European Journal of Operational Research 251 (2016) 182–197

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Decision Support

Two-stage network processes with shared resources and resources recovered from undesirable outputs

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ARTICLE INFO

Article history:
Received 17 December 2014
Accepted 24 October 2015
Available online 30 October 2015

Keywords:
Data envelopment analysis
Two-stage processes
Undesirable output
Shared resources
Non-cooperative

ABSTRACT

Data envelopment analysis (DEA) is an approach for measuring the performance of a set of homogeneous decision making units (DMUs). Recently, DEA has been extended to processes with two stages. Two-stage processes usually have undesirable intermediate outputs, which are normally considered be unrecoverable final outputs. In many real situations like industrial production however, many first-stage waste products can be immediately used or processed in the second stage to produce new resources which can be fed back immediately to the first stage. The objective of this paper is to provide an approach for analyzing the reuse of undesirable intermediate outputs in a two-stage production process with a shared resource. Shared resources are input resources that not only are used by both the first and second stages but also have the property that the proportion used by each stage cannot be conveniently split up and allocated to the operations of the two stages. Additive efficiency measures and non-cooperative efficiency measures are proposed to illustrate the overall efficiency of each DMU and respective efficiency of each sub-DMU. In the non-cooperative framework, a heuristic algorithm is suggested to transform the nonlinear model into a parametric linear one. A real case of industrial production processes of 30 provincial level regions in mainland China in 2010 was analyzed to verify the applicability of the proposed approaches.

1. Introduction

Developed by Charnes, Cooper, and Rhodes (1978), data envelopment analysis (DEA) is a non-parametric mathematical approach, which is used to evaluate the relative performance or efficiency of a group of homogenous decision making units (DMUs), especially those with multiple inputs and multiple outputs (Cook, Liang, Zha, & Zhu, 2009; Cooper, Seiford, & Tone, 2007; Liang, Wu, Cook, & Zhu, 2008; Thanassoulis, Kortelainen, Johnes, & Johnes, 2011; Wu & Liang, 2010). In conventional DEA approaches, all DMUs are treated as black boxes and the internal structure is always ignored (Lewis & Sexton, 2004). Recently, a number of research projects have studied DMUs that have a two-stage network structure with intermediate products existing between the two stages.

For example, Seiford and Zhu (1999) measured the profitability and marketability of US commercial banks based on a two-stage process. In their paper, the first stage is called the profitability process, which uses inputs of labor and assets to produce outputs of profits and revenue. Those first stage outputs are then used as second stage input resources to output market value, returns, and earnings per share. Zhu (2000) applied the same two-stage processes to Fortune Global 500 companies. Kao and Hwang (2008) studied the efficiency of 24 insurance companies based on a two-stage process where operating and insurance expenses are used to generate premiums in the first stage, and then the underwriting and investment profits are produced in second stage by using the intermediate premiums as a resource. The same two-stage process has been applied in other contexts (An, Yan, Wu, & Liang, 2015; Chen & Zhu, 2004; Chen, Liang, Yang, & Zhu, 2006; Sexton & Lewis, 2003; and many others). All of the above examples, however, use the assumption that the intermediate products are the only inputs to the second stage, i.e., there are no additional independent inputs to that stage. There are, of course, other types of two-stage processes where the second stage has other inputs in addition to those produced by the first stage. For example, Liang, Yang, Cook, and Zhu (2006) use a two-stage process to measure the performance of supply chains with two members. The second stage uses as input not only the first-stage outputs, but also its own additional inputs. Li, Chen, Liang, and Xie (2012) applied this two-stage process to a case of regional research and development in China. In the second stage of the technology market, the inputs include the contract value (CV), a resource not used by the first stage. More detailed reviews of two-stage network structures can be seen in Cook, Liang, and Zhu (2010) and Halkos, Tzeremes, and Kourtzidis (2014).

In this paper, we generalize an innovative two-stage network process to account for those settings where some outputs from the first

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http://dx.doi.org/10.1016/j.ejor.2015.10.049
0377-2217/

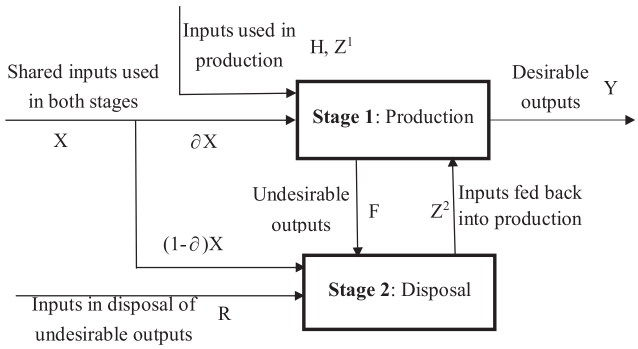

Fig. 1. Two-stage network process with shared flow and feedback.

stage are undesirable and may be processed in the second stage to obtain some desirable resources. These desirable resources are immediately fed back into the first stage process as inputs. We assume that the undesirable products of the first stage flow continuously to the second stage as inputs and that the second stage continuously sends its recycled products to the first stage as inputs. This means that the two stages run concurrently and feed each other, as can happen when the two are integrated in the same company. The second stage can be regarded as the purification or recycling of undesirable products (or parts of the undesirable products). Sometimes this processing is called *disposal* of the undesirable products but it should be noted that in our model "disposal" includes changing some or all of the undesirable products into desirable resources. An example of reusing the undesirable products would be melting down a malformed metal object to reuse the metal. Other examples include selling "factory seconds" (marred but functional products) to get income and taking good components out of bad products to build up supplies for later use in repairs. In our two-stage process, there also exist some shared inputs. Fig. 1 shows the framework of this type of process.

For further visualization of these concepts in a practical setting, we may consider the mode of circular economy (CE). Proposed by Pearce and Turner (1990), the mode of CE involves transforming the traditional "resource-products-pollutions" mode into "resources-products-regenerated resources" mode, which means turning wastes at one point in a value chain into inputs at another point. CE realized a closed loop of resource and energy flows in economic systems (Mathews & Tan, 2011). In recent literature, Yang and Feng (2008) provided a detailed case study on a circular enterprise, namely Nanning Sugar Co., Ltd., to show the successful transition and their essential impact factors. Hu et al. (2011) discussed the ecological utilization of leather tannery waste in the leather industry. Some CE progress in Dalian has been reviewed by Geng, Zhu, Doberstein, and Fujita (2009) as a regional level example. Finally, Wu, Shi, Xia, and Zhu (2014) indicated that CE framework contained three sub-systems, namely the resource saving and pollutant reducing (RSPR) subsystem, the waste reusing and resource recycling (WRRR) subsystem, and the pollution controlling and waste disposing (PCWD) subsystem. In the WRRR subsystem, some waste such as industrial waste water and solid waste are reused by the production stage process after processing in a disposal stage. Some of the disposal stage's input resources, like labor, are also used in the production stage process, which makes them shared resources in our model.

There are some DEA studies of undesirable outputs in two stage frameworks. Lozano and Gutiérrez (2011) proposed a distance approach to deal with network DEA problems in which undesirable outputs are generated. The distance approach was applied to the problem of modeling and benchmarking airport operations. Fukuyama and Weber (2010) considered undesirable outputs for evaluation of bank efficiency in a two-stage series system. Maghbouli, Amirteimoori, & Kordrostami, 2014 proposed a network DEA approach with undesirable intermediate products. In their paper, the undesirable intermediate products are studied either as final outputs or as intermediate outputs used as inputs to the next stage. Song, Wang, and Liu (2014) carried out a systematic study of the SBM model considering undesirable outputs and further expanded the SBM model from the perspective of two-stage networks. Wang, Huang, Wu, and Liu (2014) studied the efficiency of the Chinese commercial banking system in a two-stage network with undesirable non-performing loans.

Recently, some further studies of two-stage network processes have begun to involve shared resource flows. The shared resource flow in many production scenarios is defined as the resources which can be shared among different departments. Chen, Du, David Sherman, and Zhu (2010) indicated that in many real world cases, some inputs are actually shared by the two stages and it is impractical to determine the proportion used by each stage. For example, different departments of a university may share equipment and general expenditures (Beasley, 1995). As previously mentioned in Seiford and Zhu (1999), we point out that labor and assets are actually shared inputs for both stages i.e., both stages use the labor and asserts of the bank, and many of these inputs cannot be separated into the elements that are directly used for generating profits and revenues, in contrast to generating market value, returns, and earnings per share. Shared flows have been studied in the DEA literature. For example, Cook and Hababou (2001) developed DEA models to consider shared inputs. However, their models do not take into account the sharing proportions of shared inputs and two-stage network structures. Chen et al. (2010) developed DEA models for measuring the additive efficiency of two-stage processes with shared inputs that cannot be split. Chen's model considered only additive efficiency. Zha and Liang (2010) offered an approach for studying shared flows in a two-stage production process in series. Their approach is based on the assumption that shared inputs can be freely allocated among the different stages. Amirteimoori (2013) divided the shared flows into perfect and imperfect outputs by DEA in a two-stage decision process. Yu and Shi (2014) proposed a two-stage DEA model with additional inputs in the second stage and some of the intermediate products as final output. However, the above three papers all assumed uniform proportions of shared inputs for all DMUs when evaluating the efficiency of a DMU. Wu, Zhu, Chu, Liu, and Liang (2015) set different proportions of each shared resource for different DMUs to evaluate the efficiency of a parallel transportation system.

In the existing literature, we have found no paper that discusses the phenomenon of the undesirable intermediate outputs being processed into desirable resources for the first stage, and in fact even shared resources have not been studied in this two-stage structure. Murty, Russell, and Levkoff (2012) formulated DEA specifications of pollution-generating technologies that are a composition of two technologies: an intended-production technology and a residual-generation technology. Their pollution-generating technologies have considered the pollution-abasement activities, namely disposal of unintended outputs. Different with their paper, our paper is based on a two-stage network structure and has discussed the phenomenon of reusing the unintended outputs. The purpose of this paper is to develop an approach for measuring efficiency for DMUs that have a two-stage network process with a shared flow and feedback as shown in Fig. 1. Our two-stage structure is different from previously-studied two-stage processes, and the previous analysis techniques are not suitable for our case. Therefore we firstly proposed a weighted sum efficiency formula, namely additive efficiency (Chen, Cook, Li, & Zhu, 2009), to evaluate the overall efficiency of the two-stage process. Then, considering the difference of the two stages in that stage 1 is always used for production while stage 2 is always used for purification and processing of undesirable outputs, we apply the non-cooperative game (leader-follower) models proposed by Liang et al. (2006) and Liang et al. (2008) in DEA to distinguish the importance