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A multiple criteria approach to two-stage data envelopment analysis

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ABSTRACT

Two-stage data envelopment analysis (DEA) models are commonly used in the evaluation and benchmarking of sustainable operations and processes across multiple research fields. To date, however, little attention has been given to the unrealistic weight distribution and weak discrimination power in the modeling and evaluation of the two-stage sustainable operations when using two-stage DEA models. In order to overcome this methodological weakness, we use the multiple criteria DEA (MCDEA) approach in the evaluation of the two-stage processes. The outcome is a multiple criteria two-stage DEA model which yields more realistic weights for the inputs and outputs and thus has better discrimination power than traditional two-stage DEA models. The developed model is tested and validated by assessing the sustainable design performances of a sample of car product designs.

Introduction

Two-stage data envelopment analysis (DEA) models are used to evaluate the efficiency of the processes which are made up of two separate and distinct stages. The first stage of such a two-stage process consumes some inputs and produces some outputs. The outputs of the first stage, which are called the intermediate measures, are then used as the inputs of the second stage. The main difficulty in the modeling and measurement of the efficiency of the two-stage processes arises from the presence of the intermediate measures since larger values of these measures represent the better performance of the first stage and worse performance of the second stage.

Traditional DEA models use a “black-box” approach in measuring the efficiency of the activities and do not relate the sources of the inefficiency of the processes to their different stages. However, this approach is limited in its measurement of the efficiencies of activities which are consist of two stages (or sub-processes) where the outputs of one stage are the inputs of another stage (Chen et al., 2012). By applying the traditional black-box approach to the measurement of the efficiency of a two-stage process it is not always possible to track the sources of the inefficiencies. However, by using a two-stage DEA model to measure the overall efficiency as the combination of two separate efficiency ratios, i.e. efficiency ratio of stage 1 and efficiency ratio of stage 2, it is possible to identify not only the overall efficiency of the activities, but also the

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efficiency status of their sub-processes. This is, clearly, more informative than simply measuring overall efficiency as the ratio of the final outputs of the whole system to its inputs.

Moreover, by opening the black box and applying the two-stage DEA models, optimization of the decision making units (DMUs) and activities can be achieved by adopting different scenarios. It can be reached by: (i) simultaneously optimizing the efficiencies of the stages 1 and 2 of the two-stage process, or (ii) optimizing the efficiency of the stage 1 as the more important and the leader stage first, and then optimizing the less important and the follower stage 2, or (iii) optimizing the efficiency of the stage 2 first and then the stage 1. These alternative scenarios are not possible with the traditional DEA models since each activity and process is not represented by the combination of its sub-processes.

Seiford and Zhu (1999) introduced one of the first two-stage DEA models and these authors used this to evaluate the efficiency of the US commercial banks by measuring their overall efficiency as a result of the two sub-processes of the marketability and profitability. However, the efficiency of each step was measured by a separate DEA model and thus did not reflect the potential conflict between the two stages. Following this initial approach, the focus shifted to the measurement of both the efficiency of each of the steps and also the overall efficiency in an integrated model. To achieve this, Liang et al. (2006) applied the concepts of the cooperative and non-cooperative games from the game theory literature to measure the efficiency of the DMUs through a two-stage process. In the non-cooperative context, the efficiency score of the more important stage (the leader) is measured and optimized first, and then the efficiency score of the less important stage (the follower) is measured subject to keeping the efficiency of the leader stage unchanged. In this cooperative approach, the efficiency scores of the both stages are simultaneously measured and optimized. It should be noted that both the cooperative and non-cooperative models developed in Liang et al. (2006) are non-linear models and are solved as parametric linear programs.

Liang et al. (2008) went on to develop a further set of linear cooperative and non-cooperative two-stage DEA models. In order to create a linear cooperative model, Liang and his colleagues defined the overall efficiency as the product of the efficiency ratios of the stages 1 and 2. This allows for the linear formulation for the cooperative model since the intermediate measures exist in the denominator of the efficiency ratio of the first stage and in the numerator of the efficiency ratio of the second stage. By multiplying the efficiency ratios of the stages 1 and 2, the intermediate measures are omitted and the overall efficiency is maximized by maximizing only one efficiency ratio. Kao and Hwang (2008) also used a similar approach whereby the product of the efficiencies of the stages was treated as the overall efficiency, and this allowed them to maximize the efficiencies of the stages simultaneously.

Chen et al. (2010) took the discussion further by highlighting that, due to the existence of intermediate measures, defining improvement targets for the inefficient DMUs is a challenging task. As a result, these authors developed an approach to determine the benchmark efficient DMUs for the inefficient DMUs within a two-stage structure. Chen et al. noted that, although many of the two-stage DEA models in the literature are able to measure the efficiency scores of the DMUs, they do not provide any information as to where the DEA efficiency frontier is located. Therefore, the projection of the inefficient DMUs onto the efficiency frontier is not possible. Using the model developed by Kao and Hwang (2008) as an example and employing two different tests, Chen et al. showed that the projections defined by this model do not yield efficient target DMUs for the inefficient DMUs.

Chen et al. (2009) also developed an additive efficiency decomposition to measure the efficiency of the two-stage processes under both constant returns to scale (CRS) and variable returns to scale (VRS) assumptions. In a subsequent review of the existing two-stage DEA models, Cook et al. (2010) showed that all the approaches found within the literature can be categorized as using either non-cooperative or cooperative game concepts. Li et al. (2012) extended the work of Kao and Hwang (2008) and Liang et al. (2008) by considering some other inputs entered into the second stage which were additional to the intermediate measures. They argued that, due to the existence of the additional inputs to the second stage, application of the product of the efficiency of the two stages will lead to a non-linear program. In order to find the global optimal solutions, they converted the non-linear models to parametric linear models. Wang et al. (2014) also developed the additive model proposed by Chen et al. (2009) by considering undesirable outputs and applied this approach to an efficiency evaluation of the Chinese commercial banks.

However, from this overview of the extensive literature of the two-stage DEA models one common issue emerges. Current models do not consider the lack of discrimination power and unrealistic weights distribution among input, intermediate measure and output factors. This is not a new issue in the sense that it has been raised in the literature relating to the traditional one-stage (black box) DEA models where different solutions have been suggested. However, it is posited that the arguments made in the literature relating to one stage DEA models (where the focus is on improving discrimination power and gaining more realistic inputs and outputs weights) are also applicable in the two-stage DEA models.

As a result, the main focus of our paper is to make a link between the approaches suggested and applied in the original black box DEA models literature to improve the discrimination power and weighting system of the two-stage DEA models. At the same time, since the two-stage DEA models are frequently used in sustainability assessment of different types of DMUs or processes, our developed procedure will contribute to a better and more effective application of the two-stage DEA models in this very important area.

It will also be appreciated that the two problems of lack of discrimination and unrealistic weights distribution are inter-related and thus, as noted by Li and Reeves (1999) they are usually found simultaneously. The weak discrimination