inefficient. Figure 2 presents efficiency score for the inefficient DMUs. These DMUs obtained an average score of 0.6, with the lowest value of 0.2 (DMU 37) and highest value of 0.9 (DMUs 22, 27 and 30).

Inefficient DMUs produce 65% less raspberries than the efficient ones, despite they use 17% less fertilizers, 34% less pesticides and 34% less pruning

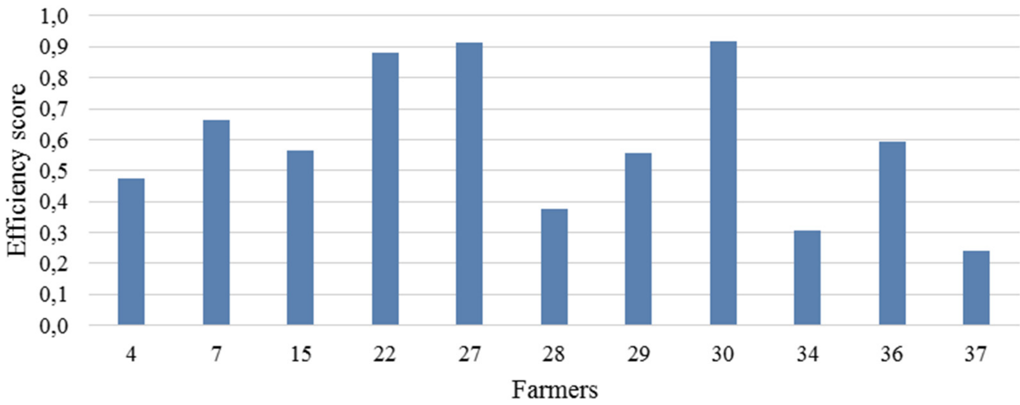

Figure 2: Efficiency score using FDH DEA model.

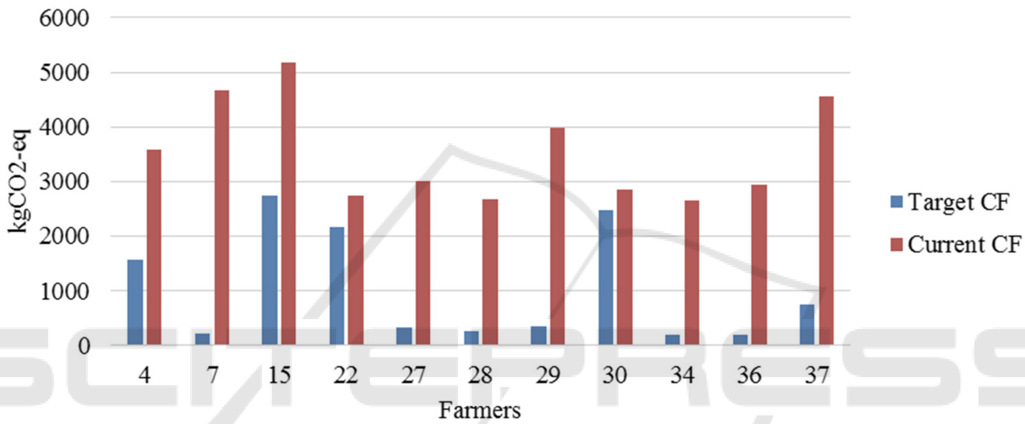

Figure 3: Current and targets CF level.

waste. This implyes that, even though farmers use less inputs, their actual operation points is much fewer than the efficient operating point. Therefore, they should reduce actual amount of inputs consumed.

For each inefficient DMU, FDH model provides one benchmark, making suitable from a practical point of view, since inefficient farmers should focuss only on one efficient farm. For instance, farmer 9 (efficient) is benchmark of farmer 36 (inefficient). Both produce the same amount of raspberries (2500 kg), however, farmer 9 uses 96% less fertilizers, 41% less pesticides and 73% less pruning waste than farmer 36. Consequently, if farmer 36 want to improve their actual performance, it is advisable to review operational practices of farmer 9.

3.4 Carbon Footprint using Target Values

This step presents the new CF performed using the targets provided by DEA model in step 3 for inefficient DMUs. Figure 3 presents current and target CF for the 11 inefficient DMUs. As can be seen, on average inefficient farmers could reduce their actual level of CF from 3530 kg $CO_{2\text{-eq}}$ until to 1021 kg $CO_{2\text{-eq}}$ which represents 71%. The most dramatic reduction is observed in farmer 7 and 36 (95% and 94%, respectively).

3.5 Interpretation and Eco-efficiency Assessment

In this last step, eco-efficiency level of the raspberry farmers is analyzed. Eco-efficiency comprises operational and environmental aspects. From an operational point of view, the most critical reduction observed for inefficient DMUs is related to fertilizers (71%), followed by pesticides (55%) and prunning waste (50%). It is importan to observe that fertilizers are also the main contributor to the current CF level (see Sub-section 3.2) This operational reduction implies also an improving of CF performance.

On the other hand, the use of FDH model allows the implementation of best practices easier than the actual existing DEA models in the LCA+DEA literature. Since, for the inefficient farmers it is possible to provide operational factors through bechmarking of one efficient farmer. Therefore, it is recommendable that inefficient farms have to follow the agricultural practices of the efficient farms, which coul ensure not only achieving the CF targets but also the final production targets.

4 CONCLUSIONS

This study integrates the FDH aproach into the joint use of LCA+DEA methodology. The main contribution is to suitability of FDH model into LCA+DEA methodology from a practical point of view in order to provide operational and environmental targets for inefficient DMUs based on one benchmarks.

The case study considered 37 chilean raspberries farmers. The five-step CF+DEA method was employed. The environmental assesssment (CF) was evaluated in a cradle-to-gate system boundary considering fertilizers, pest control (use of pesticides), prunning waste and plastic waste. While the DEA assessment considered the FDH model through input orientation.

A total of 11 farmers were classified as eco-inefficient, for whose operational and environmental targets were proposed. On average, the highest reduction is observed for fertilizers and pesticides. This reduction implies a decrease of CF level of 71% for the inefficient farmers.

The use of the FDH model appears as a suitable DEA model for it use in the LCA+DEA methodology since it allows to identify one benchmark (best-practice) for inneficient DMUs. This enable that inefficient farmers could follow agricultural practices of the efficient ones in order to reduce operational levels and CF, while maintaning actual raspberry production.

Despite its novelty for LCA+DEA methodology, future works could extend the use of the FDH model comparing it with others DEA models widely used in LCA+DEA literature, such as BCC, SBM or CCR. Moreover, future works can propose further methodology in order to rank the efficient DMUs and increase the discrimination of the model.

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REFERENCES

Banker, D., Charnes, A., & Cooper, W. W. (1984). Some models for estimating technical and scale innefficiencies in Data Envelopment Analysis. *Managment Science*, 1078–1092.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, *2*(6), 429–444. https://doi.org/10.1016/0377-2217(78)90138-8

Consultora Campo Nova Ltda. (2011). *Diagnóstico y Propuesta: Acuerdo de Producción Limpia para la Cadena Comercial de Berries Región del Maule*. Talca.

Cooper, W. W., Seiford, L. M., & Tone, K. (2007). *Data Envelopment analysis: A Comprehensive Text with Models and Applications* (Second Edi). Nueva York: Springer Science+Business Media.

Deprins, D., Simar, L., & Tulkens, H. (1984). *Measuring Labor Inefficiency in Post Offices. In The Performance of Public Enterprises: Concepts and Measurements*. 243–267.

Fernández Cáceres, J. R. (2018). *Análisis de ciclo de vida (ACV) de producción de frambuesas de exportación en la región del Maule*. University of Talca.

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., … Udo de Haes, H. (2002). *Handbook on Life Cycle Assessment*. Dordrecht: Kluwer Academic Publishers.

ISO. *ISO 14040 - Environmental management - Life cycle assessment - Principles and framework*. , (2006).

ISO. (2018). *ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification*. Geneva, Switzerland.

Larrañaga, P., Osores, M. A., Henríquez, G., Villa, R., Woywood, C., Peña, J. C., … González, J. (2016). *Catastro Frutícola. Principales resultados. Región del Maule. Julio 2016*. Retrieved from http://bibliotecadigital.ciren.cl/handle/123456789/26205

Lozano, S., Iribarren, D., Moreira, M. T., & 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*, 1744–1754.

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., & Humbert, S. (2015). *Methodological Guidelines for the Life Cycle Inventory* *of Agricultural Products. Version 3.0. World Food LCA Database (WFLDB). Quantis and Agroscope*. Lausanne and Zurich, Switzerland.

Nikolaou, I. E., & Matrakoukas, S. I. (2016). A framework to measure eco-efficiency performance of firms through EMAS reports. *Sustainable Production and Consumption*, *8*(February), 32–44. https://doi.org/10.1016/j.spc.2016.06.003

Otter, V., & Theuvsen, L. (2014). ICT and farm productivity: Evidence from the Chilean agricultural export sector. *Gesellschaft Fur Informatik*, *206*, 113–116.

Rebolledo-Leiva, R., Angulo-Meza, L., Iriarte, A., & González-Araya, M. C. (2017a). Joint carbon footprint assessment and data envelopment analysis for the reduction of greenhouse gas emissions in agriculture production. *Science of the Total Environment*, *593–594*, 36–46. https://doi.org/10.1016/j.scitotenv.2017.03.147

Rebolledo-Leiva, R., Angulo-Meza, L., Iriarte, A., González-Araya, M. C., & Vásquez-Ibarra, L. (2019). Comparing two CF+DEA methods for assessing eco-efficiency from theoretical and practical points of view. *Science of the Total Environment*, *659*, 1266–1282. https://doi.org/10.1016/j.scitotenv.2018.12.296

Rybaczewska-Błażejowska, M., & Gierulski, W. (2018). Eco-Efficiency Evaluation of Agricultural Production in the EU-28. *Sustainability (Switzerland)*, *10*(12), 1–21. https://doi.org/10.3390/su10124544

Safari, H., Jafarzadeh, A. H., & Fathi, M. R. (2020). Evaluation of the branches of Iran Insurance Corporation based on data envelopment analysis-free disposal hull in the presence of weight restrictions. *International Journal of Mathematics in Operational Research*, *16*(2), 202–216. https://doi.org/10.1504/IJMOR.2020.105871

Schmidheiny, S., & Stigson, B. (2000). Eco-efficiency: Creating More Value With Less Impact. In *WBCSD: World Business Council for Sustainable Development*.

Ten Raa, T., & Greene, W. H. (2019). The Palgrave handbook of economic performance analysis. In *The Palgrave Handbook of Economic Performance Analysis*. https://doi.org/10.1007/978-3-030-23727-1

Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, *130*(3), 498–509. https://doi.org/10.1016/S0377-2217(99)00407-5

University of Manchester. (2016). CCaLC2 v.1.7 Software and database. Retrieved January 1, 2018, from www.ccalc.org.uk

Vásquez-Ibarra, L., Rebolledo-Leiva, R., Angulo-Meza, L., González-Araya, M. C., & Iriarte, A. (2020). 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*, 139–538. https://doi.org/10.1016/j.scitotenv.2020.139538

Vázquez-Rowe, I, & Iribarren, D. (2015). Review of Life-Cycle Approaches Coupled with Data Envelopment Analysis: Launching the CFP + DEA Method for Energy Policy Making. *The Scientific World Journal*, *2015*, 10. https://doi.org/10.1155/2015/813921

Vázquez-Rowe, Ian, Iribarren, D., Moreira, M. T., & Feijoo, G. (2010). Combined application of life cycle assessment and data envelopment analysis as a methodological approach for the assessment of fisheries. *International Journal of Life Cycle Assessment*, *15*(3), 272–283. https://doi.org/10.1007/s11367-010-0154-9

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8