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On the feasibility of using emergy analysis as a source of benchmarking criteria through data envelopment analysis: A case study for wind energy

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ABSTRACT

The definition of criteria for the benchmarking of similar entities is often a critical issue in analytical studies because of the multiplicity of criteria susceptible to be taken into account. This issue can be aggravated by the need to handle multiple data for multiple facilities. This article presents a methodological framework, named the Em + DEA method, which combines emergy analysis with Data Envelopment Analysis (DEA) for the ecocentric benchmarking of multiple resembling entities (i.e., multiple decision making units or DMUs). Provided that the life-cycle inventories of these DMUs are available, an emergy analysis is performed through the computation of seven different indicators, which refer to the use of fossil, metal, mineral, nuclear, renewable energy, water and land resources. These independent emergy values are then implemented as inputs for DEA computation, thus providing operational emergy-based efficiency scores and, for the inefficient DMUs, target emergy flows (i.e., feasible emergy benchmarks that would turn inefficient DMUs into efficient). The use of the Em + DEA method is exemplified through a case study of wind energy farms. The potential use of CED (cumulative energy demand) and CExD (cumulative exergy demand) indicators as alternative benchmarking criteria to emergy is discussed. The combined use of emergy analysis with DEA is proven to be a valid methodological approach to provide benchmarks oriented towards the optimisation of the life-cycle performance of a set of multiple similar facilities, not being limited to the operational traits of the assessed units.

1. Introduction

Systems are often analysed with the aim of providing benchmarks for their performance. When sufficient data are available for a large set of similar entities, measures of the relative performance of each entity are usually desired. In this respect, data envelopment analysis (DEA) is a linear programming methodology to measure the relative efficiency of multiple homogeneous entities (called decision making units, DMUs) when the productive process shows a structure that is composed of multiple inputs and outputs [1]. In addition to efficiency scores based on the comparison between the operational inputs/outputs of the evaluated decision making units (DMUs), DEA also provides analysts with target (and feasible) operating conditions that could potentially turn inefficient DMUs into efficient entities [1–3]. In other words, DEA arises as a suitable operational benchmarking tool when multiple data are available for multiple facilities.

However, operational benchmarking can fail to cover relevant aspects that should be embedded in the provided benchmarks, as it is usually limited to the operational traits of production systems. For instance, in the current context of general public environmental concerns, these benchmarks should lead to a better environmental performance of the evaluated facilities throughout the supply chain. In this sense, the use of Life Cycle Assessment (LCA) in combination with DEA (commonly referred to as the LCA + DEA methodology) has been proposed in the literature [4,5] in an effort to quantitatively verify the potential environmental benefits linked to improved resource management.

Even though the LCA + DEA methodology constitutes a proven tool for the operational and environmental benchmarking of multiple DMUs [6–9], resulting environmental benchmarks are a direct consequence of operational benchmarks due to the underlying

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optimisation of resources. Hence, concerns on the suitability of benchmarking criteria based on operational parameters still persist regarding this type of studies. Direct environmental benchmarking as an alternative to indirect environmental benchmarking through operational optimisation may highlight the socio-environmental responsibility of the different actors involved in the supply chain, acting directly on the current environmental performance of the production systems rather than on their operational flows.

Among the wide range of criteria susceptible to be taken into account for direct environmental benchmarking, the use of life-cycle indicators as benchmarking criteria could be an appropriate choice given their holistic nature [10]. In this respect, the direct use of impact indicators quantified through LCA as inputs in DEA studies could be considered, but concerns exist on the methodological consistency of such approach due to the correlation between certain impact categories (which could result in contradictory benchmarks). This article aims at outlining a novel methodological framework for the direct environmental benchmarking of multiple similar facilities based on the combination of a more appropriate life-cycle approach and DEA. Thus, emergy analysis is explored as a consistent source of robust life-cycle benchmarking criteria to be implemented into DEA studies, and compared with other conventional energy-based LCA indicators.

Emergy is an approximation of the solar energy previously provided to generate a product and/or to support a system and its level of organisation [11]. Emergy is interpreted as the memory of the (solar) energy that has been consumed in the past or accumulated over time [11,12], or the memory of the geobiosphere exergy provision (environmental work) related to economic systems through the use of natural resources [13,14]. By examining the different quality of the various energy forms and acknowledging that their use involves differing environmental efforts, emergy has been widely used to address the assessment of human-driven systems and technologies (e.g. [15–18]). Compared to energy-based indicators such as cumulative energy demand (CED) [19] or cumulative exergy demand (CExD) [20], which essentially evaluate the cumulated use of natural resources by considering their energy or exergy contents (user-side perspective), emergy accounts for the environmental effort performed to make the resources available (donor-side perspective). For instance, while CExD values the resources according to their ability to perform work [20,21], emergy evaluates them according to the total (solar) energy involved in their formation. Hence, emergy indicators arise as ideal candidates for their use in direct environmental benchmarking. They provide the benchmarking process not only with a life-cycle perspective, but also with an ecocentric perspective.

Despite the criticisms that emergy has received related to its practical application in complex case studies and to the conceptual interpretation of its algebra [22], emergy can be consistently used in combination with LCA to assess the consumption of natural resources when extracted and transformed into products [23–27]. In this framework, emergy is seen as a valuable addition to LCA, providing a complementary donor-side perspective, a unified measure of the provision of environmental support (via the "solar emjoules" or seJ), and an indication of the effort performed by the environment that would be needed to replace the resources that are consumed [27]. The combination of emergy with DEA is proposed in the current study to enhance benchmarking processes, orienting the joint method towards environmental sustainability with an ecocentric life-cycle perspective. In fact, this article evaluates the feasibility of using emergy analysis for direct environmental benchmarking to provide a consistent framework that widens the scope of assessment at a primary resource level, thus filling the methodological gap between life-cycle indicators and direct environmental benchmarking.

2. Materials and methods

2.1. Em + DEA method

This study considers the use of emergy values as DEA inputs for the benchmarking of multiple DMUs. A three-step Em + DEA method is proposed to that end. As can be observed in Fig. 1, the three steps include: (i) data collection, (ii) emergy analysis, and (iii) DEA.

The first step addresses the preparation of the life-cycle inventory (LCI) of each individual DMU. Once the LCIs are available, they are used in the second step in order to carry out the emergy analysis of each DMU. Fig. 1 shows that alternative analytical approaches could be used instead of emergy analysis. In particular, the analysis of CED and CExD as alternative sources of life-cycle indicators to be benchmarked is discussed later in Section 4.2. CED- and CExD-based approaches are selected for comparison with the emergy-based method since they are well-established methods for LCA that also assess life-cycle resource consumption through energy-based indicators, but with intrinsically different scopes and principles.

In this study, emergy values are computed by using the recently developed "Software for CALculating Emergy based on life-cycle inventories" (SCALE) [28]. The application of SCALE instead of the conventional emergy accounting procedure [12] is justified by the fact that it calculates emergy values per functional unit and per resource category in compliance with the emergy algebra rules [12], using comprehensive and detailed LCI systems which would be unmanageable through the conventional assessment method. Further details on the procedure can be found in the literature [28,29]. It should be noted that other computation procedures beyond SCALE could be used, as long as the correct methodological choices are undertaken.

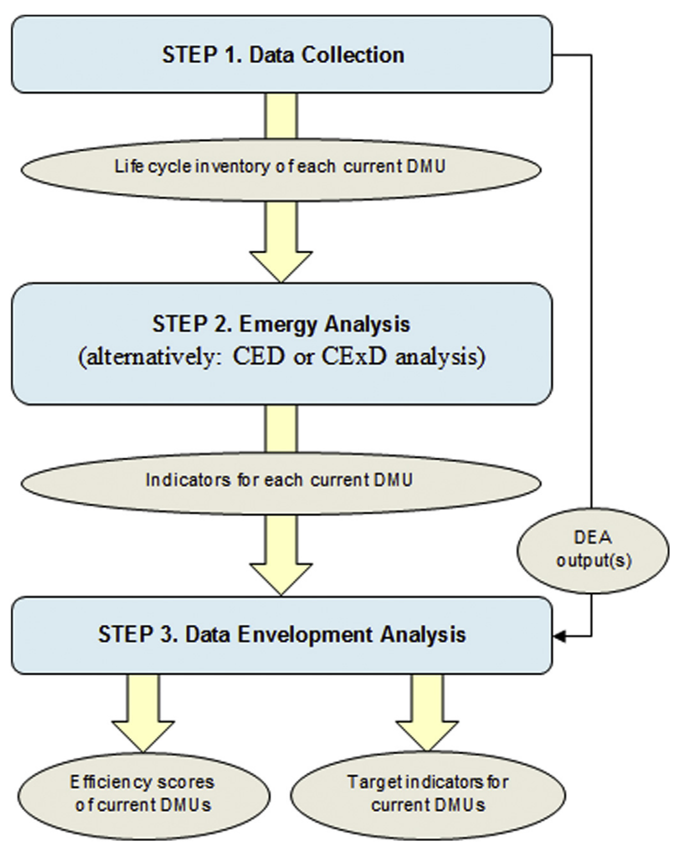

Fig. 1. Representation of the combined three-step emergy and DEA (Em + DEA) method.